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Fundamental Conceptual Errors in First-Year Engineering Mathematics: A Thematic Analysis

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ABSTRACT

CONTEXT

Engineering technology students at KU Leuven, Belgium, face a rigorous mathematics curriculum in their first semester, including Analytical Geometry, Linear Algebra, and Calculus. These courses are fundamental for advanced topics in engineering but often present conceptual challenges to students transitioning from secondary education. This study investigates those challenges faced by engineering students during their first-semester mathematics curriculum. Oral examinations provide a unique opportunity to identify these gaps by capturing students' verbal explanations alongside their written solutions.

PURPOSE OR GOAL

The purpose of this study is to identify and analyse conceptual errors made by students, as part of an action research approach. With the findings, we hope to guide educators in adjusting their teaching methods during lectures and exercise sessions to address these misconceptions and improve students' understanding.

APPROACH OR METHODOLOGY/METHODS

The research is based on observations recorded during nine oral examination sessions for the Fundamentals of Mathematics course. Each session involved 12–15 students, with exams lasting 6–15 minutes. In total, 210 students were observed, and their verbal explanations were documented alongside their written work. A thematic analysis of these notes was conducted, supported by K-means clustering algorithm to detect recurring themes and patterns in student responses.

ACTUAL OR ANTICIPATED OUTCOMES

The purpose of this study is to identify (and analyse) conceptual errors made by students, as part of a mixed-method research approach. For example, conceptual errors found after thematic analysis for a topic in linear algebra included failing to show the zero-vector criterion for subspaces, confusing subsets with subspaces or subspaces with vector spaces. These recurring issues highlight areas where classroom emphasis and targeted exercises can address gaps in understanding. With the findings, we hope to guide educators in adjusting their teaching methods during lectures and exercise sessions to address these misconceptions and improve students' understanding.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

This study underscores the importance of addressing conceptual misunderstandings in first-year engineering mathematics. The oral examination format also evaluates mathematical competencies like mathematical reasoning, communication, and mathematical thinking, which are often underemphasized in traditional assessments. The findings provide actionable recommendations for educators to enhance teaching strategies and better support student learning.

KEYWORDS

Engineering Education, First-Year Students, Student Misconceptions, Thematic Analysis.

Introduction

First-year engineering technology students often face a steep learning curve when transitioning from secondary mathematics to the more abstract and structured demands of university-level courses. At KU Leuven, the mathematics curriculum in the first semester of the Engineering Technology program includes Analytical Geometry, Linear Algebra, and Calculus, three domains that are foundational to the rest of the engineering curriculum. These courses are designed to develop and to cultivate students' understanding of mathematical reasoning, representation, and thinking. However, despite the preparatory knowledge expected from students which is judged using admission criteria as well as preparatory courses (Parul & van Waterschoot, 2024), many encounter persistent conceptual hurdles that can undermine their ability to apply mathematics in future engineering courses.

Misconceptions in mathematics are not isolated to specific populations or education systems. Decades of research have documented how students at all levels can carry fragmented or faulty concept images into new mathematical domains, particularly in abstract topics such as vector spaces, linear systems, and limits (Tall & Vinner, 1981; Muzangwa & Chifamba, 2012). In engineering education, these misunderstandings are especially critical to address, as they compromise the mathematical foundation needed for modelling, analysis, and problem-solving in technical fields (Almasalmeh, 2020; Aygör & Özdağ, 2015).

In Analytical Geometry, students must visualize three-dimensional objects, interpret coordinate systems, and transition between cartesian and polar forms. These are tasks that require spatial reasoning and fluency with vector representation. Calculations involving intersections, projections, and norms further test the ability to connect geometric intuition with algebraic formulation. Linear Algebra introduces greater abstraction through topics like subspaces, inner product spaces, and orthogonal projections (Ancheta & Subia, 2020; Li & Chen, 2024). These concepts are frequently misunderstood, as students define subsets with subspaces in the same way, confuse vector spaces with Euclidean space, and misapply dot and cross products. In Calculus, while procedural skills from secondary school often remain intact, students struggle to grasp the conceptual meaning of limits, convergence, and the nature of transcendental functions which are topics that require a shift from computational focus to analytical as well as visual reasoning (Rittle-Johnson & Schneider, 2015).

Understanding and remediating such conceptual errors requires more than traditional assessment formats. Oral examinations offer a unique window into students' thought processes, revealing how they interpret mathematical language, justify reasoning, and connect representations which are often hidden in written assessments (Odafe, 2006). This paper reports on a mixed-methods study involving 209 first-year students at KU Leuven. Oral examinations in the Fundamentals of Mathematics course were employed to identify conceptual misunderstandings at a detailed, topic-specific level, with the aim of informing the development of content-specific interventions.

By combining insights from mathematical education literature (Ay, 2017; Delastri, 2023) with context-specific observations, this study aims to support engineering educators in refining instruction and addressing the conceptual errors that persist in first-year engineering education.The findings point to the need for more targeted pedagogical strategies that support deeper conceptual understanding. Guided by this lens, the study explores the following research questions:

RQ1: *Which topics are most frequently assessed during oral examinations? How are questions distributed across the different mathematical domains?*

RQ2: *Which topics show the highest proportion of students who are able to attempt or respond meaningfully?*

RQ3: *What are the most common conceptual misunderstandings associated with each topic?*

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Methodology

We adopted a mixed-methods approach to investigate the conceptual challenges faced by first-year engineering students during oral mathematics examinations. This approach integrates qualitative and quantitative techniques within a thematic analysis framework, as illustrated in Figure 1. The four-phase analytical process includes initial coding of student responses (qualitative), scoring to identify misconceptions (quantitative), clustering using the K-Means algorithm (quantitative), and theme extraction informed by both coding and clustering (qualitative).

After each oral examination session, we reviewed students' verbal explanations and written solutions, noting key moments where conceptual misunderstandings or hesitations occurred (Appendix A). These preliminary concepts were later compared with data-driven clusters to assess alignment and strengthen validity.

To structure this process, observations were organized in a spread sheet, with each column representing responses to a single question. Each question was coded according to the main topic being tested, and the corresponding student scores were analyzed to provide a quantitative measure of success rates. Importantly, these scores were assigned by the examiner based on a predetermined answer key that was followed strictly. This ensured that the quantitative results were independent of researcher interpretation, minimized the risk of bias, and strengthened the validity of the mixed-methods design. These scores helped us quantify topic-specific performance and identify which mathematical topics presented the greatest difficulties. We visualized this performance data by generating plots that illustrated the distribution of scores across questions and topic area.

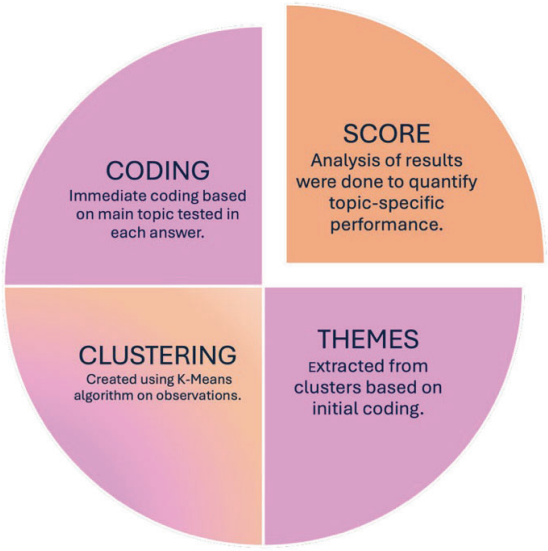


Figure 1: Visual representation of the four-phase analytical framework. Purple quadrants denote qualitative methods. Orange quadrants represent quantitative methods

To deepen the analysis, we applied Term Frequency–Inverse Document Frequency (TF-IDF) and K-Means clustering to the coded responses. TF-IDF transformed student explanations into weighted numerical vectors, while K-Means grouped similar responses to reveal five dominant clusters, each representing a theme named using the researcher's observation codes. After conducting cluster analysis and comparing the results with the preliminary conclusions drawn after each exam, the emerging themes were categorized as difficulties (–) or insights (+) and grouped under the corresponding topic tested.

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For example, in a question asking students to compute higher order derivative of a function, the main topic was coded as *"nth-order derivative."* Observation notes showed detailed difficulties such as misinterpreting factorial notation, incorrectly applying the chain rule and confusing notation. These response patterns were captured in three of the clusters, where frequent keywords such as "factorial," "power," and "chain" emphasized the recurring misconceptions.

The dataset (summarised in Table 1) included responses from **209 students**, gathered during **eight** oral examination sessions in the course as well as **scores** received in these examinations for **759 students**. Each observation session involved between 20 and 29 students, with individual exams ranging from 6 to 15 minutes. For each student, we documented verbal responses, written work, and question-specific scores.

Table 1: A summary of the examination sessions, topics covered, and the number of students observed is shown below.

Exam Topics	Exam Codes	Exams Graded	Exams Observed
Space Geometry & Vector Spaces	SG_VS	125	20
Plane Geometry & Integrals	PG_IN	114	27
Plane Geometry & Derivatives ~ Integrals	PG_CA	109	28
Vector Spaces & Projections (Subspaces)	VS_SS	55	27
Vector Spaces & Projections (Parameters)	VS_PR	79	27
Sequences and Series & Integrals	SR_IN	59	29
Function Series & Derivatives (Irrational)	FS_LM	122	26
Function Series & Derivatives (Logarithmic)	FS_DE	95	25
Total	—	**759**	**209**

Results

In this section, we present the results derived from the analysis of the oral examination data and focusing on the distribution of student performance across the seven sets of mathematical topics.The findings are visualized through plots, which highlight key aspects such as question distribution (**RQ1**), the numbers of students unable to attempt or respond correctly to questions and the proportion of correct responses by topic (**RQ2**) and conceptual errors shown by themes extracted for each topic (**RQ3**).

The questions were categorised into the following seven sets:

1. Plane and Space Geometry
2. Vector Spaces and Inner Product Spaces
3. Sequences, Series, and Function Series
4. Derivatives and Applications
5. Integration and Applications
6. Best Approximation
7. Functions.

In Figure 2, the largest portions are attributed to Sequences, Series and Function Series and Vector Spaces and Inner Product Spaces, indicating these areas had the highest number of questions. Moderate shares were allocated to Integration and Applications,

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Derivatives and Applications, Plane and Space Geometry. Functions and Best Approximation received the smallest shares, suggesting these topics were less emphasized in the assessment (**RQ1**).

Figure 3 illustrates student performance across seven mathematics topics, with the total number of questions asked per topic shown in blue and the number of students who answered correctly or partially correct shown in red. The topics Sequences, Series and Function Series and Vector Spaces and Inner Product Spaces had the highest number of questions. However, the number of students answering these questions correctly is markedly lower, indicating a performance gap. Best Approximation and Functions had fewer questions and correspondingly low correct response rates. Overall, the chart highlights areas where students struggled despite high assessment coverage, suggesting the need for targeted instructional support in those domains. An analysis of the mathematics exam data reveals key trends in both the distribution of questions and student performance across topics (**RQ2**).

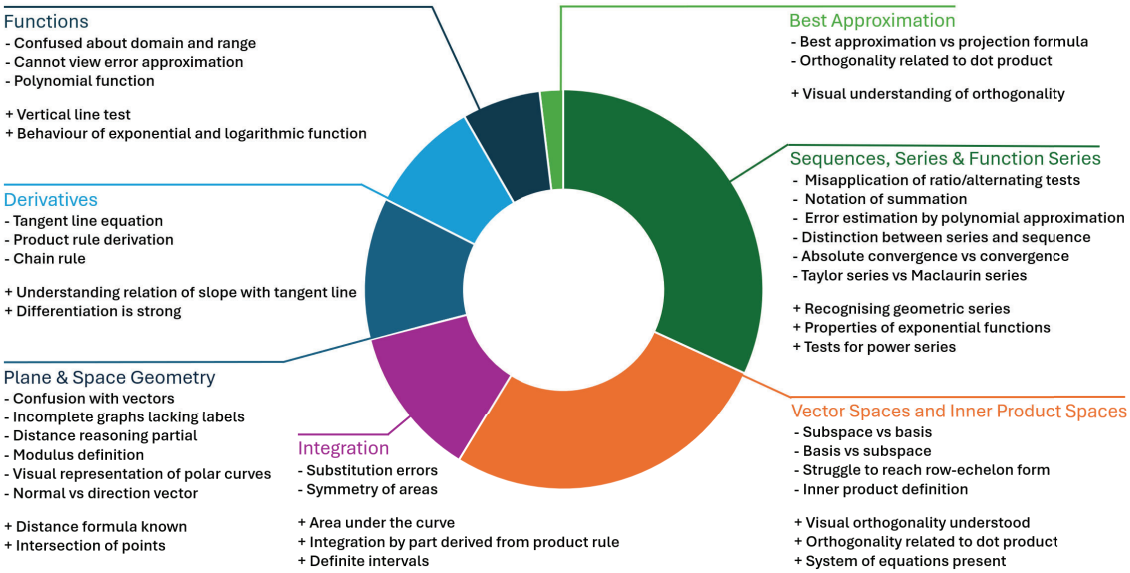


Figure 2: Themes shown for every topic (-) indicating difficulties and (+) student insights along with a chart indicating the distribution of exam questions across the seven topics

Figure 4 presents the percentage of correct responses by students across seven mathematics topics based on the data from Figure 3. Each bar represents the proportion of questions answered correctly out of the total asked in that topic. Despite their prominence, student performance in Sequences, Series and Function Series and Vector Spaces and Inner Product Spaces was notably low, with only 28% and 34% of questions answered correctly, respectively (Figure 4). In contrast, topics such as Plane and Space Geometry, Best Approximation, and Derivatives and Applications saw higher success rates (61%, 55%, and 51%, respectively), even when they were less frequently assessed.

We move on to expanding the difficulties that the students faced based on each topic indicated in the Figure 2, allowing us to answer **RQ3**.

Plane and Space Geometry

While the distance formula between a point and a line is typically recalled, students struggle to manipulate expressions involving the absolute value. Another major confusion lies in the use of vectors: direction vectors are incorrectly used to determine parallelism between planes when normal vectors should be used. This indicates a conceptual block in distinguishing types of vectors and their geometrical meaning. Parametrization is a key challenge here. Students have difficulty linking cartesian coordinates x and y to a parameter t, and often misinterpret two

parametric equations as representing a plane instead of a line. The connection between the *x*-*y* coordinate system with the polar coordinate system is not seen by students and therefore they find it hard to graph polar curves.

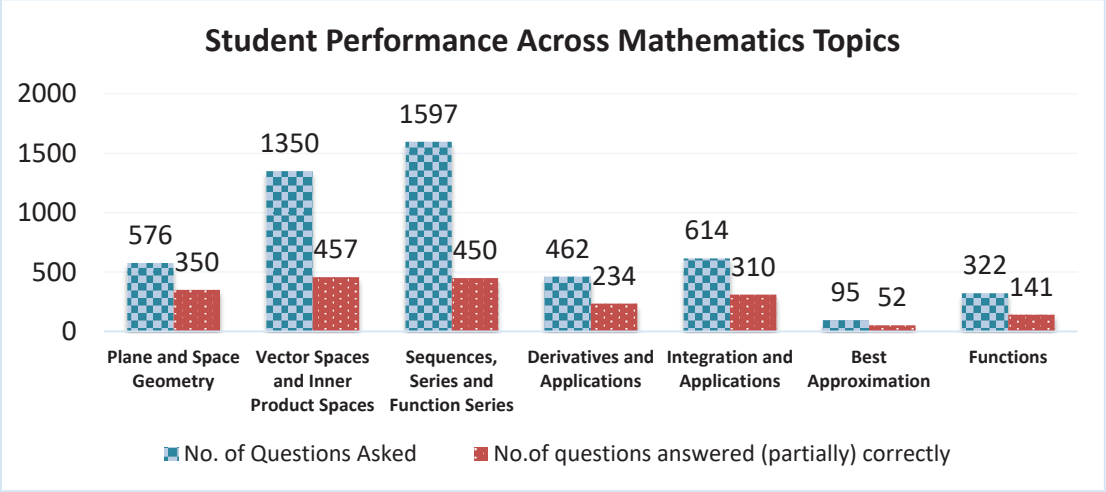


Figure 3: Student Performance Across Mathematics Topics

Vector Spaces and Inner Product Spaces

Students show significant difficulty with the foundational concepts of subspaces and inner products spaces. A common issue is the omission of the zero vector when determining whether a set forms a subspace, or the failure to demonstrate closure under addition and scalar multiplication. Inner products are misunderstood, with students incorrectly producing vector outputs instead of scalars. Notation of inner products involving summations is often avoided or written incorrectly.

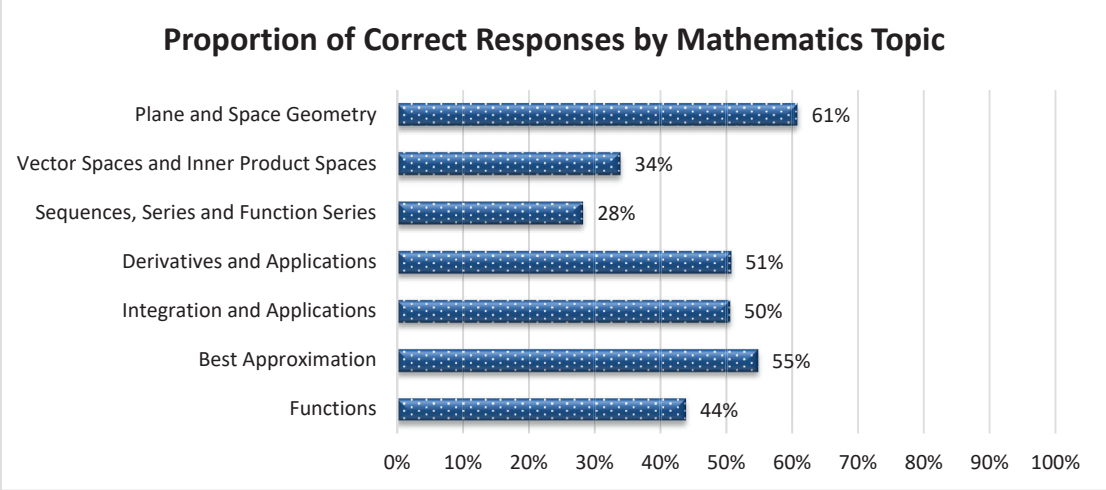


Figure 4: Proportion of Correct Responses by Mathematics Topic

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Sequences, Series, and Function Series

This area reveals high cognitive load and persistent confusion. Students often blur the lines between sequences and series. Application of convergence tests like the ratio or Leibniz test is frequently incomplete as students identify the correct test but omit the necessary conditions. Notation is inconsistent: the limit $n \to \infty$ is frequently missing. The interval of convergence for function series is also a struggle, with students unclear about endpoint inclusion. Those who succeed tend to rely on visual understanding but are weak in oral or written explanations. We also notice that the link between function series and polynomial approximation is not understood. Taylor and Maclaurin series are not clearly distinguished and students don't grasp the role of the expansion point, nor the conceptual difference between the two. Students tend to expand series fully instead of identifying patterns, which impedes generalization. There is confusion over whether the goal is to approximate a function, a value, or a polynomial, indicating a blurred understanding between function series and their outputs.

Derivatives and Applications

Derivative-related tasks show a moderate error rate. A key misunderstanding is equating the derivative directly with the tangent, rather than recognizing it as the slope of the tangent line. Students often struggle to construct a tangent line equation from a point and a derivative. Errors in differentiation increase when square roots are involved. The chain rule is inconsistently applied and students frequently make symbolic errors.

Integration and Applications

In definite integration, students frequently leave problems unsolved, although they correctly identify the integration limits. Many misunderstand the instruction to find “enclosed area,” often shading incorrect regions, which points to a weak interpretation of geometric visuals. In polar coordinates, formula use is inconsistent: although formulas for area and arc length are provided in a formularium, students often ignore them. Mistakes also arise from forgetting the chain rule during differentiation inside integrals. When analyzing rose curves, some students do not recognize symmetry. Notational confusion is also evident, the arc length formula is sometimes mistaken to involve a second derivative rather than being computed from the first derivative squared.

Best Approximation

Students exhibit both conceptual and language-based misunderstandings in approximation problems. The phrase “best approximates” is often interpreted as a general estimation rather than referencing a specific best approximation concept, such as in linear algebra. The idea of a vector projected in a plane being the best approximation is often confused with the projection formula of a vector in the *x*-*y* plane.

Functions

While some correctly observe the presence of vertical tangents, students often misidentify curves, such as ellipses, as functions. Graphs of trigonometric functions, such as cosine curves, are drawn well in terms of neatness. In logarithmic functions, students are usually aware that the domain must be positive but cannot adequately justify it or apply this understanding when solving domain-related problems. There is a general discomfort in transitioning between representations, *r*–*θ* to *x*–*y*, and limited understanding of how such transformations relate to underlying function properties.

Discussion & Conclusions

These plots, along with the analysis of student responses, provide insight into recurring conceptual challenges and areas where targeted instructional interventions may be most effective. Some overarching discussion points that can contribute to the discourse of

fundamental conceptual errors that occur in first-year engineering mathematics are highlighted below.

Challenges in visual and abstract concepts: The results showed that students performed less well in Sequences, Series and Function Series and **Vector Spaces and Inner Product Spaces**, indicating significant conceptual challenges. Challenges in visualizing limits and comprehending abstract spaces may stem from the lack of concrete representations, making these concepts more difficult to grasp. These findings align with previous research, which suggests that students often struggle with visualizing higher-dimensional spaces and abstract mathematical structures (Aygör & Özdağ, 2012).

Stronger performance in applied topics: In contrast, topics like **Best Approximatio**n, **Derivatives and Applications**, and Plane and Space Geometry showed higher performance with fewer errors. These topics are more directly tied to real-world applications, which may have made them more intuitive or accessible for students. The findings suggest that students tend to perform better in areas where the concepts have clear applications and are less abstract in nature, a trend observed in other studies of engineering education (Almasalmeh et al, 2020). Additionally, calculus is often introduced at the secondary school level, suggesting students may be more familiar with its procedural aspects, contributing to more frequent correctness in calculations.

Understanding and distinguishing closely related definitions in Vector Spaces: **Vector Spaces and Inner Product Spaces** presented significant challenges as shown by the high percentage of students unable to attempt certain questions. This aligns with the well-established finding that students struggle with the abstract nature of these topics, particularly when it comes to understanding key definitions and applying them correctly (Santiago et al, 2018). Misunderstandings such as confusing vector spaces with subspaces or failing to understand the inner product were common among students, indicating a need for more targeted teaching interventions in this area.

Notation as a burden rather than a computational aid: Symbolic fluency is an overarching concern: students frequently misuse notation in differentiation, summation, and interval representation, indicating a surface-level engagement with formalism. For many students, mathematical notation does not act as a scaffold for reasoning but instead becomes a barrier to conceptual understanding. Instead of aiding communication and precision, symbolic language particularly in the context of summation, limits, and derivatives introduces additional layers of abstraction that students have not yet internalized. These issues are compounded in some cases by language-related misunderstandings of key mathematical terms such as “modulus,” “argument,” “approximate,” or “projections”.

Procedural proficiency chosen over conceptual understanding: Taken together, these findings point to a pattern of symbolic manipulation overshadowing conceptual clarity. Students often rely on rote procedures without fully understanding the structures they are working within, leading to incomplete knowledge that breaks down under new or combined problems. When questions from various topics are combined it is often seen that the ability to make the connection is weak. In many cases, language also appears to be a mediating factor. These observations underscore the need for instructional strategies that emphasize structural understanding, mathematical communication, coordinated use of multiple representations and mathematical reasoning.

Recommendations & Future Work

The results of this paper give a cohesive knowledge about the mathematical conceptual errors that occur in first-year engineering students and highlight the importance of identifying very specific errors in each topic in order to have an effective intervention or assessment. Future research could explore the effectiveness of different pedagogical approaches in improving

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students' understanding of topics that they have shown to struggle with in communicating as well as reasoning.

Several directions for instructional practice and research emerge and they are expanded below.

- Formularium interventions

Providing a formularium, especially in topics such as sequences and series, may help students engage with the material without becoming overwhelmed by notation-heavy content.

- Teaching sequence adjustments

Since students tended to perform poorly on topics taught at the end of the semester, shifting more challenging topics to mid-semester while reserving relatively stronger topics (e.g., applications of derivatives and integration) for later weeks may improve learning outcomes.

- Surveying background knowledge

Collecting demographic information and prior mathematical pre-requistes can provide insight into the origins of misconceptions.

- Focus groups and interviews

Group discussions and feedback sessions could help uncover why misconceptions persist and how students perceive their own difficulties.

Integrating related definitions: Illustrating closely linked definitions and concepts during teaching allows confusion to surface during contact hours rather than in high-stakes assessments.

- Exit slips

Short checks at the end of exercise sessions can be used to clarify student understanding of notation and symbolic differences across topics.

Limitations of oral examinations: Oral exams can be affected by exam anxiety, time constraints, and language barriers. This may obscure a full picture of student thinking and hence analysing other forms of evalation is necessary.

These findings point toward a research and teaching agenda focused on fine-grained identification of conceptual difficulties. In addition to clearing misconceptions about the abstract concepts it would be helpful to provide practical examples that help students make sense of these concepts. Given the high percentage of students who struggled with these topics, there is an opportunity for instructional interventions that can be implemented to provide support to students.

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***APPENDIX A*: Themes extracted for each topic based on preliminary analysis.**

Topic	Difficulty Level	Detailed Difficulties & Preliminary Notes
Vector Spaces and Inner Product Spaces	**Very High**	**Subspaces**: Often forget to include the zero vector or prove closure under operations.
		Basis Confusion: Students confuse the basis of $\mathbb{R}^3$ with the basis of a subspace.
		Inner Product Misunderstood: Treated like a dot or cross product; results wrongly as vectors.
		Matrix/Vector Confusion: Difficulty in seeing matrix addition vs. vector addition.
		Notation Weakness: Summation notation is avoided; students prefer writing individual terms.
Sequences, Series, and Function Series	**Very High**	**Terminology Confusion**: Series vs. sequences, alternating sequence vs. alternating series.
		Test Misuse: Incomplete application of Leibniz or Ratio test.
		Notation Gaps: e.g., missing limit expressions ($n \to \infty$), sloppy $\sum$ notation.
		Series Evaluation: Students confuse index manipulation.
		Visual vs. Algebraic: Students with correct answers often rely on visuals; oral explanation weak.
		Interval of Convergence: Trouble with endpoints, open/closed intervals poorly represented.
		Taylor/Maclaurin Series: Confused about the difference and purpose; point of expansion often unclear.
		Remainder Theorem: Not applied or understood.
		Series vs. Polynomial: Unclear whether they are approximating the function or its sum.
Best Approximation	**High**	**Language Confusion**: Students misunderstand "best approximates" as a general term, not a specific approximation concept.
		Projection Formula: Incorrect usage instead of best approximating on a subspace.
Integration and Applications	**High**	**Definite Integrals**: Often not solved, though bounds are written.
		Area Misinterpretation: Students shade wrong regions; misunderstanding of "enclosed."
		Notation Errors: Square of derivative confused with second derivative in arc length formula
Derivatives and Applications	**Medium–High**	**Slope vs. Tangent**: Students think the derivative *is* the tangent rather than the slope.
		Algebraic Errors: Square root derivatives create common mistakes.
		Equation of Tangent: Using (x, y) and derivative at a point is not intuitive.
		Notation Weakness: Chain rule used inconsistently or with symbol errors.
		Patterns in higher order derivatives: Students expand fully and miss the general form or factorial pattern.
Plane and Space Geometry	**Medium**	**Parametrization**: Students struggle to link x, y with parameter *t*.
		Line vs. Plane: Confuse line representation (system of two equations) with a plane.
		Distance Formula: Solving equations involving absolute values creates errors.
		Direction vs. Normal Vectors: Criteria for parallelism wrongly tied to direction vectors instead of normal.
		Formula Ignored: Provided polar area formula not used; formula sheet underutilized.
		Petal Symmetry: Confusion about symmetry in rose curves.

***APPENDIX A*: Themes extracted for each topic based on preliminary analysis.**

Topic	Difficulty Level	Detailed Difficulties & Preliminary Notes
		Sinusoid Curve: Wrong period indicated, confused r–θ coordinate system vs. x–y coordinate system.
		Polar Coordinates: Chain rule forgotten; integral repeated when using parts.
Functions	**Medium**	**Misclassification**: Students mistakenly identify ellipses as functions.
		Graph Interpretation: Understanding of vertical tangents without deeper reasoning wrt differentiation; Vertical-line test for functions.
		Logarithmic Domain: Trouble explaining domain of ln(x); can state the argument is non-negative but can't justify why.
		Representation Gaps: Function domain and range manipulation unclear when logs or exponents are involved

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