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Supporting First-year Students in an Introductory Mechanical Engineering Course to Succeed in Statics

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Abstract

This research explores scaffolding strategies employed at Washington State University Vancouver to support first-year students in succeeding in an introductory mechanical engineering course, with a particular focus on their subsequent performance in Statics. As in many undergraduate engineering programs student retention has been a concern, especially in the lower division of the mechanical engineering program. In the past two years the introductory mechanical engineering course has been redesigned to prepare students for the rest of their engineering curriculum by incorporating several design projects, involving senior students and faculty as mentors, and giving freshman a more robust preparation for the challenging second year course: Statics. The results show an improvement in student retention, with 92% of students passing the introductory course in the experimental years compared to 80% in the control years. Furthermore, the percentage of students passing Statics with a C or better increased from 47% in the control years to 54% in the experimental years. However, there was a slight increase in the rate of non-passing grades in Statics for the experimental years. Analysis revealed that students' strength in math significantly influenced their success in the introductory course and Statics, highlighting the importance of sufficiently preparing students in lower-division courses for student retention.

1. Introduction

Mechanical engineering programs often offer introductory engineering courses (Mechanical Engineering 101 or Engineering 101) for their first-year students to provide a broad understanding of engineering principles, practices, professions, and problem-solving skills [16]. These courses tend to incorporate hands-on group activities, fostering active engagement with the discipline and honing crucial soft skills like communication and teamwork. Unlike other lower-division mechanical engineering courses, such as Statics and Dynamics, the content of these introductory engineering courses exhibits notable variation across programs, some are project-based others focus more on giving students an idea of what engineers do with guest speakers and field trips. Indeed, this diversity arises from the need to tailor the introduction of mechanical engineering concepts to specific program requirements, instructional settings, and the characteristics of the incoming cohort of first-year students.

Understanding freshman retention rates is crucial in unraveling the diverse outcomes of first-year students pursuing mechanical engineering degrees. An often-quoted statistic is that fifty percent of engineering majors either drop out or change majors before graduating [1]. Given these statistics, freshman retention rates can serve to evaluate the effectiveness of educational programs, reflecting the intricate challenges and strengths unique to each institution. According to the Arizona Board of Regents of several Arizona Universities, an average of 79.8% for overall freshman engineering retention was reported, and the mechanical engineering's retention rate of 77.5% is slightly lower than the average [2]. A study of freshman retention and six-year graduation rates from Colorado State University reported an overall freshman engineering retention of 90.5% and a mechanical engineering retention of 89.2% [3]. However, a study at Kennesaw State University exploring adding a first-year seminar course to the mechanical engineering curriculum to improve freshman retention reported baseline data, before the course was added, of an overall engineering retention of 57% and a mechanical engineering freshman retention of 61% [4]. Although nationwide data is not available for freshman retention in engineering the above samples suggests retention rates, a critical metric in assessing the effectiveness of educational programs, vary when reflecting each institution's unique curricula, challenges, data collection methods, and statistical processes.

Many US mechanical engineering programs implement innovative pedagogies to engage their first-year students. US Coast Guard Academy introduced cyber-physical system design and realization by integrating a Bilge Pump design project. The first-year students were exposed to various engineering skills, including SolidWorks, machining, sheet metal work, 3-D printing, and programming using Arduino to build and test pumps [5]. Virginia Military Institute implemented a nine-week Arduino-controlled Potato Cannon project in which students built a potato cannon controlled by an Arduino microcontroller. Pre- and post-project assessments reveal significant improvements in students' self-assessed skills in various areas, including mechanical design, fabrication, electronics, and programming. Most students expressed strong interest in participating in more electromechanical design projects in the future [6]. Villanova University integrated three impromptu design exercises, including design competitions with marshmallow and straw bridges, decision-making competitions with Beetlebots – a remote-controlled robot, and optimization competitions with enclosed beer storage tank modeling [7]. Montana State University included reverse engineering and design-build-test exercises, aiming to familiarize students with mechanical engineering concepts, curriculum, and career prospects [8]. South Dakota School of Mines and Technology introduced systems engineering to apply students' systems thinking and engineering skills to their buoyant boat design and fabrication projects [9]. Auburn University and Hampton University took a slightly different tack, employing case study in their introductory course to engage students with the discipline. They included four case studies, the STS 51-L (Challenger) case, Della case, Lorn case, and Mauritius Auditorium Design case, [10] to engage students with complex engineering problem-solving and enhance students' higher-order cognitive skills [11]. Each mechanical engineering program adopts a distinctive approach to its first-year introductory courses, ensuring they effectively address the unique considerations of their respective student body and align with the overarching goals of the program.

The mechanical engineering program at Washington State University Vancouver has proactively sought inventive methods to enhance the learning experience and engagement of first-year students in the discipline; however, student retention in the lower division has remained a major concern of the program. About half of the first and second-year students left the program. Notably, Statics, a required course in the second year, has a historically high DFW (D, F, or withdrawal) rate. Statics has been believed to be a gatekeeper course in mechanical engineering, and it is the first rigorous engineering course to require the students to demonstrate strong problem-solving skills with reliance on college-level mathematics [12-14] and after passing Statics a majority of students at Washington State University finish the program. Many mechanical engineering programs have tried to improve student learning, retention, and engagement in Statics [12-17]. Although most studies have been limited to the improvement of the Statics course, some studies suggested connecting the introductory mechanical engineering courses and their Statics courses to promote scaffolding of the learning process [18,19]. Cederqvist and Lyons [18] assigned hands-on projects related to fundamental statics knowledge on an introductory mechanical engineering course. Peuker et al. [19] integrated foundational concepts of Statics in their introductory engineering course and provided multiple-choice questions to assess students' learning. These studies provided the scaffolded approach to the students in the introductory mechanical engineering courses; however, the impact and limitations of such a scaffolding approach have not been fully studied. This paper outlines the process employed over the past four years to implement the scaffolding approach to the introductory mechanical engineering course, with the aim of reducing the student DFW rate in Statics. The results of this study address how the reform of the course contributed to the retention of our lower-division mechanical engineering students.

2. Methodology

2.1 The institutional context

Washington State University Vancouver, one institution of the multi-campus system of Washington State University and the state's land-grant university, offers the two-semester credit introductory mechanical engineering course in the second semester of the program's first year. More than half of Washington State University Vancouver undergraduate students meet Pell eligibility requirements, signifying low household incomes, and are correlated with first-generation college students and/or underrepresented minorities. Student recruitment in the lower division has been one of the critical issues with the program; therefore, the introductory mechanical engineering course had a prerequisite of College Algebra to recruit more students to the program. However, the program struggled with the historically high DFW rates in both the introductory mechanical engineering course and Statics. Through a series of faculty meetings in AY 2018-2019, the program decided to emphasize the following two aspects in the introductory mechanical engineering course: 1) improving students' interests in mechanical engineering discipline and career, and 2) instructing foundational engineering principles to enhance students' success rate in Statics, a 2nd year course. Most students who pass Statics pass other 2nd year courses to enter the 3rd year.

2.2 The Introductory Mechanical Engineering Course Contents in 2019 and 2020.

Table 1 summarizes the course topics and the design project offered in-person in the spring terms of 2019 and 2020. As shown in the table, most of the content was foundational, such as vectors, forces, energy, and work. The instructor has covered chapters 1, 2, 4, and 6 of the textbook written by Hagen [20]. Midterm and final exams were closed book and note and questions were related to force vectors, a material's stress-strain curve, free body diagramming of a beam, and energy conversions.

Table 1 Summary of the introductory mechanical engineering course offered in 2019 and 2020.

Course objectives: 1. Define mechanical engineering problems and propose solutions. 2. Participate in a team-based class project to design and build a prototype with constraints 3. Write a technical report on the class project and give a professional presentation at the end of the course. 4. Learn about engineering ethics, continuing education, contemporary issues, global context, etc. 5. Learn about the importance of using computers and software in solving engineering problems.	
Course textbook: • Kirk D. Hagen, Introduction to Engineering Analysis, 4^{th} Ed. Pearson.	
Course topics:	Design Project:
• What's Mechanical Engineering? • Trigonometry Review and Units • Vectors and Applications • Forces and Applications • Energy and work • Free body diagrams • Stress and strain • Engineering ethics, Contemporary issues	The student teams are assigned to predict the speed and distance traveled by a Hot Wheels toy car along a defined track. Each team was requested to synthesize the appropriate equations related to the conservation of energy for the toy car chosen. The results and an explanation for the deviation between the test results and the predicted results are reported in a report format and a presentation.
Grading policy: • Homework: 20%, Two exams: 30%, Design project: 50%	

When combining 2019 and 2020, the introductory mechanical engineering course had 63 students enrolled in total. Out of 63 students, twelve students, or approximately 19% of the enrolled students, withdrew or failed the course. This withdrawal/failure rate was the largest among the program courses. For this study, the courses offered in 2019 and 2020 are the control or the baseline.

2.3 Improvement in the Introductory Mechanical Engineering Course Contents in 2021 and 2022

Before offering the course in the spring semester of 2021, the instructor collaborated with the Statics instructor to strengthen the links between the two courses. The two instructors identified the foundational knowledge before taking Statics to possess the technical proficiency required. They also scaffolded the content of the introductory mechanical engineering course to support the first-year students to develop their skills as self-regulated learners. The results of course reform are the following:

- The updated course strengthened force vectors, force equilibrium, and free body diagrams, which are directly connected to the content of Statics, when compared with the offerings in 2019 and 2020.
- Instead of offering one significant project, the course offered three small design projects. Student teams spent an average of three weeks conducting hands-on projects related to Statics to apply their learning to the engineering design process in team settings.
- The instructor invited the program's seniors and alumni to interact with the first-year students.

Table 2 shows the summary of the course content offered in 2022 when the course was offered fully in-person. Note that the course was delivered synchronously online in 2021; however, the course topics were identical between 2021 and 2022. The only variation was the three design project topics, and the student team conducted multiple reverse engineering projects in 2021. The course offerings in these two years are the experiment for the study.

Table 2 Summary of the introductory mechanical engineering course offered in-person in 2022. (2021 course delivery mode was synchronous online.)

<table>
<tr><td colspan="2">Course objectives:
1. Explore mechanical engineering professions and careers.
2. Define fundamental concepts in mechanics: vectors, forces, work, energy, etc., for engineering problem-solving.
3. Discuss engineering ethics/economics on engineering problem-solving.
4. Participate in teamwork class projects to design and realize mechanical systems.
5. Disseminate the class project by writing a team technical report and giving a professional team presentation at the end of class.</td></tr>
<tr><td colspan="2">Course textbook:
• Kirk D. Hagen, Introduction to Engineering Analysis, 4th Ed. Pearson.</td></tr>
<tr><td>Course topics:</td><td>Design Projects:</td></tr>
<tr><td>• What’s Mechanical Engineering?
• Meeting with mechanical engineers
• Engineering design process
• Trigonometry Review
• Vectors and Applications
• Forces and Applications
• Free body diagrams
• Force equilibrium</td><td>Project 1: Student teams design and build balloon rockets to travel in a wire for longer than 10 feet.
Project 2: Student teams design and build a tower made of popsicle sticks to support 100 pounds.
Project 3: Student teams design and build a popsicle stick crane and a low-speed DC motor to life a pop can.</td></tr>
<tr><td colspan="2">Grading policy:
• Homework: 20%, Two exams: 40 %, Design projects: 40%</td></tr>
</table>

3. Results and Discussion

3.1 Comparisons Between the Control (2019 and 2020) and the Experiment (2021 and 2022)

The program’s main concern about the introductory mechanical engineering course was a high withdrawal and failure rate. Table 3 shows that only 80% of students passed the course in the control years (2019 and 2020), while 92% of the students in the experiment years (2021 and 2022) passed. It should be noted that one or two students were enrolled as transfer students and were not in their first year of the program. The new approach of emphasis on force vectors and free body diagrams, three small design projects, and inviting the program’s seniors and alumni to interact with the first-year students had a positive impact on the withdrawal and failure rate.

Table 3. Number of Enrollment, W/F, passing, and non-first-year students.

Term	The delivery mode of MECH 101	Enrollment in MECH 101	W or F in MECH 101	Passing MECH 101	Non-first-year students
2019 Spring	In-person	32	6	26	0
2020 Spring	In-person	31	6	25	1
2021 Spring	Synchronous online	35	1	34	2
2022 Spring	In-person	34	2	32	2

We investigated the students who passed the introductory mechanical engineering courses to see how they performed in Statics, and presented the summary in Table 4. For the control years, out of 51 students, 29 students passed Statics with a C or better, which is the program requirement to be a major student. 10 students received a C- or lower grades, requiring a retake. 14 students did not attempt to take Statics and left the program. For the experiment years, 35 students out of 62 students received a C or better in Statics to move to the next mechanical engineering course sequence. 12 students needed a retake due to their grades with a C- or lower. Nine students left the program without taking Statics. Six students have not taken Statics yet to take prerequisite math and science courses.

Table 4. Student performance in Statics

Term of MECH 101	The delivery mode of MECH 101	First-year students passing MECH 101	Passing Statics with C or better	DFW and C- in Statics (requiring a retake)	Statics not taken yet	Out of the ME program without taking Statics
2019 Spring	In-person	26	16	4	0	6
2020 Spring	In-person	24	13	3	0	8
2021 Spring	Synchronous online	32	18	7	1	6
2022 Spring	In-person	30	17	5	5	3

The results of Tables 3 and 4 are combined and plotted in Figure 1. The pie charts show the percentages of first-year mechanical engineering students' paths until Statics after enrolling in the introductory mechanical engineering course when the total students (51 for the control and 62 for the experiment) were considered 100%. The rate of passing Statics with a C or better in the experiment years was 54%, which increased from 47% in control. This suggests the new scaffolding approach used in the experiment to strengthen the links between the two courses positively impacted student performance. The total number of students who withdrew or failed the introductory mechanical engineering course and left the ME program decreased from 32% in the control to 19% in the experiment. The new approach to enhancing students' interests in the discipline through networking with seniors and alumni and offering multiple design projects might contribute to the reduction. However, the rate of a C- or DFW in Statics increased from 11% (control) to 18% (experiment). These results will be elaborated in the next section.

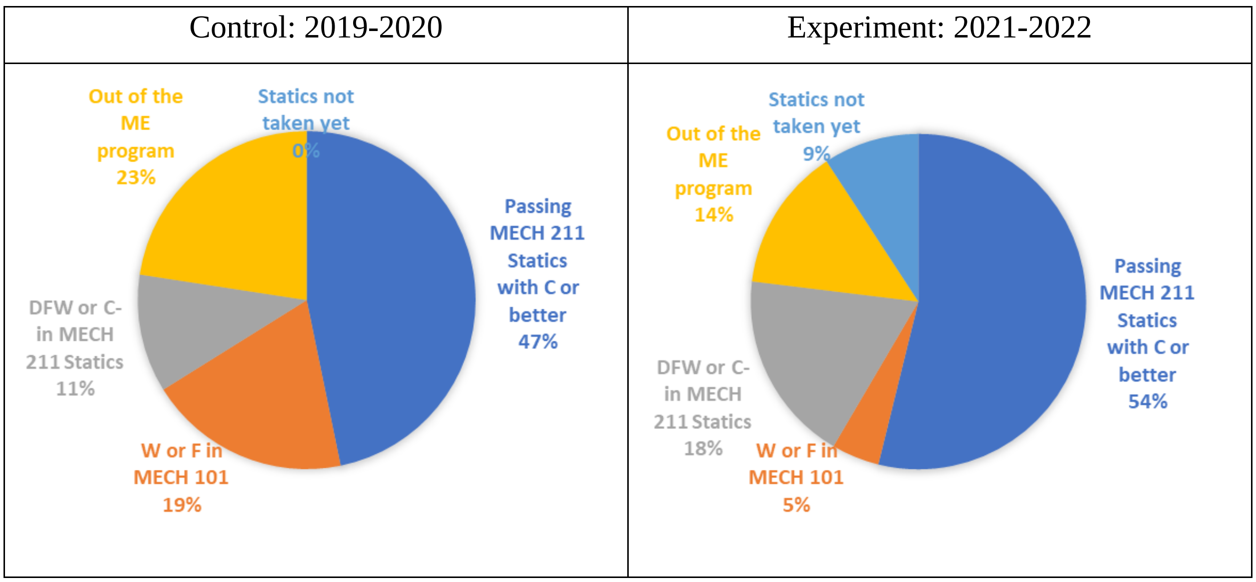

Figure 1. Comparison between the control years and the experimental years.

3.2 The Relations of the First-year Students' Math and Science Preparation and their Performance in Statics.

The in-depth analysis is conducted to investigate the factors affecting the first-year students' learning in the introductory mechanical engineering course and their relations with their performances beyond the course. We have focused on the 62 first-year mechanical engineering students who enrolled and passed MECH 101 in the two experimental years. Based on the students' paths related to Statics, we can group the 62 students into the following four categories:

- Group A: Passing Statics with a C or better (n = 35)
- Group B: Receiving a C- or DFW in Statics, resulting in a retake (n = 12)
- Group C: Planning to take Statics (n = 5)
- Group D: Quitting the ME program without taking Statics (n = 10)

Group A students are the ones who passed Statics with a C or better to move forward in the program to take Dynamics and Solid Mechanics. As mentioned earlier, this group of students typically pass other 2nd year courses to join the upper division. Students in Group B received a C- or DFW in Statics; therefore, they needed to retake Statics. Generally, most of these students retook Statics, but only some passed the course. Group C students were not ready to take Statics due to a lack of the prerequisites: Calculus 2 or concurrent enrollment; Physics 1 or concurrent enrollment. Students in Group D have quit the program without taking Statics.

Table 5. Math and science background among the students in Groups A, B, C, and D of the experimental years.

	Count	% of the students took Calculus 1 or higher.	% of the students took college chemistry.	% of the students who took high school or college chemistry.	% of the students who took college physics.	% of the students who took high school or college physics.
Group A	35	62.9%	80.0%	91.4%	25.7%	74.3%
Group B	12	16.7%	91.7%	100.0%	8.3%	58.3%
Group C	5	0.0%	60.0%	80.0%	0.0%	80.0%
Group D	10	30.0%	70.0%	80.0%	10.0%	60.0%

Table 6. The program's first-year courses available in the University Catalog.

	Course(credits)
Fall semester	Calculus 1 (4), Chemistry (4), Engineering Graphics (2), Arts (3), History (3)
Spring semester	Calculus 2 (4), Linear Algebra (2), Introductory Mechanical Engineering (2), Humanities (3), Writing (3)

We first looked at how students' math and science backgrounds are related to each student group. The instructor had one-on-one meetings to record each student's background in math and science. Table 5 shows the percentage of students who took the math and science courses when enrolled in the introductory mechanical engineering course. To better understand Table 5, the program's first-year curriculum available in the University catalog is introduced in Table 6. By the spring semester of the first year of the major, students are expected to complete Calculus 1 and College Chemistry. As shown in Table 5, less than half of the students meet that expectation. The notable variation comes from their math preparation. 62.9% of students in Group A completed Calculus 1, while only 16.7%, 0%, and 30% of students passed Calculus 1 in Groups B, C, and D, respectively. The math preparation in Groups B to D was much lower than that in Group A. More than half of the students in each Group took College Chemistry, and only a few students took College Physics when taking the course. Therefore, the relation between college science courses and the student performance in the introductory mechanical engineering course is not clear. If we count high school chemistry and physics, all four Groups have more than half of the students who took those. It can be concluded that the first-year students' math preparation is highly related to their success in Statics after passing the introductory mechanical engineering course.

3.3 Performance Analysis of the First-Year Students Enrolled in the Introductory Mechanical Engineering Course during the Experimental Years (2021-2022)

We continued to use the same four Groups (Groups A to D) to investigate how each Group performed in the introductory mechanical engineering course in the experimental years. The course had four assessment pieces: homework (15%), exams (45%), and projects (40%). Table 7 compares the four Group's average achievements in each assessment piece. Group A's average scores are highest in homework and exams, resulting in the highest in total. This group of students did not show much difficulty in problem-solving for the course content. Average scores of Group B are not too distinct from those of Group A. Note that Group B students received a C- or DFW in Statics. The most significant variation between Groups A and B might be their math preparation, as shown in Table 5. A majority of Group B students were behind in their math sequence in their program of study. Their math skills were sufficient to follow the topics in the introductory mechanical engineering course, which were straightforward. However, the students need to apply multiple math concepts to solve much more complex programs in Statics, mostly involving rigorous coursework and demanding assignments that can be overwhelming for the students in Group B. The high workload, complex mathematical concepts, and technical requirements may cause low achievement in this group, suggesting that the problem-solving attitude and confidence of more experienced math students may be important parts of the student’s success in Statics.

The students in Group C show unique characteristics in their performance in the introductory mechanical engineering course when compared to the students in Groups A and B. First, their project average scores are similar to those from Groups A and B, which means this group of students actively participated in the team projects. If the students actively participated in the design projects and contributed as productive team members, they typically earned high scores. Unlike the students in Groups A and B, the Group C students, who were least prepared in math, struggled in the exams. Group C students’ exam scores are approximately 20% lower than those from Groups A and B. Although the course content was straightforward, this group of students struggled with problem-solving related to force vectors, force equilibrium, and free-body diagrams.

Group D students are grouped as the students who quit the program after taking the introductory mechanical engineering course. Their achievement was the lowest across all assessment pieces, including the projects. The Group D students struggled with homework, exams, and project participation, although this group of students’ math preparation is slightly better than that of Group C. Their low achievement in the projects indicates that this group of students was not active in participating in the projects. Further investigation is needed on the root-cause analysis of the departure of Group D students; however, it is apparent that this group failed to engage with the introductory course.

Table 7. Average achievement scores of each Group in the Introductory Mechanical Engineering course.

	Count	Total	Homework	Exam 1	Exam 2	Projects
Group A	35	90.8	92.1	91.8	91.2	89.5
Group B	12	89.2	87.9	89.5	88.4	90.0
Group C	5	84.6	86.2	76.5	77.9	91.2
Group D	10	78.5	79.6	79.1	68.8	82.4

Conclusion

This research paper examined the transformation of an introductory mechanical engineering course at Washington State University Vancouver and its impact on first-year students' success, particularly in the subsequent years of the Statics course. The redesigned introductory course focused on enhancing students' understanding of foundational knowledge of Statics. Strengthening the connection between the introductory course and Statics proved crucial in enhancing students' performance. The rise in the percentage of students passing Statics with a C or better suggests that aligning course content with subsequent courses is essential for student success. Also, multiple design projects and involving senior students and alumni as mentors were effective strategies for enhancing student engagement and learning outcomes. These hands-on experiences helped students apply engineering principles in practical contexts. The redesigned introductory mechanical engineering course led to an increase in student retention in the first year, with 92% of students passing the course in the experimental years compared to 80% in the control years. This demonstrates the effectiveness of innovative pedagogical approaches in engaging and retaining students.

The study also highlighted the critical role of math preparation in students' success in engineering courses. Students who had completed Calculus 1 or higher were more likely to excel in the introductory course, which provided a solid foundation for Statics. This group of students was mostly successful in passing Statics. This emphasizes the importance of assessing and addressing math readiness for incoming engineering students.

This research offers valuable insights into how proactive course redesign and pedagogical innovation can positively impact first-year engineering students' retention and performance. It underscores the importance of aligning course content, addressing math preparedness, and providing experiential learning opportunities. More research could be done into ways of better preparing incoming mechanical engineering students for the rigorous workload of courses like Statics to improve retention.

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