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When did Statics become so difficult? A root cause analysis of the high failure rates in a high-enrollment foundational course

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Abstract

A trend that has been observed at many institutions, and which has seemingly increased in momentum in post-pandemic years, has been the perception among many engineering students that the foundational Engineering statics course is extremely daunting and one of the most challenging courses in the curriculum. At the authors' institution – a large enrollment public land-grant university – this perception is supported by the fact that in recent years, the course has had the highest DFW rate (course was dropped before completion, the course was failed, or the earned grade was 'D') of any large-enrollment course across the entire institution. Given an annual course enrollment exceeding one thousand students, the statics course has developed a reputation of being an extreme obstacle in the way of progress toward degree, and a source of growing negative sentiment among students, and frequently, their parents. As a means of better understanding the reasons behind the current challenges to success in statics, the authors have conducted an in-depth investigation in an attempt to identify root causes of the issues witnessed both within the course structure itself as well as bigger-picture upstream curricular issues. The three primary phases of this investigation included: 1) identifying and objectively exploring common anecdotal assumptions about root causes, such as 'poor' trigonometry skills, a lack of physics 'knowledge', not 'understanding' vectors, etc.; 2) developing a conceptual map of course topics that clearly identified precedence and dependencies among topics; and 3) aligning learning assessments with the conceptual mapping to determine specific topics where students first struggled, thus leading to the inability to master concepts later in the course. Key findings of the work have included relatively precise identification of the basic vector arithmetic skills necessary for course success, and discovery of a significant difference in the assumptions made about student mathematics skills coming into statics versus the actual level of math preparation. It is this latter point that has led to further exploration of how to address a potential gap in the curriculum with the hopes of better preparing students for success in Statics. The results of this investigation serve not only to inform continued course redesign and improvement at the authors' institution, but also as a roadmap for other institutions who are exploring ways to address the challenges to student success in their respective statics courses.

Introduction

A strong foundational understanding of statics concepts is vital to success in various engineering disciplines due to the prominent role that solid and fluid mechanics play in these fields. As the curricular bridge between first-year mathematics and physics content and downstream mechanics and kinematics concepts, best practices in statics pedagogy and assessment have been the focus of significant investigation [1]. While statics concepts may seem elementary when compared to downstream topics in mechanics, dynamics and kinematics, the former can pose considerable challenge to students in the first semesters of embarking upon their engineering-intensive courseloads in their chosen majors. It has been noted extensively in the literature that statics poses several new challenges to students, such as the need to synthesize some of the relatively abstract concepts from math and physics into relevant real-world applications of the concepts. This difficulty in the transfer of foundational knowledge has long been a significant challenge to statics students, but it appears that in recent years it has begun to evolve into a barrier to downstream success for many students, such that investigators are seeking ways to better foster such knowledge transfer [2].

It has been shown that students' pre-statics math and physics preparedness impact knowledge retention and transfer in early-career college-level engineering courses. Studies have shown that math skills [3], [4] combined with algorithmic and logical skills [5] are essential, but not entirely sufficient to be successful in engineering courses, where higher-level problem solving is vital. Challenges to learning are shown to persist when students do not possess sufficient qualitative knowledge and meta-cognitive skills [6]. This can manifest in courses like statics where students are often comfortable with procedural proficiency in approaching problems so long as there is an example solution process to follow, yet they face difficulty in adapting such processes where greater conceptual understanding is required. Some have studied the use of hands-on physical models [7] or the use of augmented-reality or 3D modeling approaches [8], [9] to address the need to focus more on conceptual understanding. However, while there has been better understanding of the causative effects of these skills, a clear and direct pedagogical remedy, especially in the face of resource constraints, has been elusive. While these issues have been observed for some time, there is evidence that learning challenges have become more pronounced in many curricular areas in the aftermath of the global pandemic [10].

In addition to these academic challenges faced by both students and instructors, it stands to reason that many early-college students might develop a negative impression of foundational engineering courses such as statics. At some institutions the course serves as a 'gatekeeper' course, where it discourages or prevents struggling students from proceeding into their major [11]. This may have some role in creating the perception that all institutions use the course for such a purpose, especially if the level of rigor is perceived to be much higher than courses in the pre-statics curriculum. And while this perception may be a direct product of the need for improved pedagogy, it may also be an unearned byproduct of suboptimal preparation in the curriculum prior to students taking statics. Considerable recent work has been done on better understanding student perceptions in statics and there have been some insightful findings that incorporate not only the in-class aspects of the technical challenge of the course but also the impact of non-academic factors. Investigators have reported the student experience in statics is a strong product of how much students struggle with foundational skills in math and science, and especially with conceptualizing equilibrium problems requiring higher-order thinking [8], [12].

While others have even observed that a number of students come into statics believing that they are inherently lacking in their grasp of mechanics or math, thus negatively impacting the students' engagement with the course concepts [13].

In this study, the authors report on the results of their investigation of student performance in statics, informed by its relatively low success rate when compared to prerequisite math and physics coursework for early-career engineering students at the institution. A flow diagram of dependencies among course topics was developed and used to deploy precisely targeted assessments with the goal of identifying key locations in the course where students begin to struggle with concepts. Furthermore, pre-statics curriculum data was analyzed to explore the potential sources of students' struggles with prerequisite concepts, as well as determining if there were indications of misalignment with the level of academic rigor in statics. Such an inconsistency could conceivably reinforce a perception that the expectations in statics are unreasonably high. These results are reported in the hopes that other institutions find value in applying similar approaches to foundational curriculum challenges.

Methods

This study was conducted at a large-enrollment land-grand public university which has admissions policies designed to provide access for students from a broad array of academic and financial backgrounds. Due to the number of different engineering majors which require Engineering Statics (hereafter referred to simply as 'statics'), the three-credit course is taught during both standard academic semesters during the year – fall and spring – and has annual enrollments typically exceeding 1200 students. The course is generally taken by engineering students in their third or fourth semester, dependent on their first-semester math course placement, and has the following enrollment requirements: 1) completion of Introduction to Classical Physics I ('Physics I', 5 combined credits of lecture and laboratory), and 2) completion or concurrent enrollment in Calculus II (4 credits). Statics has been taught for the past several years by the same instructional team with a mindset on course improvement while being mindful to maintain consistent standards of rigor and assessment format. The success metric 'DFW' – percentage of students who either earned a grade of D+ or below or dropped the course before completion – is employed by the institution as a first-pass indicator of areas of curricular concern. For reference, the DFW rate for statics has steadily increased from the low 30% range in years prior to the global pandemic, to nearing 50% in more recent semesters. This study incorporated several different data sources starting in the Spring semester of 2021, but with the bulk of targeted investigative efforts reported here involving students who took the course in the Spring and Fall semesters of 2024, as noted below. This study has been reviewed and approved by the institution's Institutional Review Board (IRB).

To begin the root cause analysis approach, the research team (consisting of the departmental course instructor team and administrators in the College of Engineering) developed a flow diagram of course topics and their dependency structure, indicating how each of the 31 unique course topics depended on one or more topics presented earlier in the course. This graphical tool indicated the causative relationships among topics and served to identify particular checkpoints where a single course topic had impact on multiple downstream chains of course topics. This dependency diagram is referred to hereafter as the 'concept map' of the statics course. Once the concept map was completed, the investors considered methods to directly assess student mastery of each topic in an appropriate manner within the existing course structure, as well as with additional low-stakes assessment in targeted areas. As part of the existing course structure, the majority of students' semester grade in the course comes from three common mid-term and one common final examination administered to all students, with each exam typically consisting of four long-form engineering problems which involve multiple calculations and synthesis of various concepts. The exams are graded with partial credit using a rubric to award an appropriate number of points for each question. Two approaches were employed to gather targeted data on mastery of individual course topics corresponding to the concept map. The first approach included the development of sub-questions on the standard exams, but which: a) assessed a level of understanding that could be considered as being on the borderline of *Application*-to-*Analysis* Bloom's level [14] mastery of a concept (rather than the full exam question which spanned *Analysis*-to-*Synthesis* boundary); and b) had clear correct or incorrect answers leading to a binary result for the sub-question. These sub-questions are referred to as 'binary questions' and were designed such that they addressed one of the steps required to complete the full exam problem, but focused solely on the concept map topic being assessed. Each semester exam included approximately eight binary questions integrated within the four top-level engineering problems. The second method of targeted assessment of concept map topics was developed to gain further insight into issues identified during the analysis of exam binary question results early in the study. The latter method included the use of short low-stakes assessments administered within the first week of the semester. These included an eight-question vector skills quiz, a quiz of 3D visualization skills consisting of select problems from the standardized Revised Purdue Spatial Visualization Test (PSVT:R) [15], and the administration of the standardized Force Concept Inventory (FCI) [16]. The first-week assessments not only served to identify skills deficiencies of incoming students prior to the first exam (which was administered in the fifth week of the semester), but also served as a benchmark to determine if the first few weeks of statics instruction helped students master these topics.

To assess potential pre-statics factors that could impact DFW rate, the investigators obtained student records indicating which mathematics course was completed by each statics student during their first semester at the institution (both direct from high school and transfer students), from the following list (of which course covers topics that are prerequisite skills for the following course): College Algebra, Preparation for Calculus, Calculus I, II, III, or Elementary Differential Equations and Laplace Transforms ('Differential Equations'). This data was deemed relevant because students are placed in their first-semester math course based on their performance on a standardized assessment, ALEKS [17], but may change, drop or fail their math course subsequent to placement. The investigators focused solely on which course was ultimately completed in the first semester and whether this had a predictive relationship to statics performance.

Results

Statics Concept Dependency Map

Figure 1 illustrates the resulting concept map that was developed to indicate knowledge dependencies among the thirty-one topics covered in the course. Course topics directly align with the required textbook, which is widely used by various institutions for statics [18]. The topic names have been converted to three-letter unique signifiers for the purposes of the figure, with a portion of the map enlarged to show full topic names. The percentage of students in Spring 2024 who successfully demonstrated mastery are shown in the enlarged region for select topics. Table 1 provides detailed information on select examples from the concept map, for the purposes of illustration. The full list of course topics is included in the Appendix. Examination of the map shows that there are multiple parallel flow paths of skills dependency across the topics in the course, with some skills having a single immediate prerequisite and others having multiple inputs. On downstream side, some topics have multiple immediate successor topics or serve as distinct branching points for lengthy downstream topic threads. Thus, they exhibit a strong influence on student success in the course because of their importance. These topics are encircled in red in the map and include: Cartesian Vector Addition (ACV), 2D Equilibrium and Free Body Diagrams (FBD), Equilibrium Equations and Two-Force Members (EET), and Internal Loading in Structural Members (ILS). The analysis of student mastery of various topics in Spring 2024 motivated the use of the targeted first-week vector skills assessment in Fall 2024, whose results are reported in the next section.

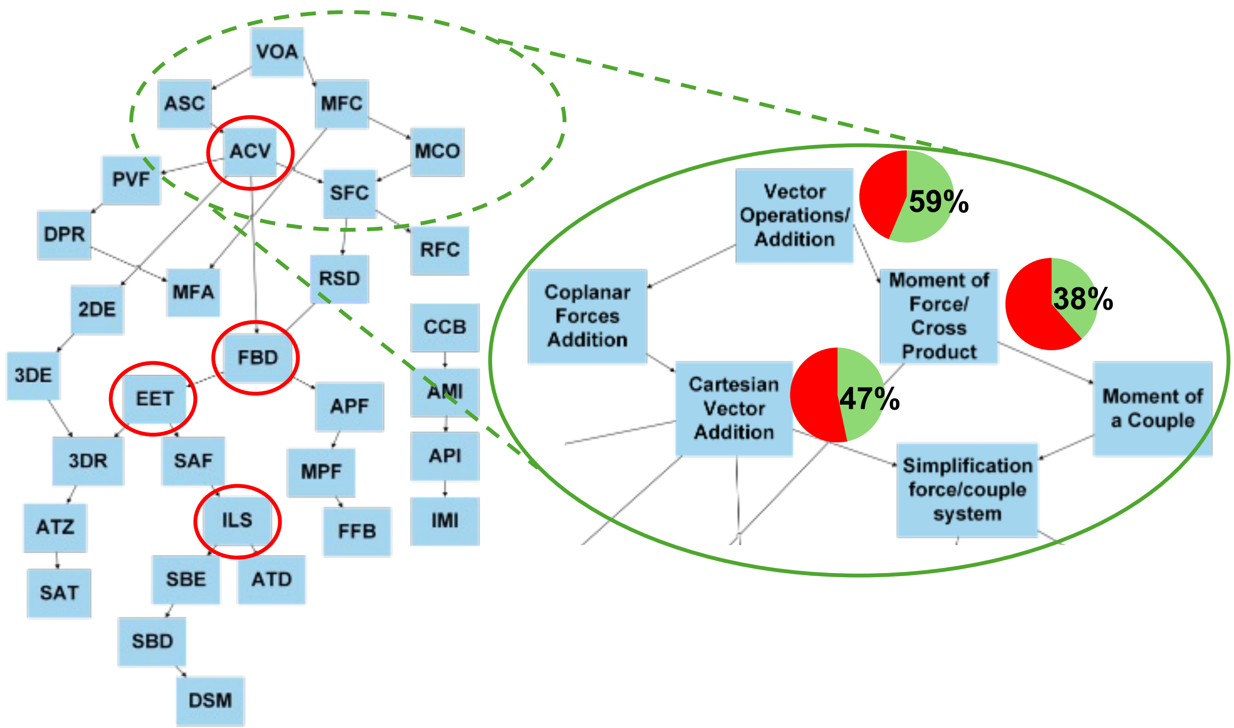

Figure 1. Concept map of the 31 topics covered in the statics course showing the knowledge dependencies among topics. Three-letter codes are used to represent the topics, while an expanded portion of the map is shown on the right. Student performance on select topics is shown in the expanded portion with the red fraction of the pie graphic indicating the percentage of students who did not demonstrate mastery of the topic on the exam binary questions. Red ellipses indicate 'checkpoint' topics that had multiple ties to downstream topics. A table listing all topics and corresponding figure codes is provided in the Appendix.

Table 1. Topic dependency information for select statics topics from the concept map

Topic	Figure code	Prerequisite Topics	Successor Topics
Vector Operations/Addition	VOA	–	• Coplanar Forces Addition • Moment of a Force/Cross Product
Dot Product	DPR	• Position vectors, force components	• Moment of force about an axis
Moment of force about an axis	MFA	• Dot Product • Moment of a Force/Cross Product	–
Reduction of distributed loading	RSD	• Force/couple simplification	• 2D Equilibrium and Free Body Diagrams

Vector skills assessments

The completion of the concept map, which clarified topic dependencies, directed the development of the targeted assessments (exams, binary questions and first-week quizzes), to attempt to detect and quantify the precise locations of skills deficits in the course topic flow with minimal confounding with other topics. The results of the first-week vector operations assessment administered in Fall 2024 (n = 658 students) are shown in Figure 2. The assessment consisted of eight questions and required students to perform operations on two given vectors, A and B, given in three-dimensional basis vector (‘*i-j-k*’) notation. The results show that the majority of students calculated the correct answer for operations such as vector addition (83% of students answered correctly), subtraction (78%) and magnitude (73%), but it must be noted that these results also show that dozens of students had not mastered these prerequisite skills by the time they started statics. Far lower proportions of students were able to correctly demonstrate understanding of calculating unit vectors (28%), angle between a vector and the x-axis (6%) or calculating the dot product (27%). As indicated in the concept map, fundamental vector operations such as addition and magnitude are prerequisite skills to determining unit vectors and calculating dot product, and examination of the vector assessment results show that the vast majority of students who struggled with the elementary skills (magnitude, addition) also did not answer the latter questions correctly (unit vectors, dot product, etc.). Thus, student mastery of vector magnitude and addition became fundamental metrics tracked by the investigators in terms of impact on later course performance.

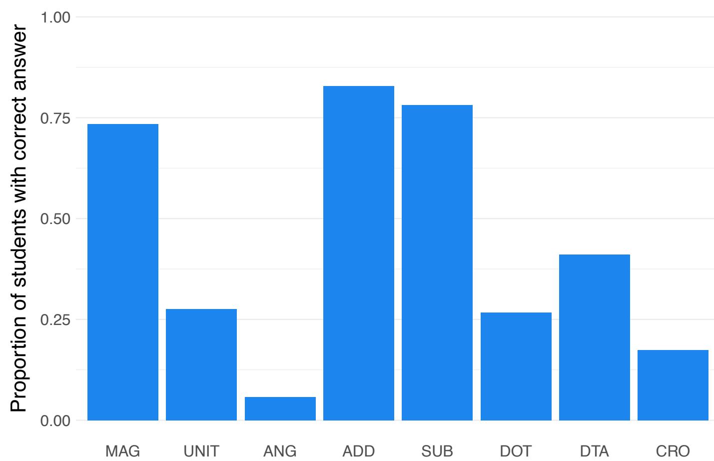

Figure 2. Student performance on the first-week vector operations quiz in the Fall 2024 semester (n = 658 students). Each bar represents an individual topic (labeled with a three-letter abbreviation). 'MAG' and 'ADD' signify vector magnitude calculation and vector addition, respectively. 'ANG' and 'DOT' signify calculation of angle that the vector makes with the x-axis and calculation of the dot product between two vectors, respectively.

Figure 3 shows the impact on Exam 1 scores (administered in the fifth week of the semester) for students, grouped by whether they correctly calculated the magnitude of a vector on the first-week assessment. The results show a clear difference not only in mean exam score of the two groups, but also a marked difference in the exam score distributions.

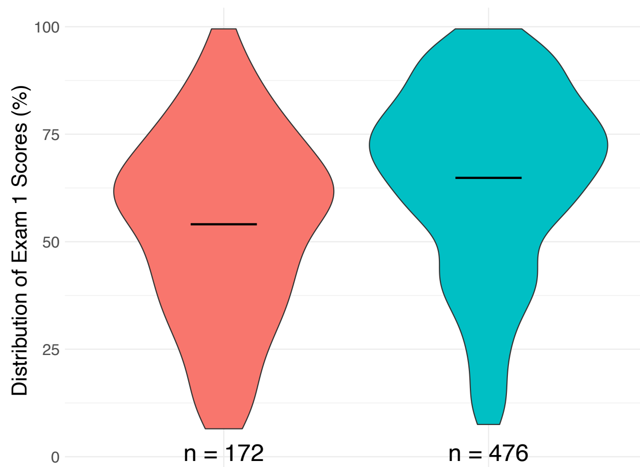

Figure 3. Comparison of Fall 2024 Exam 1 scores grouped by performance on first-week vector magnitude question (MAG). The group on the left answered the magnitude question incorrectly and the group on the right answered correctly. The shapes' silhouette width is scaled to the distribution of exam scores within the group. The mean exam score for each group is indicated by the bold horizontal line.

Delving deeper into other areas of the first-week vector skills assessment and the question of whether students were able to gain mastery of topics in the first weeks of statics, the investigators looked at the binary questions integrated in the first exam that reassessed skills measured in the first week. Figure 4 illustrates the evolution of student performance in calculating the dot product of two vectors between the first week and the first exam in Fall of 2024. In addition to dot product (where 70% showed mastery on the exam), improvement was observed in the three other vector concepts which were tracked, yielding the following results: unit vector calculation (89%), cross product (58%) and angle with axis (81%). While all four topics showed improvement, a significant number of the students could still not demonstrate mastery of these fundamental concepts at the time of the first exam.

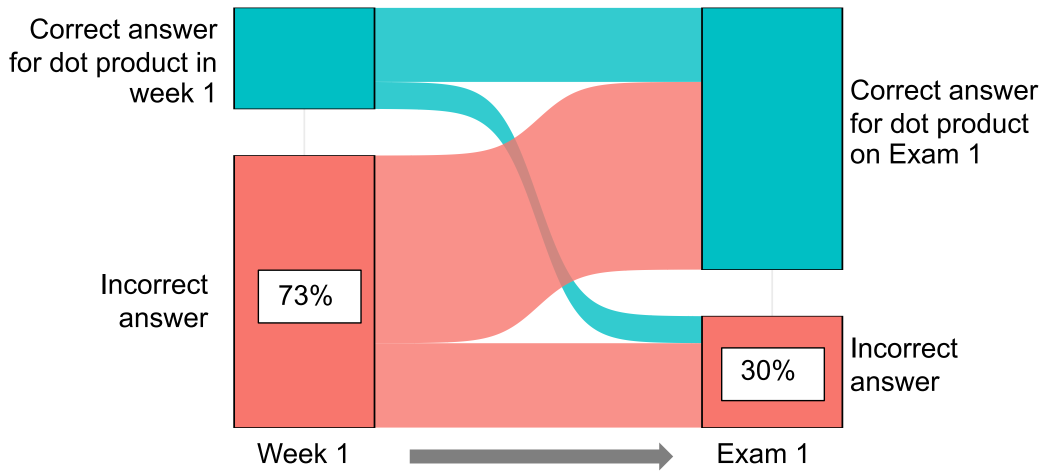

Figure 4. Fall 2024 trajectory of student ability to correctly calculate the dot product of two vectors, measured at the first-week assessment and Exam 1 going from left to right, respectively. The teal group indicates the proportion of students who answered the dot product questions correctly, while the salmon color indicates those who did not. Note the proportion of students (30%) who were never able to demonstrate understanding of the dot product.

Pre-statics Curriculum Effects

In addition to assessments and student data obtained during the semesters of enrollment in statics, institutional records were used to evaluate the academic history of students in semesters prior to the course. This yielded two distinct routes of further inquiry. The first focused on math preparation of students prior to statics, and the second focused on whether there is a knowledge gap in the pre-statics curriculum with regards to vector operations. Figure 5 reports a finding that is directly relevant to the first focus. It illustrates the number of tracked students enrolled in statics in Spring of 2024 (n = 482 students) based on whether they successfully completed statics (i.e., they received grades of A, B or C) in the top row, or if they well within the DFW group (grade of D, failed or dropped the course before completion) in the bottom row. Each column of vertically aligned ellipses encompasses the students in the cohort who completed a particular math course in their first semester of study at the institution, and the columns represent the ordered sequence of math courses from left to right, starting with College Algebra and ending with Differential Equations. Each data marker indicates a unique student and his or her final grade in their respective math course. The relative numbers of data markers in each group can be converted to the probability of statics success for a student based on their first math course taken and grade earned. These probabilities will be reported in the Discussion section.

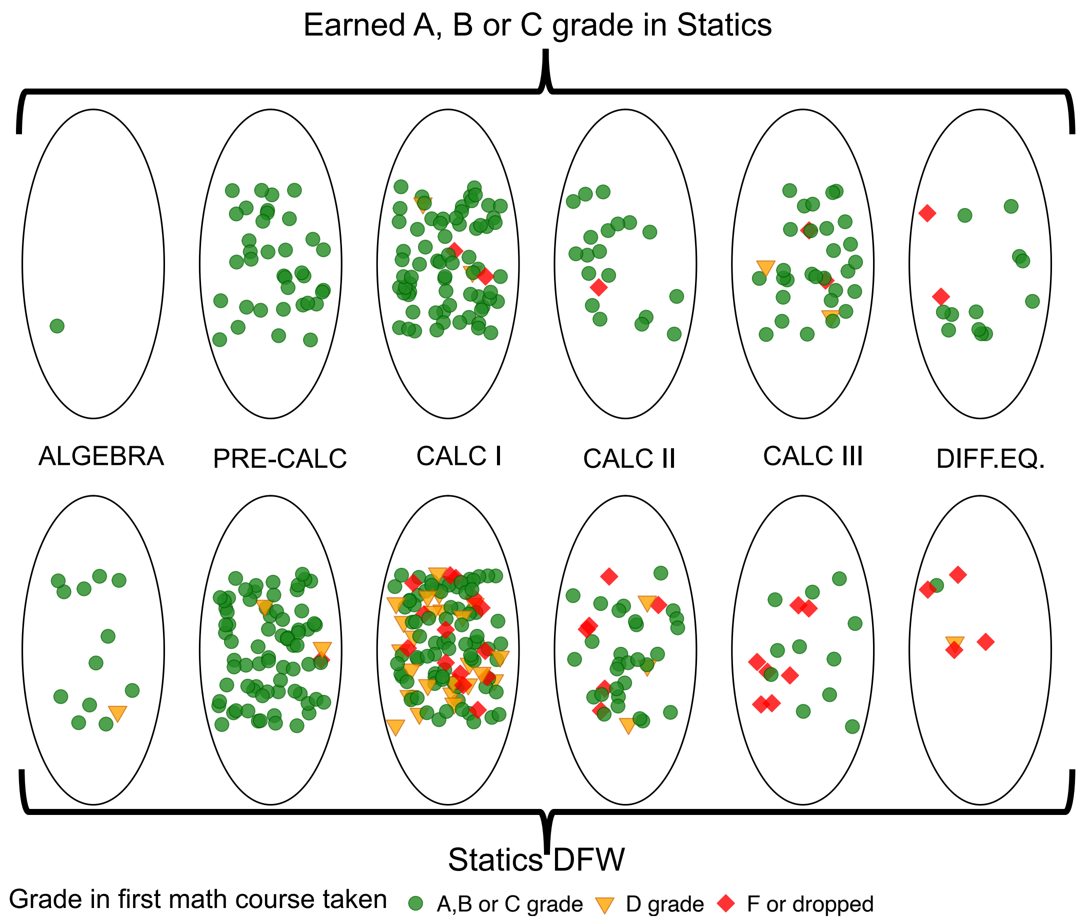

Figure 5. Performance of students in statics grouped by performance in first math course taken at the institution (left to right). Top row are groups of students who were successful in statics. The lower row are the students who received a D+ or lower or dropped statics. The data marker shape and fill color indicate the grade received in the math course taken. Individual markers are scattered from each other to improve legibility.

Discussion

Analysis of the results of this study provided insights both into the sources of student struggle during the statics course, and into some of the root causes for the perception of the course as being unreasonably difficult. The exercise of tracing knowledge dependencies among the course topics and converting this to a graphical representation provided the ability for the different members of the investigative team to share their perspectives on topic priority as well as illustrate the critical topics that have large impact on course success. As shown above in the results, of the 31 course topics, some follow a linear thread of successive topics building upon each other, while there are other topics that have multiple successor topic threads and thus have the potential to greatly impact overall course success. Furthermore, the ability to visualize such dependencies allowed for higher precision assessment of skill deficiencies and targeted curricular improvement. For example, the concept map facilitated the development of binary sub-questions in Spring of 2024 targeted at equilibrium concepts, both two and three dimensional, denoted by the blocks '2DE' and '3DE'in Figure 1. Assessment of these two topics revealed that only 46% of students demonstrated understanding of 2D equilibrium and even fewer – 32% – grasped 3D equilibrium by the time of the second exam. These results are concerning in isolation, but when assessment results were tracked back along this sequence of topics in the concept map, it was discovered that only 59% of students showed mastery of the very first topic in the overall sequence – Vector Operations/Addition (VOA), which is the first topic covered in the course and intended to be a refresher of prerequisite skills that students were assumed to have mastered prior to taking statics. This realization led to the decision to administer the first-week vector skills assessments in Fall of 2024 which more clearly illuminated how fundamental the skills deficiencies in vector operations were for incoming students.

The premise that poor understanding of fundamental vector skills had a significant and persistent impact on course performance was reinforced by the results shown both in Figure 3 and 4. Students struggling with vectors performed worse overall on the first exam in Fall of 2024, but perhaps more troubling is the fact that several weeks of instruction about vectors – in the context of their representation of forces in statics problems – still did not yield mastery of these fundamental skills at exam time. This result poses questions that get further at root causes of the problem. While most students post-statics would likely reflect on these basic vectors skills, such as vector addition and magnitude, as straightforward, it is not clear if or how the transition occurs between being a novice and being able to apply these operations. The authors have postulated that some of the challenge may come down to students being uncomfortable with *i-j-k* basis vector notation, lack of a mental image that ties the vector abstraction to real-world phenomena, or possibly even lack of clarity about the rationale for applications where vectors provide benefit over the use of scalars. Further investigation will be required to pursue these potential explanations.

This evidence of the impact of vector operations on statics success – and student perception of course difficulty – identified a fundamental, and ultimately incorrect, assumption about students starting statics: That prerequisite coursework in mathematics and/or physics had meaningfully prepared all students to understand and apply basic vector operations such as addition, magnitude and dot product. In terms of the question 'Where do students learn vectors?' in the pre-statics curriculum, a search for an answer involved entailed two potential explanations. Firstly, was this lack of prerequisite mastery due to poor preparation of students in an upstream course?; and secondly, was this skills deficit due to an as-yet unrealized gap in the pre-statics curriculum with regard to coverage of vectors and related concepts? Upon inspection, both explanations looked to have some merit. Looking at the pre-statics curriculum, one of the stated course objectives for the institution's Physics I course is:

- *Students will be able to implement basic vector algebra and calculus to explain and successfully solve problems.*

Clearly, this objective is in line with statics preparation, and a review of the course curriculum showed that vector topics were indeed covered in the physics course. Yet the findings here show that a significant proportion of students were not able to demonstrate the most basic of these skills post-Physics. The investigative team has been involved in an ongoing curriculum improvement project to seek ways to address this deficiency. On the other hand, there has also been an assumption that fundamental vectors skills are imparted in upstream math courses such as Pre-Calculus or somewhere in the Calculus sequence. Review of the curricula of the institution's math courses and discussion with administration in the math department has indicated that these courses do not cover vectors, and it is not until Calculus III (often taken in the semester after statics is taken) where such topics are introduced. The authors have concluded that fundamental vector operations, while introduced to students in the prerequisite Physics course, may not be sufficiently prioritized in the wider pre-statics curriculum for the goal of statics success.

Further consideration of pre-statics mathematics coursework also illuminated a particularly concerning outcome, as illustrated in Figure 5, for the Spring 2024 semester. Aside from the issue of whether vectors are covered in upstream math courses, the figure shows that initial math placement when starting a degree at the institution had a profound effect on the probability of being successful in statics (which is typically taken in the third or fourth semester). Strikingly, only 7% of students who placed into College Algebra in their first semester, in spite of passing the course and subsequent math courses, were successful in statics (i.e, earned a grade of C- or higher). The situation for initial Pre-Calculus students was not much better, with only 32% succeeding in statics. This trend continued with students starting in Calculus I and II. It was not until the cohort of students starting college in Calculus III was analyzed that the probability of successfully completing statics (64%) became likely. These results, aside from the concerns regarding vector skills, suggest that the institution's math placement process and/or math curriculum requirements may not be adequately calibrated to the academic requirements of the statics course.

Conclusions

The results of the study provided the authors with greater insight into why statics may be perceived as an extremely challenging course for early engineering students. It is likely that the challenge level of the course is exacerbated by instructor's incorrect assumptions of student prerequisite skill mastery when starting the course. This combination has the potential to expose a disconnect between the rigor and out-of-class effort demanded by statics versus upstream prerequisite courses such as calculus and physics. This latter finding is a complex institutional-level question and can be very difficult to quantify given its qualitative nature and potential for subjective assessments. In addition to gaining insight into general root cause of perceived statics difficulty, the authors have made the following specific finding from this study:

- This work has produced a useful mapping of topic dependencies in the statics course, and this concept map provided utility in precisely highlighting opportunities to incorporate targeted assessments in the course. The results of these assessments shed light on several root causes of the DFW rate of the course.
- A significant share of the difficulty in statics was found to stem from many incoming students' insufficient understanding of basic vector operations, such as vector addition and magnitude calculation. The results show that mastery of these two concepts is a necessary, but not sufficient, condition for understanding and applying higher-level vector operations such as resolving components of force, calculating moments produced by forces and equilibrium of forces. These latter concepts are vital to successfully completing the course.
- The math course completed by students in their first semester at the institution, prior to statics, has very strong predictive power on determining a student's probability of success in statics. This is largely independent of the grade earned in the math course. The probability of

earning a statics grade of D+ or lower – or dropping the course – was greater than 50% for students who completed College Algebra, Pre-Calculus, or Calculus I in their first semester of college.

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Appendix

Table 2. Key for Figure 1 showing the complete list of statics topics corresponding to the codes shown in the concept map

Topic	Figure code
Vector operations; vector addition of forces	VOA
Addition of a system of coplanar forces	ASC
Addition of Cartesian vectors	ACV
Position vectors; force vector along a line	PVF
Dot product	DPR
2D equilibrium of a particle	2DE
3D equilibrium of a particle	3DE
Moment of a force; cross product	MFC
Moment of a force about a specified axis	MFA
Moment of a couple	MCO
Simplification of a force and couple system	SFC
Resultant of a force and couple system	RFC
Reduction of a simple distributed loading	RSD
2D rigid-body equil.; free-body diagrams	FBD
Equilibrium equations; two-force members	EET
3D rigid-body equil.; statical determinacy	3DR

Topic	Figure code
Structural analysis of frames and machines	SAF
Analysis of trusses; zero-force members	ATZ
Structural analysis of trusses	SAT
Internal loadings in structural members	ILS
Axial force diagrams; torque diagrams	ATD
Shear & bending moment equations	SBE
Shear & bending moment diagrams	SBD
Distributed load/shear/moment relations	DSM
Analysis of problems involving dry friction	APF
More problems involving dry friction	MPF
Frictional forces on flat belts	FFB
Centroid of a composite body	CCB
Area moment of inertia; radius of gyration	AMI
Area product of inertia	API
Area moment of inertia about inclined axes	IMI