Engineering Studio Pedagogy – First Experience in Integrating Novel Studio Sessions in Biomedical Engineering Courses

Viswajith S Vasudevan, Ph.D.
Meinig School of Biomedical Engineering
Cornell University
Ithaca, NY, USA
viswajithsv@cornell.edu
ORCID: 0000-0003-2827-9763

Stephanie M Fuchs, Ph.D.
Meinig School of Biomedical Engineering
Cornell University
Ithaca, NY, USA
smf245@cornell.edu
ORCID: 0000-0001-9264-3094

Jonathan Butcher, Ph.D.
Meinig School of Biomedical Engineering
Cornell University
Ithaca, NY, USA
jtb47@cornell.edu
ORCID: 0000-0002-9309-629

***Abstract*— This innovative practice full paper describes the first experience introducing Engineering Studio Pedagogy in Biomedical Engineering courses at Cornell University. Biomedical Engineering is undergoing a thorough introspection to improve the curriculum and teaching methods for undergraduate courses. Innovations in teaching techniques have been shown to impact student learning positively. With many evolving needs in preparing tomorrow's biomedical engineers, identifying key skills is paramount to a successful program. At Cornell University, following the adaptations that were necessitated due to the events at the turn of the decade, an initiative by the University was taken up to foster active learning amongst students. Our biomedical engineering program aimed at providing a pedagogical method that would challenge students with real-world "open-ended" engineering problems, promote teamwork and in a low-stakes setting. We called this pedagogical method the Engineering Studio Pedagogy. This paper summarizes the experience of implementing this as a pilot at Cornell University in Fall 2023, outlining how these studios were designed, the student experience obtained through surveys, and the instructional team's experience. The studio sessions demonstrated noticeable improvements in students' learning, teamwork, and motivation, particularly in a low-stakes setting. However, the results for tackling "open-ended" engineering problems were more mixed.**

Keywords— Engineering Studios, Open-Ended Problems, Student Learning, Low-stakes.

I. Introduction

In the past few years, surrounding the events associated with the global pandemic, and the shutdowns, Engineering departments had to adapt quickly to new teaching circumstances. At Cornell University a concerted effort was undertaken to integrate more active learning into the classrooms of all majors. Cornell Engineering is a key participant in this initiative known as the Active Learning Initiative. Beginning the Fall 2023 semester, the Meinig School of Biomedical Engineering, a department under Cornell Engineering embarked on a 3-year project that was funded under the initiative by the University, to introduce an active learning component in the curriculum of the Biomedical Engineering (BME) major.

Biomedical engineering's inherent nature enables creativity and practical problem-solving. The Active Learning Initiative project allows us, as BME instructors and faculty members, to make a strategic shift and introduce a pedagogical approach that empowers students to think creatively while learning course material collaboratively. In this paper we outline the motivation for innovation in the BME curriculum, the pedagogical approach we introduced during the Fall 2023 semester, and the learnings from that experience both from the instructors' side as well as the experience of the students.

A. *Motivation For Innovation in BME Curriculum and Pedagogy*

Biomedical Engineering (BME) has seen significant growth in undergraduate interest over three decades, driven by its relevance to addressing clinical and societal issues[1]. However, the vast amount and diversity of knowledge required for success in this field presents challenges and opportunities for educators[1-3]. Nationally BME as an undergraduate major has struggled to define its discipline-specific knowledge and skills, which has blunted its impact on professional training. Currently, most BME curriculum consists of the following: (1) Initial courses across traditional engineering disciplines; (2) Required pre-health biology/chemistry sequences; and (3) A capstone design project.

White et. al, in their editorial cover broadly different core competencies of BME as a discipline, in which one of the questions explored is "How does Design Distinguish BME graduates from other engineering disciplines?"[3]. Their study indicated that BME departments are good at teaching interdisciplinary knowledge, understanding anatomy and physiology, and understanding biological constraints, among others. However, it raises questions about the department's effectiveness in teaching engineering skills, principles, and constraints.

According to the US Department of Labor's statistics, as of 2022, approximately 19,200 biomedical engineering positions are available. Moreover, projections indicate a steady growth rate of 5% annually from 2022 to 2032[4]. A study on BME graduates' early career pathways found that respondents framed their careers in two ways. Those with positive opinions valued engineering degrees, particularly problem-solving skills. In contrast, alumni with negative opinions expressed concerns about links to engineering[5]. This highlights the need to revisit how to prepare students for engineer roles.

This work was funded by Cornell University's Active Learning Initiative. https://teaching.cornell.edu/programs/faculty-instructors/active-learning-initiative

B. *Engineering Studio Pedagogy - Background*

Biomedical Engineering as a discipline has increasingly adopted anchored instructional pedagogy such as Problem-Based Learning[6-10], Project-Based Learning[11] and Challenge-Based Learning[12]. For instance, Georgia Tech employs a group-based problem-solving approach facilitated by a faculty member. Problem-based learning is common in medical schools, which is not the case in engineering[1]. In traditional medical problem-solving, students are presented with a single diagnosis task that culminates in a predetermined single answer expectancy. In contrast, the Georgia Tech implementation introduced a more nuanced approach, where problems were deconstructed into manageable parts, constraints were identified, and an analytic framework was developed to facilitate multiple possible solutions. This novel pedagogical strategy mirrored design-based challenges, a less formal process than traditional design protocols. The outcome of this innovative instructional move was a significant boost in student confidence, inquiry skills, teamwork abilities, and faculty-student connections – all without requiring the same level of resource allocation as traditional lecture courses.

The National Science Foundation (NSF) established an Engineering Research Center (ERC) in the 1990s, one of which was the Vanderbilt-Northwest Texas-Harvard/MIT (VaNTH) ERC[1]. This ERC employed the How People Learn (HPL) framework[13]. HPL framework prioritizes pedagogy centered on knowledge, assessment, learner, and community. By collaborating with learning scientists, VaNTH successfully implemented HPL through a challenge-based instructional approach in courses like Biomechanics[14-16]. For implementing HPL effectively, the VaNTH ERC's work highlights the importance of teaching techniques such as the STAR Legacy Cycle[14, 17, 18]. The main idea of the STAR Legacy Cycle is to present students with a challenge, followed by idea generation, multiple perspectives, research and revision, synthesis and testing, and finally presentation of the solution. The implementation of HPL principles aimed to develop adaptive expertise in students. While some evidence supports this notion, it is challenging to test. The project developed an online learning technology to deliver problems, which offers advantages like self-paced problem-solving with rapid feedback. However, the system proved too complex for most faculty members to use[1].

C. *Engineering Studio Pedagogy – Our Implementation*

The Active Learning Initiative project allowed us to make changes to the course being discussed in this paper, by encouraging us to try and answer questions such as (1) can we adapt the best practices of the STAR Legacy teaching techniques, HPL, and a process like the Problem-Based Learning at Georgia Tech; while overcoming the limitations in HPL framework as noted above, (2) can we implement this within the framework of a course that is predominantly lecture-based, (3) can we use the minimal resources such as using just the course instructional team to support a whole class, (4) can we do it in a low-stakes environment? Introspection of these questions gave us a chance to challenge our teaching practices. Drawing inspiration from the formative feedback process in architecture studio-based courses, we implemented it in the Engineering Studio Pedagogy.

Our implementation of the engineering studio pedagogy utilizes the best practices such as providing a challenge to the students, breaking down the problem into different tasks, and exploring physiological and engineering constraints, thereby allowing opportunities for the students to research, revise, and synthesize ideas. "Open-ended" problems with multiple solutions were chosen, and the students got to work on finding a solution creatively. This enabled us to complete the full STAR Legacy cycle, providing students with multiple opportunities to present their work to their peers, receive feedback from their peers and the instructional team, and revise their work during their collaborative work time following each presentation. A detailed description of our Studio session setup can be found in Section III.

II. THE COURSE DETAILS

A. *Description of the Course*

In Fall 2023, Engineering Studio Pedagogy was introduced in one required, senior-level course in the BME curriculum at our university. The course is titled "Biomedical Engineering Analysis of Metabolic and Structural Systems". It is a 3-credit course and part of the 5-core course. The curriculum includes a 5-course core sequence that all BME major cohort students must complete as part of their graduation requirements.

The course tackles multiscale structural and metabolic physiology of organ systems and introduces engineering analysis through quantitative physiology. Four major organ systems form the basic outline of the course, and these organ systems are split into 5 modules. The 5 modules are listed in Table I below.

TABLE I. COURSE MODULES

Module Number	Abbreviation	Module Name
1	H	The Heart
2	VS	Vascular System
3	PS	The Pulmonary System
4	MS	The Musculoskeletal System
5	RS	The Renal System

B. *Course Assessments – Graded Components*

Homework assignments, primarily problem-solving questions, were assigned for a module, typically due within a few days of the end of the module. There was a total of 5 homework assignments. At the end of 2 modules, there was a preliminary exam for about 2 hours. A total of two preliminary exams were scheduled and the students as part of the chance to have a formative assessment component, were allowed to gain half the points they lost after the grades were released.

The other graded components included a 3-hour cumulative final exam covering the 5 modules. Finally, the course also had 3 laboratory sessions that allowed students to undertake hands-on investigative research related to the module material they were learning. The homework, general participation in class, labs, preliminary exams, and final exams all counted toward the student's final grades.

The engineering studios were the only non-graded component of the course. The paper's focus is the new engineering studio sessions, 5 of which were introduced into the curriculum. These happened at the end of each module and more details are given in sections II and III below.

C. Class Strength

The primary enrollees of the course were seventh-semester senior BME majors. It was an elective course for the Mechanical and Aerospace Engineering major. The demographics are given in detail in the next subsection. Juniors involved in study abroad, pre-med streams, and such special reasons were allowed to take the course provided the course was not at maximum enrolment as per university norms. In Fall 2023, the class had an enrollment of 51 students.

1) Demographics

Out of the total enrollment, 50 students were seniors, and 1 student was a junior, class had a total of 35 students who identified themselves as Women, 15 who identified themselves as Men, and 1 student who preferred not to identify. Except for 1 student the class was made up of BME major students. The ethnic distribution of the students is noted in Table II.

2) The Instructional Team

The course had 1 course instructor (CI), primarily responsible for the course. To assist the CI, there was 1 Ph.D. graduate TA and 1 Master's graduate TA. Grading of assessments and assisting during labs were the TA's main roles. The labs had a separate instructor (LI) who played no other role in the course. Finally, as part of the Active Learning Initiative that the university was undertaking, this course which falls within the initiative was provided the support of 1 postdoctoral associate (P1) who played a role in refining the course material alongside the CI running the studios. A second postdoctoral associate (P2) helped the team run the studios.

TABLE II. ETHNIC DISTRIBUTION OF CLASS

Ethnicity	Number Enrolled
White	18
Hispanic/Latine	2
Black or African American	6
Middle Eastern or North African	2
Asian	20
Others / Self-Identified	3

III. DESIGN OF STUDIO SESSIONS IN THE COURSE

Before Fall 2023, the course structure was strictly didactic lecture-based, with a laboratory component. The class met thrice a week for 50 minutes. With the introduction of the studios, the lecture schedule had to be modified, resulting in the loss of 5 lecture periods over the semester. The idea to replace the 1-hour lecture with the 3 hours of studio, was to encourage working together for 2 hours in class rather than working those 2 hours alone on homework and learning the course materials. This section details the implementation of the studio sessions, with examples.

A. Timelines and Studio Topics

The studio sessions were planned to coincide with the culmination of a course module, basically, the final lecture of a module. The Fall 2023 semester had a total of 16 weeks, and per the contact hour requirements of the University and New York State Education Department (NYSED), a typical fall 3-credit course would have about 32 to 33 lectures. With the reduction necessitated for the studios, the 5 modules were split between 28 lecture periods. This meant that the studios were scheduled on an average every 7th meeting.

Weeks with laboratories have a lecture session on Monday, with the other two days replaced with labs. Again, due to contact hour requirements, studios could not be scheduled during a lab week. On average, a studio session took place every 2 weeks, on a Monday. but in the event of a lab week, this gap between studios ended up being 3 weeks. The topics of the 5 studios and the corresponding modules are summarized in Table III.

TABLE III. STUDIO TITLES

Studio	Module	Title
1	H	Engineer a Solution for Cardiac Arrhythmia.
2	VS	Reverse Engineering a Lumped Parameter Model to Modify it to test Solution for Cardiac Arrhythmia.
3	PS	Modeling the Physiological Effects of Gravity on the Respiratory & Pulmonary Systems – Breathe Hold Free Dive.
4	MS	Engineering Fracture Healing
5	RS	Smart Bioartificial Kidney

B. Adjacency to Course Material and Assessments

We deliberately chose the studio topics to align with the lecture materials to facilitate connections between the two. In addition, the concepts covered by the studio problems and the corresponding lecture materials were part of the homework associated with the module. The reasoning for this was to synergize the different components while providing a chance for the students to get familiar with the concepts asked in the homework and receive instant feedback from the instructor on their understanding and approach to the course material relating to the studio topic. In short, we wanted to assign a problem like the questions asked in the assessments, be it the homework or exams, but not the same to avoid turning the studios into discussion or recitation sessions.

C. Studio Prompts

The week before the studio on a Monday, the studio problem is released to the students through a studio prompt. The studio prompt is primarily a one-to-two-page writeup introducing the problem. The prompts contained a short introduction, followed by the problem statement, and concluded by outlining the Engineering Studio Process. The Engineering Studio Process outlined the four main tasks which will be expanded in D below. Additional document uploads were made in the event of providing necessary reading material that introduced a concept that was not typically taught in a course. For instance, in Studio 2, the students were given additional handouts about the reverse engineering process, and the lumped parameter model they had to reverse engineer was used in a homework problem.

D. Day of the Studio

On the day of the studio, most of the preparatory work involves setting up the infrastructure necessary for the studios by the instructional team. A standard classroom was assigned for the course. The same room was to be used for the studios as well. Below are the details of the classroom modifications, duties, and responsibilities of the instructional staff of the current iteration.

1) Duties and Responsibilities

Most of the work in the studio sessions is done by the students. This streamlines the duties and responsibilities of each member of the instructional staff.

a) Postdoctoral Associate (P1):

As part of the Active Learning Initiative project, one of the primary duties of the postdoctoral associate (P1) is to set up, design, and run studio sessions. Setting up the studio session involved consulting the lecture materials to identify a real-world problem on the topics covered before the studio. The next step was consulting on the feasibility of using this real-world problem in a studio with the course instructor, and what the instructor expects from the studio session. Based on this discussion, P1 suggested topics for the studios as outlined in Table 1 and prepared the draft of the studio prompt. Upon approval from the course instructor, the studio prompt was uploaded to the students on Canvas by P1.

On the day of the studio session, the primary member of the team running the session was P1. Table IV lists the general flow of the studio session with the time allotted for each step.

The goal during the session from the instructor was to be akin to a conductor in a musical concert, where P1 was the timekeeper, leading the whole class into tasks by outlining what was expected, the directions the students could take and lastly being the lead designer by providing an example of how she/he would have approached the same task. As evidenced in Table IV, agenda item 1 is the only major time allotted for the studio instructor, P1 to deliver any content, and the role after that shifts to a timekeeper and as a resource for students in providing real-time feedback on their work.

TABLE IV. STUDIO DAY AGENDA

	Agenda Item	Time Allotted (min)
1	Introduction by P1	5
2	Design Constraints & Considerations	15
3	First Pin Up	10
4	Block Diagram	30
5	Second Pin Up	20
6	Break	10
7	Engineering Solution	60
8	Final Pin Up	30
	Total Session Time	180

b) Course Instructor (CI):

The course instructor was present during the studios for the full 3-hour block, and primarily the responsibility of the course faculty was to provide formative assessment and feedback to ensure best outcomes from the course. The CI was involved in the setup before the studio and finalized the title, prompt, and introduction slide contents for the studios in collaboration with P1.

c) Other Members of the Team:

In addition to these members and their responsibilities, there was another postdoctoral associate (P2) whose primary role was observing students working as a team and interacting with the instructional team for research purposes. P2 helped in studying the group dynamics among the students, and for the instructional team to have an account of how the session progressed and if any improvements or changes need to be made in the upcoming session. The course TAs and the lab faculty were not directly involved with the studios.

2) Classroom Arrangements and Materials

The classroom we used for the course had a seating capacity close to 80 and given the enrollment numbers were significantly lesser than capacity it was a large room. It was a standard classroom with whiteboards towards the front and a projector system, with tables and chairs, arranged in rows. Since the classroom was not specifically designed for studio sessions, the instructional team had to innovate to foster collaborative work amongst students. For the first round of studios, the students used their own devices such as laptops, tablets, and notebooks to work on the ideas, which was not very conducive to working together. We could observe that the students were sitting together but working individually on their devices.

The instructional team therefore to foster group work, before the second studio and all the remaining sessions, converted the classroom into a pod configuration (the furniture was moved into pods) as shown in Fig 1.

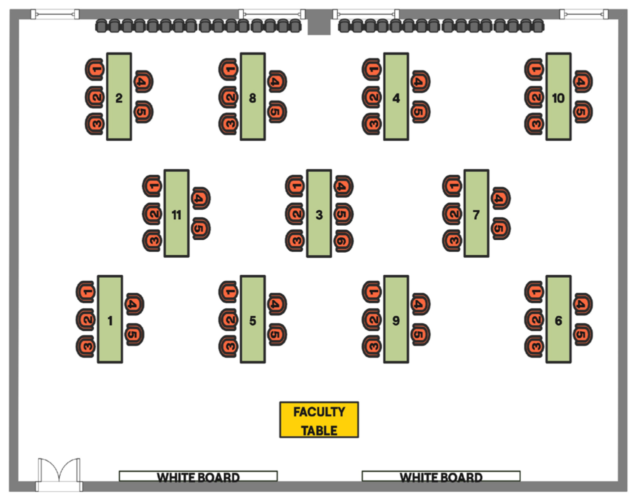

Fig. 1. Representation of Pod Formation of Classroom for the Studio Sessions.

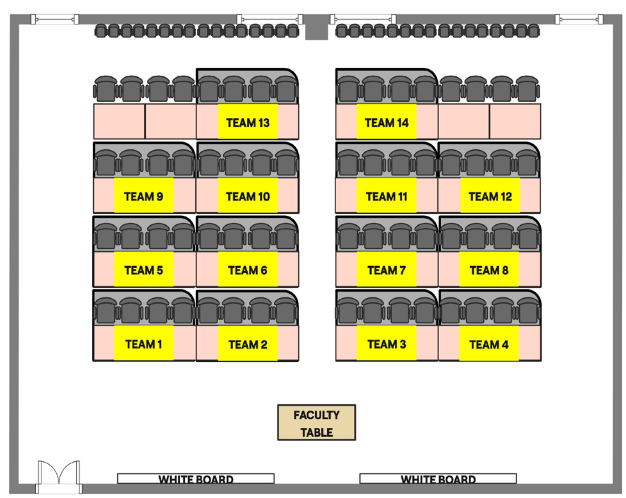

Fig. 2. Group formation for the studios based on the seating arrangement during the lecture seating arrangement.

To allow the students to work together as a team, a large sheet of paper was laid in the middle for the students to work on it like a canvas at the same time.

3) Team Formation

For the studios, the students were informed they could form their teams based on where they were seated in the normal lecture configuration. Fig. 2 shows a representation of the student seating in the classroom and how they were clubbed into the studio teams. The maximum number of students per team was kept at 4. No other restrictions were applied to the team formation, and the formation was purely based on where they were seated in the lecture session before the first studio.

E. Studio Tasks and Breakdowns

After the introduction, the students were assigned the first task. The first task was deducing the engineering design constraints and considerations. The students had to come up with what to their team were the main constraints they would encounter in designing decisions for a problem in Table III. They were also asked to list any other considerations they would have over and above the ones needed to address the constraints, and these could be associated with physiological, pathological, or ethical factors involved in these biomedical engineering problems.

A pin-up followed the first task (see Subsection F below). After the first pin-up, the students were asked to sketch a block diagram of the organ system under consideration. The task needed the students to show the interaction of the different levels of physiology, such as organ, molecular, and cellular levels. The students had to indicate the blocks affected by the disease or concern points like in the case of a breath hold free dive (Studio 3) where the oxygen consumption happens. A second pin-up followed for the block diagrams, and the students were given feedback on their work by their peers and the instructional team.

The third and final task was the engineering solution. In this task, the students had to add mathematical formulations or equations necessary to study the interaction between the different blocks. For instance, blood flow in the aortic valve could be represented as a ratio of the difference in pressure to the resistance of the aortic valve (Poiseuille's Equation). In addition, the students were tasked with finding or identifying a novel solution to the existing biomedical engineering problem. We challenged students to think outside the box, unleashing their creativity to tackle complex engineering problems. This approach was designed to prepare them for real-world scenarios where equations are essential, allowing them to seek help when needed. In the final session, each team had 3 minutes to present and discuss their innovative ideas with the instructional team and their peers.

F. Student Pin Ups – Formative Feedback

Formative feedback is defined as the information communicated to the learner to modify their approach, thinking, and in the case of the studios, design for the enhancement of learning[19]. Studies are elucidating the impact of formative feedback, specifically born out of low-stakes activities enhancing the student's learning outcomes and deliverables[20-22]. The studios provided the opportunity to include two forms of formative feedback, one from the peers and the other from the instructional team. Studies have shown peer feedback, especially in a learning environment enhances student outcomes, and therefore peer feedback was encouraged as part of the studios[23].

The concept of Student Pin Ups was borrowed from art studios, architecture firms, and fashion designers. These professionals showcase their work before its release to get feedback and make improvements. The idea is to bring this same process to engineering classrooms, where students can share their designs, receive feedback from peers, and refine their ideas iteratively. This iterative approach helps students collaborate-design-critique-refine-repeat until they arrive at a final solution. Normalizing this process prepares students for real-world design challenges that require refinement and optimization.

During every Pin-Up session, students were asked to share their work and provide a one-minute explanation of their design choices, constraints, and considerations. In the first studio session, they shared their work via Zoom Screen Share from their devices. Each team presented a photo of the worksheet from the second session. After each team's presentation, peers were given time to provide feedback either orally or through the online discussion platform used in the course, considering time management constraints. Students were encouraged to upload their work to facilitate better peer feedback. Once peer feedback was complete, the instructional team (P1 & CI) provided any additional feedback.

G. Studio Deliverables

At the end of each studio session, the students as a team were encouraged to upload their work on the online discussion platform used by the course for their peers to view and give feedback. The instructional team collected the worksheets for research purposes.

H. Grading Schemes

The studios in the course were completely ungraded. There were no attendance or participation grades, and the work that the students submitted was also not graded. The studios did not carry any weightage towards the final grade for the semester, as we wanted students to engage and take risks in solving real-world problems enhancing their engineering competency and identity, as well as keeping the studios as a practice session for other assessments in the course, such as homework and exams.

IV. Current Study & Research

The purpose of this study is to document the experience of introducing a novel pedagogical method. We seek to evaluate how well our studios achieved the research aims listed below and how the students perceived the studios through their experience of participating in the studios. We couple these results, with lessons learned from the instructional team implementing the studio pedagogy. By highlighting successes and lessons learned, we seek to use this information to encourage the implementation of engineering-studio pedagogy in biomedical engineering courses.

A. Research Aims

During the ideation phase of introducing studio learning in the BME core courses, we wanted to study how the change in pedagogical approach impacted the students. Our broad research themes: (a) Proficiency, (b) Group Dynamics and Teamwork, (c) Real-time Feedback, and (d) Student Motivation form the underlying basis for this study. The specific research questions we assessed, and the rationale are listed below.

1. What is the impact of the studio sessions on student learning?

The studios were conceived to provide a learning environment where students solved real-world problems. These problems were set up to allow the students to gain research and development experience, they may face in their careers as Biomedical Engineers upon graduation. With this specific question, we aimed to study if the students become proficient in skills required to solve real-world problems and in designing solutions to real-world problems.

2. What is the level of student's comfort with open-ended problems?

As we delved into understanding how students perceived open-ended problems, our research question took shape: How do students approach and respond to open-ended engineering challenges? Before studios, the course assessed student mastery of learning objectives through problems with singular, correct answers. Students solve these problems step-by-step in a rigid manner, often reducing complex issues to binary "right" or "wrong" verdicts. In contrast, the studio sessions aimed to provide an opportunity to tackle open-ended engineering problems that did not prescribe specific solutions. We also sought to explore the undergraduate students' level of comfort and creativity when addressing these unconventional challenges.

3. How do the Team Dynamics and Group Work impact students' learning, and ability to solve real-world biomedical engineering problems?

The studios enable students to work on these problems as a group, allowing them to discuss with their peers at every step to arrive at their solution. It provided us with a chance within a controlled environment to study the interactions between students in their groups and observe the process of teamwork in solving the problem set during a studio session.

4. What is the level of student motivation to participate, learn, and succeed in low-stakes environments?

As described in Section II, the studios were designed to provide an environment where the students could practice the course material and engineering skills, without any associated summative assessments. To investigate this question, we set the studios as a formative low-stakes environment, with opportunities for feedback and collaborative learning. We aimed to gauge the motivational levels of students in this context.

B. *Institutional Review Board (IRB)*

The Active Learning Initiative was accompanied by Institutional Review Board (IRB) approval for this study, with protocol number 0146842. As part of the research design, informed consent was obtained from all students enrolled in the course during the Fall 2023 semester at the beginning of the first week of classes.

V. Survey & Results – Student Experience

To assess the students' experience and learning through these studio sessions, students who gave consent to be evaluated were administered a comprehensive survey under the IRB protocols at the end of the semester. Assessing changes in student perceptions over an entire semester was undertaken instead of conducting surveys after every studio. The instructional team engaged with students during informal office hours to gauge the logistics of the studios and assess their overall effectiveness. Although these conversations are not documented in this paper, we will summarize the instructors' experiences in the Discussion section. Our four research questions or aims, guided the development of the survey questions.

A. *Impact of Studio Sessions on Student Learning*

The goal of the studios was to create a learning environment where students (a) solved real-world problems in a group setting, (b) undertook practical research and development experience, (c) design solutions to biomedical engineering problems as a group, (d) learn by doing in real-time, (e) learn from peers, and (f) grained practice in creative problem-solving. To evaluate these learning outcomes, we first investigated whether students believed their proficiencies changed after participating in studios using the following statements as noted in Table V. The students responded to two Likert Scale questions, rating their proficiency levels on a 5-point scale ranging from "Strongly Disagree" to "Strongly Agree". The student survey data for the same set of statements before participating in the studios and after participating in the 5 studio sessions held in the semester are shown in Fig. 3.

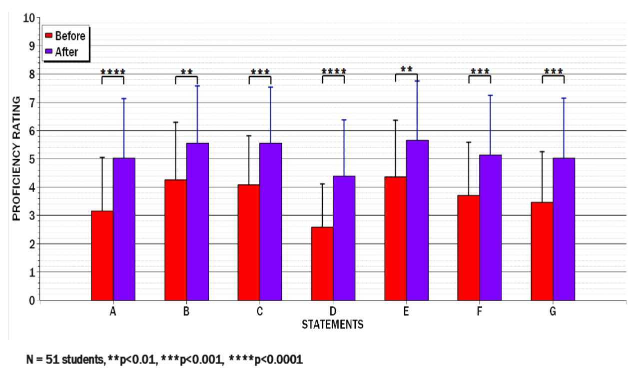

Fig. 3. Mean Value Rating for Each Statement provided by the students to assess their proficiency before and after attending studios.

TABLE V. Proficiency Assessing Statements

	Statement
A	Developing an engineering schematic
B	Identifying engineering constraints
C	Identifying design objectives
D	Formulating mathematical equations to quantify physiological systems
E	Communicating developed engineering models
F	Designing solutions that address engineering
G	Critiquing engineering models

The students reported an increase in proficiency (Fig. 3.) in all the statements from their experiences before attending the studios to after attending the studios in Fall 2023. Given, that this was their first-ever experience with any studio pedagogy, this increase is encouraging and can be attributed to the type of experience the studios introduced into the curriculum in the Fall 2023 semester.

The change in proficiency for each statement was calculated by subtracting each student's as per equation 1 where P_A is the score for the statement after attending studios, P_B is the score for the statement before attending studios and ΔP is the change in proficiency for the student.

$$\Delta P = P_A - P_B \quad (1)$$

The change in proficiency was then sorted into students with increased proficiency (ΔP>0), students with no change in

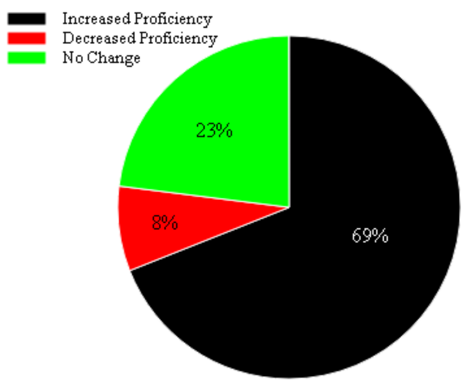

Fig. 4. Percentage Distribution of Change in Proficiency of Students as a cummulative of individual student's response to the statements before and after attending studios.

proficiency (ΔP=0), and students with decreased proficiency (ΔP<0). The percentage of students with each of increased proficiency, no change in proficiency, and decreased proficiency were calculated for each statement by dividing the numbers for each category by the total number of enrolled students. To get an overall perspective the mean percentage for each category was calculated across the statements and is shown in Fig. 4.

B. *Comfort with Open-Ended Problems*

The studios aimed to enhance the acceptance of open-ended problems assigned as part of the studio. To assess the comfort levels of the students, a Likert 5-point Scale question with 5 statements was administered the students responded to a Likert Scale question, rating their proficiency levels on a 5-point scale ranging from "Strongly Disagree" to "Strongly Agree". The statements asked as part of this question are summarized in Table VI. The responses of the students for each statement are shown in Fig. 5.

The students' reliance on instructors decreased when faced with difficulties in the studio, while they reported needing more guidance in open-ended problems. Around 31% of students changed their approach or learning due to these open-ended challenges. Most students felt that the studios didn't boost their confidence in solving open-ended problems, citing two main reasons: lack of guidance on how to proceed and uncertainty about what constitutes a correct answer.

TABLE VI. OPEN-ENDED PROBLEMS COMFORT ASSESSING STATEMENTS

	Statement
I	When I encounter difficulties in the studio, my first step is to ask an expert, like the instructor.
II	The open-ended nature made me reliant on guidance.
III	There was little to no difference in my approach or my learning.
IV	The studios improved my confidence to solve open-ended engineering problems

C. *Team Dynamics and Group Work*

The students were asked two Likert Scale questions on a 5-point scale from "Strongly Disagree" to "Strongly Agree", to evaluate learning effectiveness during group work and its relationship with team dynamics. The first question focused on their experience working in groups during the studios, as listed in Table VII.

TABLE VII. GROUP WORK EXPERIENCE ASSESSING STATEMENTS

	Statement
I	Generally, I prefer working in a group on assignments rather than alone
II	I liked being able to select my own team
III	I felt comfortable sharing my ideas with my groupmates
IV	My ideas were heard by my teammates
V	My ideas were incorporated into my group's work
VI	I was able to learn from my teammates

Most students agreed with all the statements regarding their experiences working within their groups during studio sessions (Fig. 6).

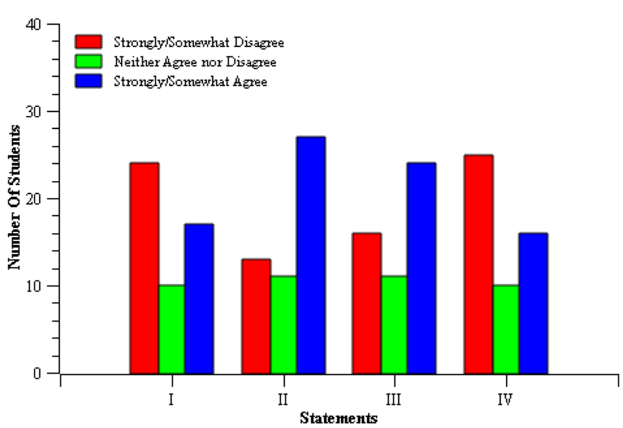

Fig. 5. Count of Students responding to each category of rating as indicated in the legend for each of the statements assessing comfort levels of "open-ended" engineering problems.

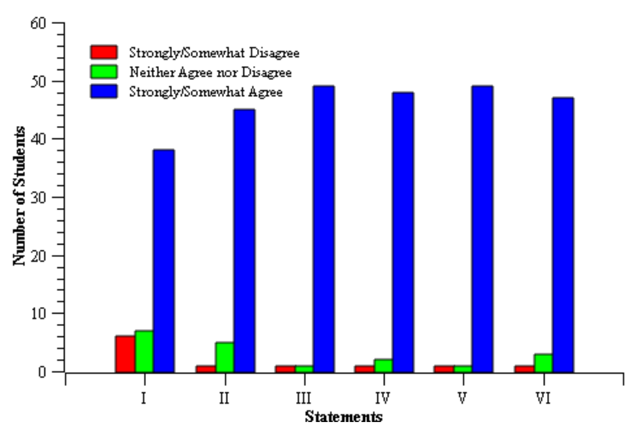

Fig. 6. Count of Students responding to each category of rating as indicated in the legend for each of the statements assessing group/teamwork experience and their learning.

Some students preferred working alone over group work, which sparked our interest. We conducted a Pearson correlation analysis to explore potential links between these statements and the students' responses[24]. The correlation coefficients between different statements are summarized in Table VIII.

A coefficient value close to 1 indicates a strong correlation between two entities. Notably, statements I and VI have a low correlation. Statements II and VI show no significant correlation in this group of students. However, students who felt comfortable sharing ideas with their peers were highly likely to share their thoughts, see them incorporated into the discussion, and learn from their teammates. The strongest correlation between statements IV and V reinforces the student comfort's importance in fostering effective learning. In conclusion, our data suggests that student comfort levels in their groups significantly influence sharing ideas, incorporating feedback, and learning from peers in a group setting.

TABLE VIII. CORRELATION MATRIX.

	Statements					
Statements	***I***	***II***	***III***	***IV***	***V***	***VI***
I		0.3816*	0.2473^	0.0128#	0.0674#	0.1575#
II			0.2802^	0.1996#	0.2316#	0.1308#
III				0.7631&	0.7767&	0.6724&
IV					0.9288&	0.6879&
V						0.7485&
VI						

- p > 0.1, ^ - p < 0.05, * - p < 0.005, & - p < 0.0005.

D. Student Motivation in Low-Stakes Environment

To gauge student motivation for learning and solving problems in a low-stakes setting (where grades aren't at risk), we examined how comfortable they felt with failure during our studios. We wanted to contrast this with high-stakes assessments like exams, homework, or projects that often prioritize getting the "right" answer. To achieve this, we used a Likert 5-point Scale question and asked students to rate their motivation and workability in low-stakes environments. The results are summarized in Table IX.

TABLE IX. MOTIVATION ASSESSMENT STATEMENTS AND DATA

Statements			
ST1	My work in the studios was ungraded, so I felt the studio was a low-pressure environment.		
ST2	If my work in the studios is ungraded, I do not feel motivated to participate.		
ST3	My goal in the studio was to finish the model as quickly as possible.		
Student Rating Data			
	Strongly/Somewhat Disagree	**Neither Agree nor Disagree**	**Strongly/Somewhat Agree**
ST1	4	6	41
ST2	27	8	16
ST3	21	15	15

We performed a correlation analysis using Pearson's correlation coefficient to explore relationships between statements. The results showed no statistically significant correlations between ST1 and other statements, except a weak correlation ($r = 0.1679$, $p > 0.2$) between ST1 and ST2. In contrast, we found a strong positive correlation ($r = 0.5312$, $p < 0.0001$) between ST2 and ST3. These correlations support the conclusions: (1) generally, students agreed that studios were a low-pressure environment; (2) The students interestingly reported that the low-pressure environment did not negatively affect their motivation to participate in the studios; and (3) Most of the students rejected the notion that they tried to get their work done as quickly as possible, indicating that they were motivated to spend time working on the studio problems

VI. INSTRUCTOR EXPERIENCE

As part of our first experience running studios in our program, we faced numerous challenges and made significant adjustments to our approach. We experimented with various methods to facilitate peer-to-peer sharing among group members and the wider class. Although the process was uncertain, our instructor and postdoctoral associate collaborated seamlessly to adapt lecture content to suit a studio pedagogy. To achieve this, we planned lecture topics, modified homework questions to tie in with studio activities, and maintained an ongoing dialogue with students to gauge their reactions to the changes. The postdoctoral associate dedicated extra time to conducting personal interviews and conversations about the studios and student experiences with the adjustments made.

Through the conversations with students, our instructional team uncovered valuable insights that influenced our planning for studio sessions throughout the semester. This ongoing experimentation required extra effort from us, which impacted the students. However, the benefits of this teamwork were undeniable - it allowed students to experience real-world problems firsthand and a pedagogical approach that was significantly different from what we used to practice previously. Our team was cognizant of the novelty factor influencing the student experience, and realized that some of the student self-reported could be influenced by this novel pedagogical approach. This refreshing and motivating shift in our teaching practices was a welcome change for us as instructors.

As an instructional team, we faced the challenge of innovating without a conducive infrastructure. While this posed a significant hurdle, it also allowed us to experiment and discover the best ways to foster teamwork and studio pedagogy in such scenarios. One valuable feedback from the students was their request for instructors' perspectives on the same problem, which we incorporated into our approach for future studios. This allowed students to self-validate their work, a crucial aspect of the studio pedagogy. A potential area for future study is to investigate the impact of instructor validation on student comfort levels when tackling open-ended problems.

VII. FUTURE ITERATIONS

The studio pedagogy in this course will be done for a second time with all the learnings from the first experience in the Fall 2024 semester. Other core courses, at different levels of the BME curriculum, will also be having starting with Spring 2024 semester studio sessions in them. This pilot implementation and its experience have played a significant role in shaping these future iterations of studios, not only in this course but also in the other ones with studios. The future implementation in Fall 2024, will be for a cohort of students who would have experienced studio sessions in other courses and will help us as an instructional team to compare the data from this iteration to see the influence of the novelty factor.

VIII. Conclusion

This past Fall semester in 2023, we introduced an engineering studio pedagogy to a required core course for senior biomedical engineering students. The experience was well received by both the students and the instructional team, with several learnings arrived at by the team to model or make these studios better in the coming Fall semester and beyond. The studios fostered student learning of course topics and introduced them to "open-ended" engineering problems and cooperative learning. The students felt the studios were a low-stakes environment that motivated them to work on these problems with minimal involvement of the instructors. The studios also helped provide formative feedback to students both through their peers and the instructors, which was certainly appreciated.

References

[1] R. A. Linsenmeier and A. Saterbak, "Fifty Years of Biomedical Engineering Undergraduate Education," Annals of Biomedical Engineering, vol. 48, no. 6, pp. 1590-1615, 2020/06/01 2020, doi: 10.1007/s10439-020-02494-0.

[2] S. Subramaniam et al., "Grand Challenges at the Interface of Engineering and Medicine," IEEE Open Journal of Engineering in Medicine and Biology, vol. 5, pp. 1-13, 2024, doi: 10.1109/OJEMB.2024.3351717.

[3] J. A. White et al., "Core Competencies for Undergraduates in Bioengineering and Biomedical Engineering: Findings, Consequences, and Recommendations," Annals of Biomedical Engineering, vol. 48, no. 3, pp. 905-912, 2020/03/01 2020, doi: 10.1007/s10439-020-02468-2.

[4] U. S. D. o. L. Bureau of Labor Statistics. "Occupational Outlook Handbook, Bioengineers and Biomedical Engineers." https://www.bls.gov/ooh/architecture-and-engineering/biomedical-engineers.htm (accessed 2024).

[5] J. Rohde, J. France, B. Benedict, and A. Godwin, "Exploring the early career pathways of degree holders from biomedical, environmental, and interdisciplinary/multidisciplinary engineering," in 2020 ASEE Virtual Annual Conference Content Access, 2020.

[6] P. T. Bhatti and J. H. McClellan, "A Cochlear Implant Signal Processing Lab: Exploration of a Problem-Based Learning Exercise," IEEE Transactions on Education, vol. 54, no. 4, pp. 628-636, 2011, doi: 10.1109/TE.2010.2103317.

[7] M. C. LaPlaca, W. C. Newstetter, and A. P. Yoganathan, "Problem-based learning in biomedical engineering curricula," in 31st Annual Frontiers in Education Conference. Impact on Engineering and Science Education. Conference Proceedings (Cat. No.01CH37193), 10-13 Oct. 2001 2001, vol. 2, pp. F3E-16, doi: 10.1109/FIE.2001.963748.

[8] W. C. Newstetter, "Designing cognitive apprenticeships for biomedical engineering," Journal of Engineering Education, vol. 94, no. 2, pp. 207-213, 2005.

[9] W. C. Newstetter, "Fostering Integrative Problem Solving in Biomedical Engineering: The PBL Approach," Annals of Biomedical Engineering, vol. 34, no. 2, pp. 217-225, 2006/02/01 2006, doi: 10.1007/s10439-005-9034-z.

[10] W. C. Newstetter, E. Behravesh, N. J. Nersessian, and B. B. Fasse, "Design principles for problem-driven learning laboratories in biomedical engineering education," Annals of Biomedical Engineering, vol. 38, pp. 3257-3267, 2010.

[11] S. Cyrus Rezvanifar and R. Amini, "Self-Efficacy Versus Gender: Project-Based Active Learning Techniques in Biomedical Engineering Introductory Computer Programming Courses," Journal of Biomechanical Engineering, vol. 142, no. 11, 2020, doi: 10.1115/1.4047924.

[12] L. K. Berland, T. H. Martin, P. Ko, S. B. Peacock, J. J. Rudolph, and C. Golubski, "Student learning in challenge-based engineering curricula," Journal of Pre-College Engineering Education Research (J-PEER), vol. 3, no. 1, p. 5, 2013.

[13] J. D. Bransford, A. L. Brown, and R. R. Cocking, How people learn. Washington, DC: National academy press, 2000.

[14] D. S. Cordray, T. R. Harris, and S. Klein, "A research synthesis of the effectiveness, replicability, and generality of the VaNTH challenge‐based instructional modules in bioengineering," Journal of Engineering Education, vol. 98, no. 4, pp. 335-348, 2009.

[15] R. J. Roselli and S. P. Brophy, "Redesigning a biomechanics course using challenge-based instruction," IEEE Engineering in Medicine and Biology Magazine, vol. 22, no. 4, pp. 66-70, 2003.

[16] R. J. Roselli and S. P. Brophy, "Effectiveness of challenge‐based instruction in biomechanics," Journal of Engineering Education, vol. 95, no. 4, pp. 311-324, 2006.

[17] S. P. Brophy, "Constructing shareable learning materials in bioengineering education," IEEE Engineering in Medicine and Biology Magazine, vol. 22, no. 4, pp. 39-46, 2003.

[18] D. L. Schwartz, S. Brophy, X. Lin, and J. D. Bransford, "Software for managing complex learning: Examples from an educational psychology course," Educational Technology Research and Development, vol. 47, no. 2, pp. 39-59, 1999.

[19] V. J. Shute, "Focus on formative feedback," Review of educational research, vol. 78, no. 1, pp. 153-189, 2008.

[20] A. Irons and S. Elkington, Enhancing learning through formative assessment and feedback. Routledge, 2021.

[21] R. Morris, T. Perry, and L. Wardle, "Formative assessment and feedback for learning in higher education: A systematic review," Review of Education, vol. 9, no. 3, p. e3292, 2021, doi: https://doi.org/10.1002/rev3.3292.

[22] L. Owen, "The Impact of Feedback as Formative Assessment on Student Performance," International Journal of Teaching and Learning in Higher Education, vol. 28, no. 2, pp. 168-175, 2016.

[23] J. Fluckiger, Y. T. Y. Vigil, R. Pasco, and K. Danielson, "Formative feedback: Involving students as partners in assessment to enhance learning," College teaching, vol. 58, no. 4, pp. 136-140, 2010.

[24] I. Cohen et al., "Pearson correlation coefficient," Noise reduction in speech processing, pp. 1-4, 2009.