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Categorizing and Understanding Common Student Errors in Statics

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Abstract

Understanding the types and causes of student errors in Statics can provide valuable insight into both conceptual and procedural challenges undergraduate students face in foundational engineering courses. Statics is one of the first engineering courses that students take which requires students to apply their math and science backgrounds including geometry, modeling, and equilibrium concepts to new systems along with maintaining procedural consistency when applying their problem solving skills. Students frequently make recurring mistakes on Statics exams that can reveal underlying patterns of deficiency in certain engineering skills. This paper investigates student errors in Statics exams across multiple instructors and course structures to identify, categorize, and measure the common patterns and trends that most inhibit student growth.

Data was collected from student exam submissions for two instructors over multiple semesters that represent a range of problem types and instructional approaches. The most frequent recurring errors were broadly classified as either conceptual or procedural. Conceptual errors are those relating to fundamental understanding of underlying principles such as the incorrect modeling of supports, the incorrect representation of equivalent force systems, or the incorrect manipulation of three-dimensional vectors. Procedural errors are those that involve improperly applying basic solution steps such as calculation errors, unit mistakes, or incorrect usage of formulas. The data was further analyzed to quantify the frequency and distribution of each error type across the sample space within and across exams, and the results were compared to students' final course grades to evaluate relationships between error patterns and overall course performance.

Preliminary findings suggest that conceptual errors are more strongly correlated with lower course performance and tend to persist throughout the semester, even after multiple exposures to similar problem types. Procedural errors, while common early in the course, appear to lessen with repeated practice and feedback. The results of this analysis have implications for assessment design, grading practices, and targeted feedback strategies. By understanding not just whether students reach a correct solution, but also how they approach it, instructors can use systematic error analysis to identify persistent misconceptions and better support students, particularly those with recurring conceptual errors.

Introduction

Statics is a foundational engineering course required for many engineering disciplines that requires students to integrate their prior math and science knowledge and apply it to a variety of physical systems. Successfully solving Statics problems requires a level of rigor in both the problem derivation and execution of the solution that is novel to these students and results in many places for errors to occur. Students must demonstrate both proper conceptual understanding and maintain procedural accuracy throughout the entire process to correctly reach the final answer. To support student learning, students can be provided with structured problem solving procedures and repeated practice opportunities to try to master these skills. Despite this support, students frequently make errors that lead to incorrect solutions. These errors range from conceptual misunderstandings like incorrectly modeling the system to procedural mistakes like algebra errors. Some of these errors identify gaps in student understanding of core concepts, while others are the result of execution errors despite the overall understanding being there. Distinguishing these different types of errors can lead to a better understanding of student learning in Statics.

As instructors for this 2nd year mechanics course, the interest is often not whether students can get the final answer, but where and why errors occur in the solution process which can provide insight into students' understanding of the course content. Identifying patterns in student errors can reveal areas that need further instructional support and highlight places where common misconceptions can occur. Statics has been documented as a challenging course for students, specifically noting that certain concepts like free body diagrams, modeling supports and loads, and correctly applying equilibrium principles pose a significant challenge [1]. Prior studies have categorized some Statics concepts that students need to solve problems or identified common errors that students have when solving some of those concepts [1, 2]. These studies range from identifying broad foundational concepts in Statics to specific concepts that occur in certain problem types that students often do incorrectly. Collectively, the literature reflects an effort to better understand this foundational course and identify errors that can occur from multiple perspectives [3-5].

Within the literature that examines errors in student work, an emphasis has been made on differentiating between conceptual errors and procedural errors [1, 2, 6]. Conceptual understanding is often defined as correctly interpreting or modeling concepts about the physical system while procedural errors involve mistakes in the execution of mathematical steps. Prior research has shown that procedural errors can decrease with repeated practice and progress, but some conceptual errors persist for students even as they reach their final semesters in school [5]. As a result, identifying and understanding the relationship between these types of errors is an important consideration for instructors.

Diving into conceptual errors, several studies have explored the reasons for conceptual errors. One study relates student spatial ability to Statics performance, suggesting that spatial ability can support visualization and better conceptual understanding of modeling systems leading to more success [4]. Other work has focused on the development of concept inventories and related instruments to assess conceptual understanding independent of computation. The Statics Concept Inventory has been widely used to evaluate student understanding of core Statics topics that students have misconceptions on at the end of their Statics course [7, 8]. These tools provide valuable insight into conceptual understanding, but their multiple choice format and predefined concept focus limits the ability to capture student reasoning when solving more open ended problems in a classroom. These open ended problems create opportunities for both conceptual and procedural errors to show up making it hard to parse through student understanding. There have been other studies that focus on the problem solving process of more open ended problems to try to identify where and how errors occur in a solution. These studies require manual grading of errors but have revealed opportunities for targeted interventions in the course content [3, 9]. One study focuses on very specific problem types, such as truss analysis, to identify errors specific to the solving process of those problems [9].

All of these studies have collectively contributed to understanding difficulties in Statics, with much of the work focused on broad conceptual challenges or problem specific concepts. There remains a gap to examine errors in a generalized Statics problem solving process to identify where errors arise at specific steps and how those relate to conceptual or procedural understanding. Further, by analyzing errors in a standardized solution framework, it allows potential for the error to be distinguished to the discipline of knowledge it is coming from, like Statics specific conceptual errors or errors resulting from knowledge of past courses such as physics or calculus.

The purpose of this study is to identify, categorize, and analyze student errors within a generalized Statics problem solving process across multiple course sections taught by different instructors. This generalized process breaks down the main requirements to solve a Statics problem into categories, and the errors of each category are systematically classified as either procedural or conceptual. These errors are tracked longitudinally throughout the semester to examine trends across exams and parts of the problem solving process. Additionally, the study explores the relationship between the frequency of each error type and overall course performance. By applying a structured error analysis, this work aims to identify patterns in student problem solving that are not evident when considering final answer or course grade alone.

Course Context

The data for this study was collected from two Statics instructors each using a single semester of data as a representative sample for this paper. The instructors had different instructional approaches and exam schedules, but the courses covered the same standard Statics topics. Instructor 1 used a flipped, mastery grading course design while Instructor 2 used lecture-centered design with points based grading. Across both instructors' sections, students were required to show a complete solution for their work resulting in handwritten submissions involving their problem solving process.

Instructor 1 administered seven single problem exams during the semester followed by a final exam consisting of multiple problems. In these sections, the students were expected to follow a standardized solution process for all problems, emphasizing a consistent procedure for every problem in the course [10]. Data from Instructor 1's final exam has been excluded from this analysis since not all students were required to solve the same final exam problems.

Instructor 2 administered three exams equally spaced throughout the semester. The last test of the three was a cumulative final and all students in the course sat for all three exams. Each exam contained five free response problems, all equal weight, but of varying difficulty. Students are expected to use creative problem solving to complete comprehensive problems with multiple parts, each often drawing from multiple lessons of instruction.

This study includes the results of student work from Instructor 1's seven in-semester exams (excluding the final exam) and Instructor 2's three course exams (the last one being the final exam). Final course grade information is also included for comparison. All student data was de-identified prior to analysis, and the results are reported in aggregate to examine relationships between error types, exam timing, and course outcome.

Error Classification Framework

To analyze the student work consistently across the courses and instructors, the two instructors collaboratively identified the key categories of the Statics problem solving process that can be generalized to all problems in the course and were common places that errors occurred. There were seven categories identified that include: (1) problem geometry, (2) free body diagram (FBD), (3) force equilibrium, (4) moment equilibrium, (5) integration of distributed loads, (6) algebra used to obtain the final answer, and (7) units. For each category, the student work was scored as *correct*, *procedural error*, or *conceptual error*.

Procedural errors were defined as mistakes during the execution of a step with otherwise appropriate understanding of the underlying principle. This included algebra errors, calculation mistakes, or transcription errors (such as incorrectly carrying out arithmetic, writing down a result from the calculator wrong, or plugging in a wrong numerical value). These errors did not reflect a misunderstanding but did lead to an incorrect result. Conceptual errors were defined as errors that come from an incorrect understanding or a misconception of part of the problem. Some examples of this type of error include an incorrect representation of the physical system, defining force components improperly, incorrect formulation of the equilibrium equations, or incorrect mathematical interpretation for a distributed load. Conceptual errors resulted in an invalid solution approach and often led to errors in multiple steps of the process.

Within this framework, student exams were analyzed to determine how procedural and conceptual errors varied across the seven problem categories and exam problems throughout a semester. This was done by summing up the frequency of each score for each exam question and in total for each student. The score frequencies were compared to final grade to explore the relationship between error pattern and overall course outcome.

Results

Longitudinal Trends for Two Categories: Geometry and FBD

The first analysis examines how the distribution of correct responses, procedural errors, and conceptual errors changed over the course of a semester for a given problem solving category. This longitudinal approach was analyzed for each of the seven categories to reveal patterns in student errors and how they progress through a Statics course. This paper will present the trends for two representative categories: (1) problem geometry and (2) free body diagrams (FBDs). Geometry was selected because it represents an early but essential step in the problem solving process which the instructors' consistently noticed students have a difficult time setting up correctly. Errors in this step will always propagate to other parts like force and moment equilibrium and solving the problem, so this category is particularly informative for identifying misconceptions. Free body diagrams were selected because they are foundational to all Statics problems and a prerequisite to correctly applying equilibrium equations. These two categories provide insight into errors in the early steps of the problem solving process, and how those can vary throughout a semester as students' develop their skills.

The two instructors had a different number of exams administered during the semester. Results will be shown with Instructor 1's course data beside Instructor 2's course data for a variety of comparisons.

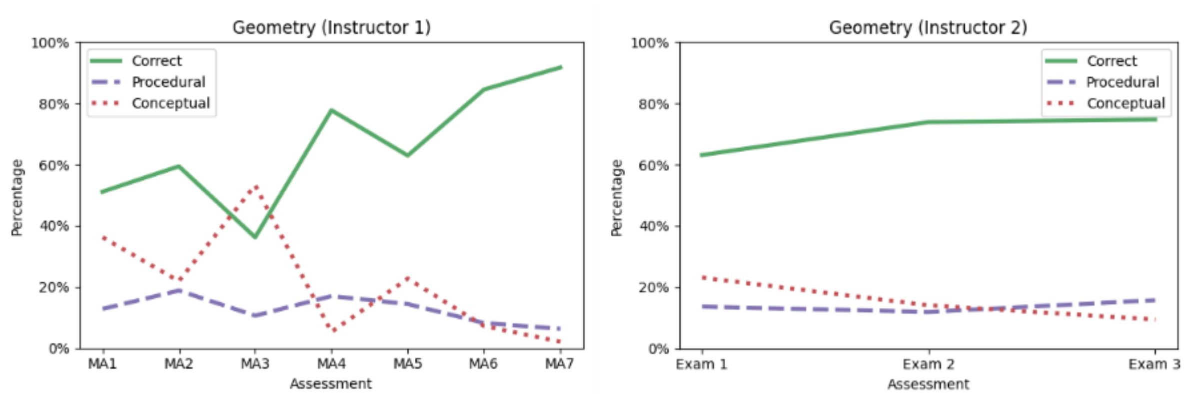

Figure 1: Data from Instructor 1's course alongside Instructor 2's course for errors in the geometry category. The geometry portion of a student's analysis is coded as being either correct, containing one or more procedural errors, or containing one or more conceptual errors.

Figure 1 presents the distribution of correct responses, procedural errors, and conceptual errors for the geometry category over the semester. Both courses show noticeable similarities in trends though Instructor 1's data shows a more detailed picture of student behavior changing with time where Instructor 2's data is less dense longitudinally. A general upward trend can be identified in both courses in the percentage of correct responses in the geometry category over time. This corresponds to mostly decreasing trends in both procedural and conceptual errors. Early in the semester conceptual errors tend to dominate over procedural errors, though this relationship flips by the end of the semester where procedural errors seem to be more prevalent than conceptual.

The errors in FBD offers similar insights. In Figure 2 a general trend upwards can be seen in the number of correct diagrams from students. A general complementary decrease in both procedural and conceptual errors also follows. Interestingly, both courses display a spike in conceptual errors mid-way through the semester alongside a smaller rise in procedural errors. This may be explained by the nature of progression through course material. The types of systems studied at the beginning of the semester include particles and simple rigid bodies and then progresses to systems of multiple rigid bodies usually somewhere around the midpoint of the semester.

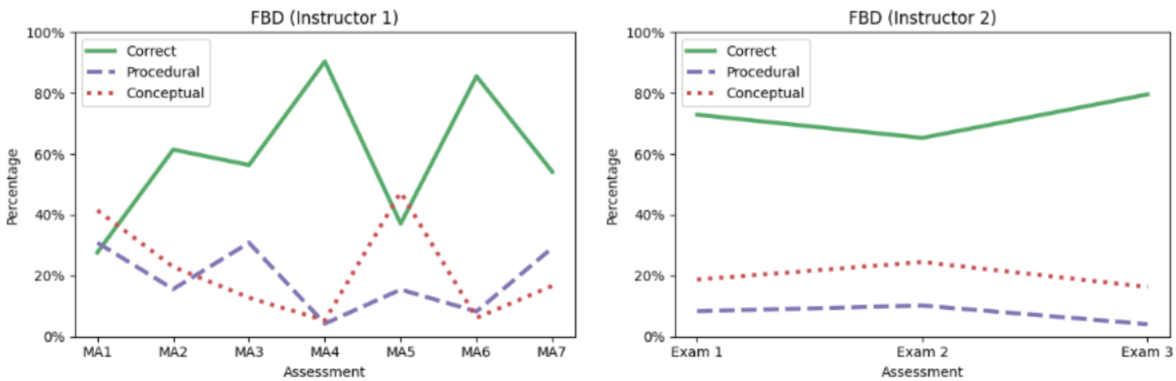

Figure 2: Data from Instructor 1's course alongside Instructor 2's course for errors in constructing free-body diagrams. The free-body diagram in a student's analysis is coded as being either correct, containing one or more procedural errors, or containing one or more conceptual errors.

Relationship Between Error Type and Final Course Grade

To examine the relationship between error types with overall course performance, students were grouped by final course grade, and the average frequency of each type of error for the entire semester was calculated for each grade. For each student, the number of correct, procedural error, or conceptual error scores for the seven categories was summed for all exams during the semester to give the cumulative student error counts. The cumulative values were then averaged within each grade group to compare score counts across each grade. Figure 3 illustrates the average number of each type of error for students in each final grade group.

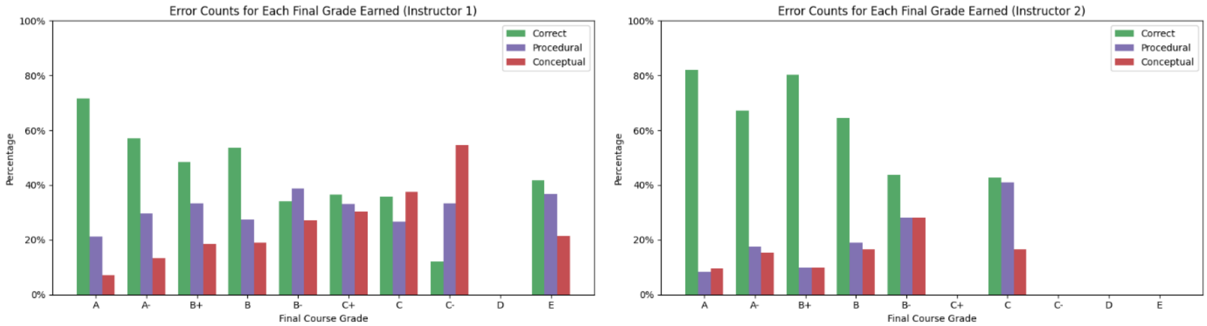

Figure 3: Total number of correct answers, procedural errors, and conceptual errors, displayed as percentages, and grouped by student's final course grades.

As expected, students earning better final grades showed fewer total errors. As grades got lower, a general trend of decreasing total correct scores and increasing errors can be seen. This trend is evident for both instructors, suggesting that the relationship between conceptual errors and lower course performance is prevalent across multiple instruction styles and assessment procedures.

There are also slight differences in the results for the two instructors. These differences likely reflect variations in assessment methods, exam structure, grading practices, and problem representation rather than fundamental differences in student capabilities.

Discussion

The results of this study suggest that conceptual errors are more strongly associated with lower course performance, while procedural errors are common across all performance levels. Although both error types decreased with practice over the semester, students earning lower final grades had persistent conceptual errors that did not fully resolve over time. This suggest that repeated practice alone does not always address an underlying conceptual misunderstanding in Statics.

The geometry and free body diagram categories provide a good example of how new problem contexts can introduce additional complexities and lead to conceptual errors for students who previously did that part correctly. The spikes in conceptual geometry errors at specific exam points in the semester represent that students may struggle with transferring their prior knowledge to a new problem context. This finding aligns with research on novice versus expert problem solvers, which states novice problem solvers focus on the surface features of a problem rather than the underlying principle of the process, whereas experts focus on the structural similarities across all contexts [11]. Although the geometry process is fundamentally consistent for all problems in Statics, the different problem contexts and representations introduce new contexts and features that can cause novice students to incorrectly set them up.

Importantly, these patterns were observed across two instructors who had different instructional approaches and exam schedules suggesting that certain error trends may be inherent to Statics and the development level of the students enrolled in the course, regardless of teaching method or course structure. The systematic error analysis provided a tool to identify these similar patterns which were not immediately clear when looking at final course grades.

An instructional implication of this information highlights the value of tracking student errors throughout the semester and identifying students who exhibit reoccurring conceptual errors. By having earlier detection of these patterns, instructors can intervene before the errors continue to happen and lead to poor performance. Instructors can also identify the common places where conceptual errors happen to provide additional instructional support.

Finally, systematic error analysis can enhance the quality of feedback to students. Rather than receiving feedback only on correctness or point deductions, students can be provided with the error type and where the error took place in the solution process. Through providing error type grading to the students, they receive more detailed information of their mistakes to better support their learning and understanding in the course. Instructors can help students focus their efforts more effectively in the places where conceptual errors persist.

Conclusions and Future Work

This study demonstrated the use of a systematic error analysis framework to examine student problem solving performance in Statics across seven key categories of the problem solving process. By identifying errors as conceptual or procedural and tracking these across exams and performance levels, this approach identified patterns in student understanding not typically captured in a final grade. It was shown that conceptual errors connect with lower course performance, but by quantifying these errors early, an instructor can intervene and better support students.

This study was limited by the differences in exam structure and timing between the instructors, and by the instructors' interpretation of student work when classifying errors. However, the results suggest that systematic error analysis is a valuable tool for identifying places of student misconceptions and informing instructional decisions.

Future work will focus on diving deeper into the data to see if there are differences in error frequencies for each category. It will also include identifying instructional interventions and targeted feedback based on these error patterns. Along with the data, student reflections can be gathered to provide further insight into student reasoning and their thought process. All of this data will provide a more holistic picture of student problem solving development in Statics.

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