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Work in Progress - Strategies for Stimulating Engineering Relevance in Statics Education

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Abstract

Most engineering students take statics as their first engineering science course. A weak understanding of this subject can cause significant learning impediments in subsequent classes. Students see statics as an extension of physics rather than an introductory engineering course. For instructors and researchers, the answer to "how to make statics relevant to engineers?" appears elusive.

This paper recommends specific strategies, with several examples, to increase engineering relevance. These strategies are simple to incorporate and designed to improve student learning. They form a five-step approach that aims to help students develop skills beyond basic algorithmic problem-solving. These steps are:

1. Start with the purpose.
2. Foster qualitative reasoning.
3. Nurture quantitative problem-solving skills.
4. Create design and research experiences.
5. Integrate digital tools.

These steps build on each other to help students develop and retain skills and solve ill-defined engineering problems. This paper provides a rationale for each learning strategy with examples. It also presents a preliminary assessment. In short, the strategies presented can ignite students' interest and engagement by providing purpose and autonomy to their learning.

1. Introduction

Statics is the first engineering science course in many engineering disciplines. It provides a foundation for upper-level mechanics courses and discipline-specific courses such as structural analysis and structural design. If the foundation is not strong, students will have significant difficulties in subsequent courses. Researchers and educators have made great efforts to mitigate these learning impediments and improve students learning. These efforts have yielded substantial and innovative educational strategies for statics such as flipped classrooms, hands-on and experiential learning activities, multimedia resources, and computer tools.

Even though evidence shows that these instructional innovations have improved students learning, there is still a gap in statics instructional strategies. Students perceive statics as an extension of physics rather than an engineering course. To make statics relevant to engineers, this paper proposes a series of learning strategies that aim to work towards addressing this question.

The organization of the remainder of the paper is as follows; section two reviews the state-of-art instructional strategies. The literature review focuses on three aspects of instructional strategies: the content, delivery formats, and activities to improve students learning. Section three outlines guiding factors and boundary conditions that faculty must consider when restructuring the course. The subsequent section describes five learning strategies for improving statics relevant to engineering with examples. Section five presents a preliminary and limited assessment of students learning. This paper is a work-in-progress. The authors plan to conduct a rigorous assessment of student learning in the fall 2022 semester. Finally, section six presents the summary and conclusions of this work-in-progress.

2. Literature Review

This section reviews the recent and relevant research on the course content, delivery methods, and activities.

2.1. Content

Based on Jonassen's typology [1], Douglas et al. [2] classified the problems in one statics textbook. They found that most problems are algorithmic except for a few rule-based and story problems. While the textbook problems reinforce well-structured problem-solving skills, they don't provide the skills needed to tackle ill-defined problems. The authors argued the need for including ill-structured problems and concluded that "Habituating students to solve ill-structured problems will better prepare them to think like engineers."

Ha and Fang [3] argue that spatial abilities, which engineering educators often overlook, play a vital role in learning engineering mechanics. They also emphasize the need for encouraging sketching instead of passively using the figures from the problems. Sullivan et al. [4] found that introducing an art module helped students to improve the ability to solve three-dimensional statics problems. Litzinger et al. [5] found that spatial reasoning doesn't predict the performance on the exams requiring the sketching of the free-body diagrams. They also identified differences between the strong and weak students. The differences include the quality of free-body diagrams and use of self-explanation strategy. Based on the insights, they recommend an intervention strategy that promotes use of self-explanation. Sadowski and Jankowski [6] describe the importance of graphical methods for promoting structural intuition by helping the visualization of forces. Mueller et al. [7] also emphasize the importance of graphic statics for nurturing design intuition.

Steif and Dollar [8] critically review the shortcomings of traditional statics instruction and propose a progressive development of topics and concepts. Steif and Dantzler [9] present a validated Statics Concept Inventory (SCI) instrument for assessing the students' understanding of the statics concepts. The instrument helps evaluate the progress and administer corrective action. Faculty teaching follow-on courses can use it for prerequisite knowledge assessment.

Johnson-Glauch and Herman [10] describe the use of heuristics by engineering students in drawing the shear force and bending moment diagrams. While novices tend to focus on salient or surface features, experts identified deep features. Gross and Dinehart [11] analyzed the errors made by over 8000 student submissions on 150+ quiz and examination problems. They found that most errors are non-conceptual errors, and therefore, students have a better understanding than their solutions show.

2.2. Delivery

To help in visualization and learning the steps, Dupen [12] propose using storyboards for teaching mechanics. Storyboards show a step-by-step process that allows internalizing the problem-solving process. Davishahl et al. [13] describe the use of flipped classrooms where students perform experiments in the class. Howard [14] describes the progress towards a game design for engineering statics course. The game design targets struggling students to help them form the necessary skills.

2.3. Activities

Wodin-Schwartz et al. [15] describe Hands On Wednesdays (HOW) at Worcester Polytechnic Institute (WPI). Students move in small groups and perform activities such as measuring reaction forces and comparing them to theoretical calculations. Sarker et al. [16] provide details of a low-cost experimental setup to complement virtual learning. The model is similar to one of the experimental setups of WPI [15] and the experimental cube of Davishahl et al. [13]. Philpot et al. [17] present two specific games to help students achieve proficiency and confidence in a competitive yet fun environment. Sadowski and Jankowski [6] describe a didactic tool for visualizing forces in a truss for architecture students. Fadda and Rios [18] describe a scalable design project for statics in the project-based learning area. Apart from building a physical model, the project involved creating a MATLAB script. MacNamara [19] describes a design competition, “Asymmetric Equilibrium,” where students design structures that are in equilibrium but look like they are about to tip over. Giancaspro and Arboleda [20] identify the challenges in teaching statics and address them by active demonstrations to engage students. They point out moments as a difficult topic for students from anecdotal evidence. To aid in the conceptual understanding, they develop a set of six activities. They also emphasize the need for relating the concepts to the students’ everyday experiences.

3. Key Factors

While reimagining and restructuring statics, instructors should keep in mind the following factors or boundary conditions:

1. *Required course:* Statics is a required course for many engineering programs. Students begin their engineering journey with this subject, regardless of their prior background or interest in physics.
2. *Prerequisite knowledge:* Students' physics, trigonometry, and other topics preparation varies depending on their high school. University physics is not always a prerequisite for statics. Some students use AP physics as a substitute for university physics.
3. *Exposure to open-ended tasks and teamwork* before engineering varies significantly depending on their high-school preparation (like PLTW, robotics/club activities).
4. *Shoshin or Beginner's Mindset:* Students are curious and open to new possibilities as novices.
5. *Time:* Typically, the course is three credit hours long, with roughly 40 contact hours. Faculty can expect students to spend an additional 80 hours outside the classroom for a typical three-credit-hour course, depending on their preparation. While many innovations are theoretically viable, the available time imposes significant limitations.

4. Increasing Engineering Relevance

This section discusses five learning strategies for increasing engineering relevance in statics education. In addition, to help in the implementation, several examples and sample student work are presented for each strategy.

4.1. Learning Strategies

To incorporate engineering relevance, we tried to innovate our statics course. We implemented five strategies based on the learning theories (see Fig. 1) in the fall 2021 semester. These strategies leverage the beginner's mindset while managing time.

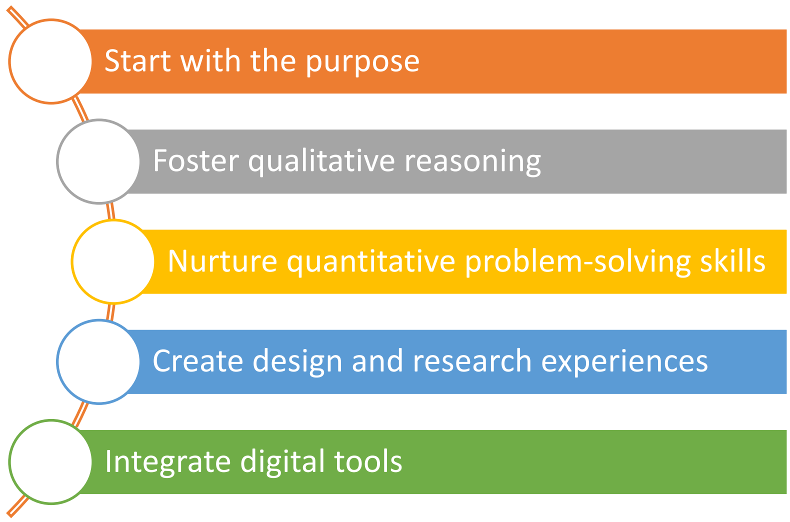


Fig. 1. Learning strategies for improving statics relevance to engineering

4.2. Start with the purpose

Pestalozzi, an educational pioneer, championed "learning with the head, heart, and hands." Learning with the heart (affective learning) is often missing in traditional engineering science courses. In these courses, engineers just find numbers or answers to numerical problems. They seldom realize the big picture - engineering as an activity addressing human needs by conceiving and analyzing new designs. The purpose, or "why," is essential for the engineering profession. This purpose is often missing in statics. A sense of mission is one of the three drivers that motivate students to see the relevance and push them to higher achievement [21].

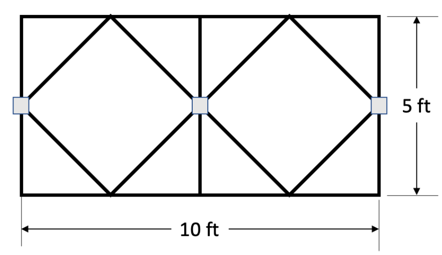
Consistent with our university's tagline "Higher purpose, Greater Good" in statics, we introduce students to a greater purpose, not just real-world applications. On the first day, the concept of structural art as defined by Billington [22] is introduced. This concept views efficiency, economy, and elegance as three essential components of structural art. In the classroom discussion, students discussed four local structures in these terms. Next, student teams created a presentation on a building, monument, or bridge as an accompanying activity. The presentation included details of the architect, structure, and what the team liked about the design. Some forms researched by the students are Akashi Kaikyo Bridge (Japan), The Bow (Canada), CCTV headquarters (China), Eads Bridge (USA), Eiffel Tower (France), O-14 (Dubai), Golden Gate

Bridge (USA), Mode Gakuen Spiral Tower (Japan), Roman Colosseum (Italy), Seattle Space Needle (USA), Sydney Opera House (Australia), Montjuïc Communications Tower (Spain), and Mjøsa Tower (Norway). The purpose of the activity was to inspire students and evoke their beginner's mindset.

Each class (or chapter) starts with a short activity that is 5-10 minutes in length. The activity took the form of a presentation of an impactful example and a high-level discussion of a need to frame learning, see the engineering relevance, and motivate students. Such activities are often not readily available in textbooks and require instructors to dig into their experiences, engineering successes, and failures. For instance, a bridge is an excellent illustration to introduce trusses. The class can engage in a discussion on the benefits of a bridge. They will realize the time and fuel saved - benefits to the humanity. A further presentation of the Bailey bridge and its significance in history, as illustrated in Fig. 2, can exemplify the role of engineering.

Quick and easy installation – The Bailey bridge – The truss that won the war

According to General Eisenhower, three pieces of military hardware - Radar, heavy bombers, and the Bailey bridge - contributed to the success of the Allied forces in World War II. The Bailey bridge is a truss structure made from standard, readily available materials. Each modular bridge side panel, measuring 10 ft ´ 5ft, weighs 570 lb. Six military personnel can easily carry these panels. They also fit a standard military vehicle for transportation. These panels can be assembled in different configurations (series or parallel or a combination) to span the desired length and support the design loads, which enabled the movement of 40-ton tankers. Finally, it was easy to construct and install without specialized equipment or cranes. Thus, the Bailey bridge facilitated the easy movement of troops and the establishment of the supply chain to support the troops, in turn, winning the war.



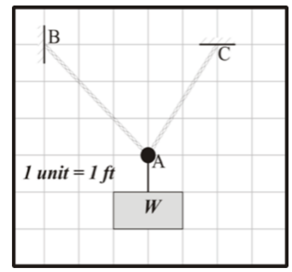
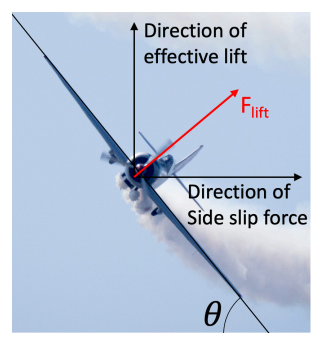
The Bailey bridge panel

Fig. 2. The Bailey bridge – The truss that won the war

4.3. Foster Qualitative Reasoning Abilities

Students learn qualitative reasoning by understanding concepts rather than equations. While numerical problems nurture quantitative reasoning abilities, they don’t help qualitative reasoning skills. In many cognitive research studies, experts rely on qualitative reasoning to analyze a problem and develop a mental model [23]. During regular lectures, instructors often interact and ask qualitative questions. To further reinforce qualitative thinking, we developed a set of multiple-choice questions (MCQs). The MCQs tackle three problem types: logical reasoning, decision-making, and troubleshooting problems. Table 1 summarizes the problem types and associate sample MCQs.

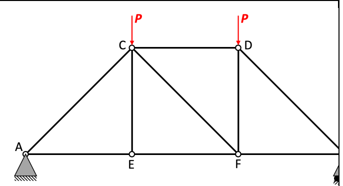
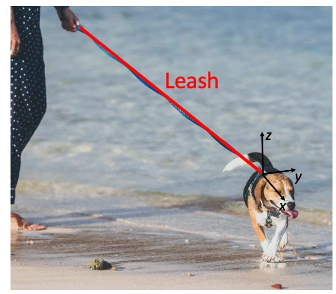
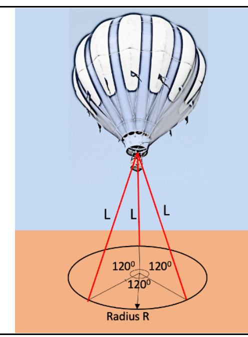
Table 1. Developing qualitative thinking using multiple-choice questions

Problem Type	Details and examples	
Logical reasoning problems	Use reasoning to solve problems requiring cognitive understanding of concepts. Weight $\boldsymbol{W}$ is applied at point A. Which of the following statement is true? A. Tension in cable AB > Tension in cable AC B. Tension in cable AB = Tension in cable AC C. Tension in cable AB < Tension in cable AC D. Tension in cable AB + Tension in cable AC = $\boldsymbol{W}$	
Decision-making problems	Involve evaluating possible options based on evaluation criteria and selecting an option. On a trip, a delivery person is carrying more than usual. To minimize the load on the strap, the best option is: A. Reduce the strap length B. Increase the strap length C. Make the straps form isosceles triangle D. The length has no effect on the load	
Trouble-shooting problems	These problems challenge students to understand why a certain phenomenon or event occurs. Asking the question "why" helps to abstract and crystalize conceptual knowledge. A trainee pilot is cruising in a plane at a constant velocity. Pilot trainee notices the planes drops in altitude when taking a turn. The reason for this phenomenon is: A. F_{lift} increases when making a turn B. F_{lift} decreases when making a turn C. Effective lift vector increases with angle θ D. Effective lift vector decreases with angle θ	

4.4. Nurture quantitative problem-solving skills

While problems that resemble examples in their solution strategy and procedure provide reinforcement, they don't enhance the ability to apply concepts to new situations. Consistent with the literature, the authors recommend exposing students to different problem types for meaningful learning and improving engineering skills (problem definition and analysis). Instructors can solve different kinds of problems in the classroom. Also, they can further reinforce learning by assigning a variety of homework problems. Table 2 presents problem types, details, and examples.

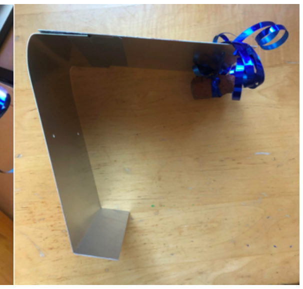
Table 2. Problem Types, details, and examples

Problem Type	Details and examples	
Algorithmic problems	The most common problem type in textbooks requiring the application of a logical procedure.	
	The truss shown consists of horizontal and vertical members of length L. The angular struts are at 45^0. Determine the load experienced by the truss members.	
Story problems	A story provides the context and embeds the details for solving the problem. Then, students frame the problem, extract the details, and decide and apply the appropriate algorithm or procedure to find the solution.	
	You are walking your dog on a beach. The tension in the leash is 18 lb. The dog (the collar's location) walks 2 ft in front and 1 ft to your left. The length of the leash is 3 ft. If you assume a coordinate system at the collar, as shown in the figure, represent the force vector acting on the dog using the Cartesian vector notation.	
Rule-using problems	Multiple procedures exist to reach the correct solution.	
	Three cables anchor a hot air balloon to the ground. The height of the anchor point from the ground is H. Cable length is L. What is the tension in each cable if the net lift force is 2.4 kN, what is the force on the balloon exerted by the cables?	

4.5. Create design and research experiences

Design tasks provide freedom to formulate the problem, pursue innovative solutions, and experiment and learn from concrete experiences. They provide significant autonomy and purpose, two critical motivators identified by Pink [21]. Furthermore, instead of only addressing the lowest common denominator students and not challenging advanced students, design problems provide differential learning opportunities that empower weak and advanced students in stretching their thinking abilities. Research questions help students explore the areas of their interest and learn state-of-the-art technology while reflecting on their findings.

Table 3. Example of design projects and research experiences

Design problems	**Sample Design Project** *Asymmetric Equilibrium* - Design an aesthetic, efficient and economical structure with the inspiration from the concepts of equilibrium, center of gravity and tipping – Based on the work of MacNamara [19]	  Sample work
Research experiences	**Sample Research Task** *Truss vs Monocoque Design* - Truss designs were common in aerospace and automobile industries. Monocoque designs, where the skin carries the load, are becoming popular now. Investigate the emergence of monocoque and semi-monocoque designs and compare their pros and cons.	 

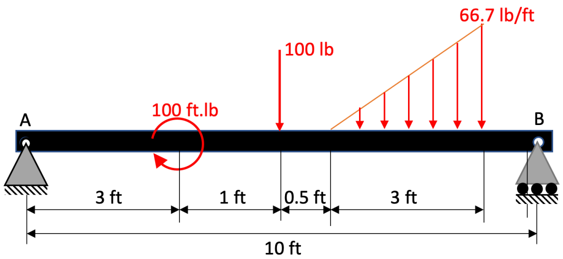
4.6. Integrate digital tools

Engineers often use digital tools such as spreadsheets and finite element analysis (FEA) software for analysis. By making these tools a part of their skill set, students can more effectively solve a wide range of problems by applying appropriate tools. It also provides additional means to verify their solutions.

According to Oke [24], "using spreadsheets provide a unique perspective on the relationship between the component of an equation – an understanding that is essential in engineering analysis." The construction of the shear force and bending moment (SFBM) diagrams lends itself to the use of spreadsheets (see Table 4). Our experience suggests a lecture, an Excel template, and handouts are sufficient to enable students to create the SFBM diagrams.

Table 4. Shear force and bending moment using spreadsheet

Task - Create the shear force and bending moment diagrams using a spreadsheet.



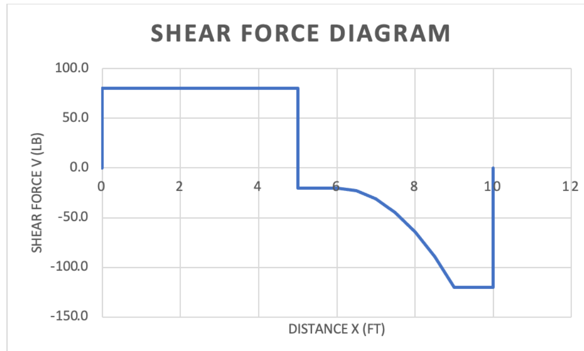
Spreadsheet data

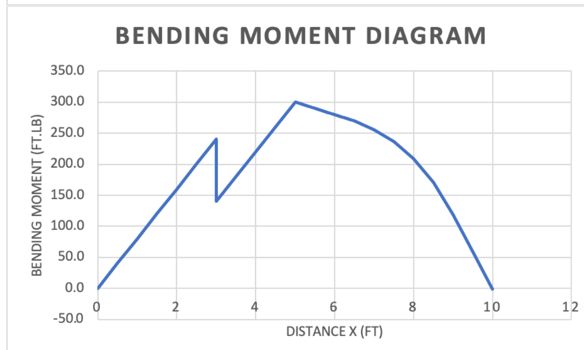
F4 =F3+ D4+((E4+E3)/2)*(A4-A3)

	A	B	C	D	E	F
1–2	Distance from A (ft)	Distributed force (lb/ft)	Concentrated force (lb/ft)	Concentrated Moment (ft.lb)	Shear Force V (lb)	Bending Moment (ft.lb)
3	0				0.0	0.0
4	0		80		80.0	0.0
5	0.5				80.0	40.0
6	1				80.0	80.0
7	1.5				80.0	120.0
8	2				80.0	160.0
9	2.5				80.0	200.0
10	3				80.0	240.0
11	3			-100	80.0	140.0
12	3.5				80.0	180.0
13	4				80.0	220.0
14	4.5				80.0	260.0
15	5				80.0	300.0
16	5		-100		-20.0	300.0
17	5.5				-20.0	290.0
18	6				-20.0	280.0
19	6	0			-20.0	280.0
20	6.5	-11.11			-22.8	269.3
21	7	-22.22			-31.1	255.8
22	7.5	-33.33			-45.0	236.8
23	8	-44.44			-64.4	209.4
24	8.5	-55.55			-89.4	171.0
25	9	-66.66			-120.0	118.6
26	9				-120.0	118.6
27	9.5				-120.0	58.6
28	10				-120.0	-1.4
29	10		120		0.0	-1.4

The small residual moment in the last cell (F29) is due to numerical approximation.

Shear force and bending moment diagrams created using Excel





The SFBM spreadsheets help understand the relationship between shear force and bending moment. Further, they enable students to tackle geometric and load variations in analyzing real-world problems such as the deflection of an airplane wing. Using this technique, faculty can also expose students to creating SFBM diagrams for three-dimensional load problems (create horizontal and vertical planes and perform a vector sum).

Commercial FEA software such as Abaqus FEA, Ansys, CREO Simulate, NASTRAN, etc., help analyze trusses or create SFBM diagrams. Several tutorials, videos, and online resources are readily available to learn these digital tools. Instructors can assign independent work as part of the life-long learning component. Fig. 3 shows a sample student work. The activity further helps visualize deflections and prepare students for the mechanics of solids course.

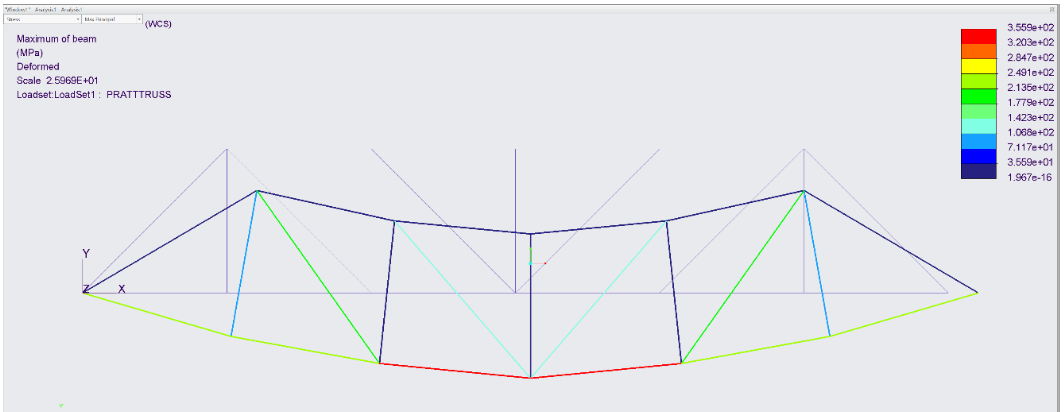


Fig 3. Sample student work analyzing a truss using CREO Simulate

5. Preliminary Assessment of Learning Strategies

The authors implemented a pilot version of learning strategies outlined in this paper in one of the two sections in the fall 2021 semester. The format lent itself to an experimental group that incorporated the learning strategies, and a control group which followed traditional course material. The authors performed an assessment of qualitative reasoning abilities in the subsequent semester in the Mechanics of Solids class. Both groups received an assessment instrument based on multiple-choice questions. The mean for the control group is 68 with a standard deviation of 24. On the other hand, for the experimental group, the mean is 74 with a standard deviation of 19. The results show that the experimental group performed better as seen in Fig. 4. Anecdotal evidence from student feedback is positive. We plan to conduct a formal study during the fall 2022 semester.

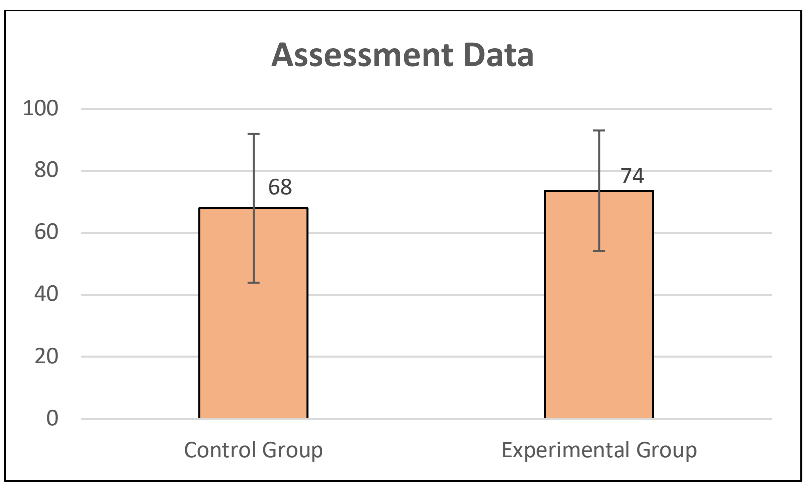


Fig. 4. A comparison of control and experimental group data

6. Conclusions

As supported by evidence in the literature, researchers and educators have made significant leaps to improve content and delivery methods. Despite these efforts, a gap in instructional strategies that make statics concepts relevant to engineering still exists. As often students see static concepts as an extension of a university physics course, they do not develop the skillset to see the big picture, learn how to approach ill-defined problems, apply reasoning skills to leapfrog to the final solution and work on open-ended tasks.

The paper presents a set of pedagogical strategies that helps students develop their engineering perspective of statics. While crafting these strategies, the authors considered limited student-faculty contact time. Table 5 summarizes these learning strategies.

Table 5. Summary of learning strategies for improving statics relevance to engineering

Strategy	Objective	Integration	Engineering Relevance
Start with the purpose	Motivate by providing context	Classroom discussion & presentation	See the big picture
Foster qualitative reasoning abilities	Reinforce conceptual understanding	Classroom interaction & multiple-choice questions	Develop reasoning, decision-making and trouble-shooting skills
Nurture numerical literacy	Enhance the ability to apply concepts to new situations	Homework	Define and analyze real-world problems
Create design and research experiences	Provide differentiated learning opportunities and concrete experiences	Mini project(s)	Synthesize solutions to open-ended tasks
Integrate software tools	Expose to alternative problem-solving methods	Independent work	Equip for industry

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