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Misconceptions of Derivative and Integral in Solving Kinematic Problems: A Phenomenological Exploration of the Experiences of Student-Teachers in Physics Education

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ABSTRACT

Keywords:
Conceptual Understanding, Physics Student-Teachers, Derivative and Integral, Mathematical Misconceptions, Physics Education.

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Undoubtedly, conceptual mastery of derivatives and integrals as the language for describing changes in nature is the cornerstone of a deep understanding of physics and its effective teaching. This qualitative study aimed to explore the conceptual understanding, attitudes, and common misconceptions of student-teachers in Physics Education regarding the fundamental concepts of derivatives and integrals and their physical applications. Data were collected through an open-ended questionnaire containing ten key questions about initial perceptions, understanding of kinematic relationships, and teaching strategies from 15 physics education student-teachers during the 2024-2025 academic year and were analyzed qualitatively. Findings revealed that although most participants were proficient in the formal relationship between derivatives and integrals in the domain of kinematics (position, velocity, acceleration), their understanding of the "reason why" behind these relationships (such as the physical reason why the integral of acceleration equals velocity) was often superficial. A key misconception was the reduction of the integral concept to "finding the antiderivative," neglecting its physical interpretation as "summing infinitely small quantities." Additionally, unsuccessful initial educational experiences and purely formula-based teaching were identified as the main factors causing fear and ambiguity. Consequently, it seems essential to strengthen the conceptual foundation of these tools through an intuitive approach, based on modeling physical phenomena and using graphical representations, to prepare future teachers.

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Introduction

Mathematics is the language of nature and a robust framework for explaining physical phenomena [1]. Furthermore, calculus, as a significant part of mathematics, plays an indispensable role in the quantitative and qualitative formulation of the laws of physics [2]. Within this, the concepts of the derivative and the integral, two fundamental pillars of calculus, hold a central place in physics education, not only as computational tools but also as a conceptual framework for understanding continuous and variable phenomena [3]. The application of these concepts in kinematics—a branch of physics that describes motion without regard to its causes—is a prime example of this integration; where velocity is defined as the derivative of position with respect to time ($v = dx/dt$) and displacement as the integral of velocity with respect to time ($x = \int v\, dt$) [4]. However, the transfer of these abstract mathematical concepts to the concrete realm of physics and their practical application in problem-solving has always been one of the most challenging stages in learning physics [5].

Extensive studies in physics and mathematics education have consistently shown that students at all levels, from undergraduate studies and including pre-service teachers, grapple with profound and persistent misconceptions in understanding derivatives and integrals and their connection to physical concepts [6, 7, 8]. These misconceptions can be categorized into several main types:

Category 1: Purely Mathematical Conceptual Misconceptions: At this level, students struggle with understanding the basic concepts of calculus itself. For example, they know the derivative merely as the "slope of the tangent line" without understanding that this slope represents the "instantaneous rate of change" of a physical quantity [9]. Similarly, the integral is often memorized as the "area under a curve" without establishing a meaningful connection to the physical concept of "accumulation" or "summing infinitely small quantities" [10, 11].

Category 2: Misconceptions Arising from the Transfer from Mathematics to Physics: This category of problems occurs when a student knows the mathematical concept in an abstract space but is unable to map it onto a physical situation [12]. For instance, a student might be able to calculate the derivative of $x = t^3$, but not understand that the result ($v = 3t^2$) represents the variable velocity of an object in the real world [13]. This phenomenon indicates a deep gap between procedural knowledge and conceptual knowledge [14].

Category 3: Misconceptions Related to Multiple Representations: Understanding kinematics requires the ability to move fluidly between different representations of a concept—such as verbal, graphical, algebraic (equation), and numerical [15]. Research indicates that one of the biggest obstacles is students' inability to interpret kinematic graphs and relate them to equations and physical situations [16]. For example, students often make mistakes in inferring velocity from a position-time graph (which requires an understanding of the derivative) or predicting the shape of a position-time graph from a velocity-time graph (which requires an understanding of the integral) [17, 18].

Category 4: Specific Misconceptions in Kinematics: Some misconceptions are directly tied to kinematic concepts. For example, a misunderstanding of the relationship between acceleration and velocity (e.g., the belief that acceleration is always in the direction of motion), or a lack of proper understanding of motion with constant acceleration and its consequences on graphs, are among these cases [19].

Diagnostic tools such as the Test of Understanding Graphs in Kinematics (TUG-K) [13] and the Force and Motion Conceptual Evaluation (FMCE) [20] have widely confirmed the existence of these misconceptions among students. However, the primary focus of these quantitative studies has been on the identification and quantification of misconceptions, with less attention paid to individuals' lived experiences of these challenges.

This gap is particularly significant for pre-service physics teachers—who are simultaneously both learners of advanced concepts and the future architects of the next generation's scientific understanding. Misconceptions entrenched in this group can be transmitted to their students in a vicious cycle [21, 22]. Research shows that teachers tend to teach in the same way they themselves were taught [23], and if their understanding of basic concepts (such as derivatives and integrals) is flawed, they will be unable to provide a deep conceptual foundation for their own students [24].

To understand this complex phenomenon, purely quantitative research approaches that merely list errors are insufficient. We need a deeper, context-rich, and qualitative understanding of how these misconceptions are formed, persist, and manifest in the minds of pre-service teachers. Phenomenological research as a robust qualitative method, focusing on discovering and describing the essence and structure of meaning in individuals' lived experiences, is a suitable tool for exploring these hidden layers [25, 26]. This method allows us to go beyond knowing what the misconceptions are and to understand how these challenges are experienced (e.g., "What is the experience of confusion when facing an integration problem in kinematics?") and why they persist from the perspective of the pre-service teachers themselves.

Therefore, this study was designed to phenomenologically explore the experiences of pre-service physics teachers in dealing with misconceptions of derivatives and integrals when solving kinematic problems. This research seeks to answer the following key questions:

1-What is the nature and structure of the lived experience of pre-service physics teachers when encountering derivative and integral concepts in the context of kinematics?

2-How do these misconceptions manifest in the process of solving kinematic problems, and what common patterns exist in their experiences?

3-What strategies, challenges, emotions, and meanings do pre-service teachers report in connection with these concepts and related misconceptions?

Research Method

This study, aiming to explore the depth of the lived experiences of pre-service teachers regarding derivative and integral concepts in the domain of kinematics, was conducted using a qualitative approach and employing descriptive phenomenology. Phenomenology as a qualitative research method focuses on understanding and describing the essence and structure of individuals' lived experiences of a particular phenomenon. In this paradigm, the goal is to reach the common essence of the experiences of different individuals by deeply identifying their perceptions, feelings, and interpretations. Since the issue of mathematical-physical misconceptions is not merely a computational error but is rooted in individuals' perceptual experiences and personal interpretations, the phenomenological method is able to reveal the hidden layers of this experience—including the contexts of formation, crystallization, and persistence of these misconceptions—and provide a rich, multidimensional description of it.

The study population consisted of second-year pre-service physics teachers from Farhangian University of Tabriz. A purposive sampling method with maximum variation was used to select participants. The inclusion criteria were having passed the courses Calculus I and General Physics I, and willingness to participate in in-depth interviews. Sampling continued until theoretical saturation was reached; that is, until new data did not add new themes to the set of findings. Accordingly, 15 pre-service teachers (8 women and 7 men) participated as the final participants in this study.

The primary data collection tool in this research was in-depth, semi-structured interviews. An interview guide consisting of 10 open-ended questions was designed, starting with general concepts (such as initial impressions of derivatives and integrals) and gradually moving to specific cases and applications in kinematic problems (such as explaining the relationship between position, velocity, and acceleration, or describing the strategy for solving a problem involving motion with variable acceleration). Each interview lasted an average of 45 to 60 minutes. In addition to the interviews, participants were asked to solve several key kinematic problems and to think aloud during the process. Furthermore, indirect observation and analysis of the notes from their problem-solving were also used as supplementary data.

For data analysis, Colaizzi's method was used [27]. The steps are as follows:

1-Familiarization: Repeatedly listening to audio files and multiple readings of the transcribed interview texts for initial understanding.

2-Identifying Significant Statements: Identifying and extracting all sentences, phrases, or statements that were directly or indirectly related to the phenomenon under study (the experience of derivatives and integrals in kinematics).

3-Clustering Meanings into Themes: Organizing the formulated meanings into coherent and recurring categories (themes).

4- Producing the Fundamental Structure: Drafting a concise statement or description that summarizes the essence of the participants' lived experience.

5-Seeking Verification of the Findings: Returning the summary of findings and final description to several participants to confirm its consistency with their lived experience.

To enhance the trustworthiness of the findings in this qualitative study, several strategies were employed, including member checking, sharing the analysis process and findings with 2 experts in physics education, and providing rich descriptions and direct quotes from participants in the final report.

Findings

In this research, five main themes were extracted. The main and sub-themes are presented in Table 1. A detailed explanation of each theme follows.

Table 1. Extracted Main and Sub-Themes

Main Theme	Sub-Theme	Sample Interview Quote
Initial Attitude and Perception	Math-Oriented vs. Physics-Oriented	"At first, I think of math... but it also has a bit of a physical sense." (P11). "They are mostly mathematical concepts." (P13)
	Negative Emotional Load and Perceived Challenge	"Bad feeling." (P9). "Complex concepts... a tool for solving questions." (P10).
	Tool for Understanding and Discovering Nature	"It's a means for solving and understanding physics concepts... for discovering unknown laws." (P8).
Understanding Kinematic Relationships	Mastery of Formal and Algorithmic Relationship	"Derivative from position to velocity, from velocity to acceleration... integral is the reverse." (P3). "From right to left=integral, from left to right=derivative." (P6).
	Incomplete Understanding of the "Why"	"I still don't have the ability to explain physics concepts precisely using derivatives and integrals." (P8). "I don't understand why that area equals velocity?" (P8).
	Providing Physical Interpretation (Change and Sum)	"Derivative in physics means zooming in... integral is the opposite, it means getting the total amount from small changes." (P2). "Derivative is the rate of change." (P11).
Conceptual Misconceptions	Reduction of Integral to "Antiderivative"	"Integration always means finding the antiderivative." (A view reported by several participants).
	Lack of Understanding the "Sum over an Interval" in Integration	"Integral is only for continuous quantities, but antiderivative can be for any type of quantity." (P6 - indicating a flawed understanding).
	Misunderstanding of Instantaneous Velocity	"At any point, by dividing the position and time of that point, we get the instantaneous velocity." (P12 - which is the definition of average speed).

Learning Challenges and Experiences	Ineffective Teaching and Lack of Conceptual Presentation	"If they had taught the concept of integral in high school courses... they would have gained a better understanding." (P4). "They focused solely on the formula." (P13).
	Fear of Computational Complexity	"I was afraid of complex integrals." (P3). "I still can't solve some of the questions to the end." (P12).
	Precedence of Physics Exposure over Mathematical Foundation	"The first time I became familiar with the integral was in physics... it was a bit problematic." (P4). "The concept of integral... because I saw it in physics before learning it in mathematics." (P5).
Suggested Teaching Strategies	Conceptual and Intuitive Teaching vs. Formulaic	"I would first explain the concept, then start teaching." (P2). "Focus on concepts instead of formulas." (P13).
	Use of Teaching Aids	"Using available facilities... using images, artificial intelligence." (P2 & P15).
	Precedence of Teaching Derivatives/Integrals in Math	"First, I put myself in their place... first, I teach the concept." (P2). "I wish they had explained it in high school." (P10).
	Connection to Real Life and Problem-Solving	"I will make the kids feel physics in real life." (P1).

Main Theme1: Initial Attitude and Perception

This theme deals with the feelings, mental associations, and overall perspective of pre-service teachers towards the concepts of derivatives and integrals.

Sub-Theme 1.1: Math-Oriented vs. Physics-Oriented: Most participants initially viewed these concepts as inherently mathematical, although some had gradually come to appreciate their physical application.

Sub-Theme 1.2: Negative Emotional Load and Perceived Challenge: For some, these concepts were associated with negative emotions such as fear, difficulty, and ambiguity.

Sub-Theme 1.3: Tool for Understanding and Discovering Nature: A smaller number of participants had a perspective beyond formulas and referred to these concepts as a language for describing the world.

Main Theme 2: Understanding Kinematic Relationships

This theme refers to the extent of participants' understanding of the connection between derivatives/integrals and kinematic quantities.

Sub-Theme 2.1: Mastery of Formal and Algorithmic Relationship: Almost all of them correctly knew that the derivative of position is velocity and the derivative of velocity is acceleration, and that the integral reverses this process.

Sub-Theme 2.2: Incomplete Understanding of the "Why": Despite knowing the "how," many were unable to provide a physical explanation for the reason behind these relationships. This was the most significant gap in conceptual understanding.

Sub-Theme 2.3: Providing Physical Interpretation (Change and Sum): Some participants had managed to achieve an understanding beyond the formula and used concepts like "rate of change" for the derivative and "summing" for the integral.

Main Theme 3: Conceptual Misconceptions

This theme identifies common errors and persistent flawed understandings among the pre-service teachers.

Sub-Theme 3.1: Reduction of Integral to "Antiderivative": The most common misconception was viewing the integral merely as the inverse operation of differentiation, neglecting its physical interpretation as a total sum.

Sub-Theme 3.2: Lack of Understanding the "Sum over an Interval" in Integration: Some mistakenly thought the antiderivative was applicable to any quantity, whereas the integral is specifically for quantities with continuous changes.

Sub-Theme 3.3: Misunderstanding of Instantaneous Velocity: Some confused instantaneous velocity with average speed at a point.

Main Theme 4: Learning Challenges and Experiences

This theme addresses the external and internal factors that have made learning these concepts difficult for the pre-service teachers.

Sub-Theme 4.1: Ineffective Teaching and Lack of Conceptual Presentation: The educational system and teaching methods of professors, with their sole emphasis on formulas and problem-solving, were identified as the main cause of ambiguity.

Sub-Theme 4.2: Fear of Computational Complexity: The computational and technical aspect of integration had created fear and anxiety for many.

Sub-Theme 4.3: Precedence of Physics Exposure over Mathematical Foundation: Being introduced to the integral for the first time in the context of physics, without a strong mathematical foundation, was problematic for many.

Main Theme 5: Suggested Teaching Strategies

This theme compiles the pre-service teachers' own suggestions for improving the teaching of these concepts and preventing the repetition of their own challenges.

Sub-Theme 5.1: Conceptual and Intuitive Teaching vs. Formulaic: The emphasis was that teaching should start with the "why" and "how," not with "which formula."

Sub-Theme 5.2: Use of Teaching Aids: The use of software, animations, experiments, and artificial intelligence to concretize concepts was suggested.

Sub-Theme 5.3: Precedence of Teaching Derivatives/Integrals in Math: They believed the mathematical foundation of these concepts should be firmly laid in high school before their physical application.

Sub-Theme 5.4: Connection to Real Life and Problem-Solving: Creating links between abstract concepts and tangible everyday phenomena and solving diverse problems were suggested as effective strategies.

Discussion

The findings of this phenomenological study, conducted with the aim of analyzing the conceptual understanding of pre-service physics teachers regarding derivatives and integrals, paint a complex picture of the challenges in teaching these fundamental concepts. Analyzing the participants' experiences through the lens of educational theories and previous research findings illuminates the various dimensions of these challenges.

The Gap Between Procedural and Conceptual Knowledge:

The most important finding of this research was the existence of a deep gap between the pre-service teachers' algorithmic mastery of formal relationships and their conceptual understanding of the physical principles behind these relationships. This phenomenon can be analyzed in light of the Levels of Processing Theory [28], which distinguishes between shallow processing (focus on superficial features) and deep processing (focus on meaning and conceptual connections). It seems the prevailing educational system has primarily reinforced shallow processing through an emphasis on memorizing formulas and computational procedures [29]. Meanwhile, deep processing, which is essential for understanding complex concepts like derivatives and integrals, has been neglected. For instance, many participants knew that the integral of acceleration yields velocity, but similar to findings on integral misconceptions [6], they were unable to explain why the area under an acceleration-time graph should represent the change in velocity. This indicates they had accepted this relationship as a mathematical fact without constructing a coherent mental model of the connection between algebraic and graphical conceptual representations [30, 31].

Persistent Misconceptions in Understanding the Integral:

The predominant misconception among participants was the reduction of the integral concept to an "antiderivative" and the neglect of its physical interpretation as the "sum of infinitely small quantities" or "accumulation." This finding aligns directly with Piaget's constructivist view, which emphasizes the active construction of knowledge in the learner's mind [32]. It appears that pre-service teachers, due to inadequate learning experiences, have constructed an incomplete and imprecise mental model of the integral in which this concept is defined solely within the limited, purely mathematical framework of the "inverse operation of differentiation," divorced from its rich range of physical applications [33]. This misconception, known as "integral = antiderivative," has previously been reported in various studies in calculus education [34, 35]. For example, this reductive view was evident in the response of one participant who stated, "Integral is only for continuous quantities but antiderivative can be for any type of quantity." This view not only contradicts the mathematical definition of the integral but also shows that their understanding of its scope and application in physics is severely flawed.

The Negative Impact of Early Learning Experiences:

Negative learning experiences, particularly purely formulaic and computation-based teaching in high school and early exposure to the integral in physics without a strong mathematical foundation, were identified as main factors creating fear, anxiety, and ambiguity among participants. This finding can be analyzed through the lens of Self-

Determination Theory (SDT) [36]. It seems that the traditional, problem-focused teaching approach failed to satisfy three basic psychological needs of learners:

Need for Competence: Placing students in front of complex problems without providing a strong conceptual base created a sense of helplessness and incompetence.

Need for Autonomy: Imposing memorized, uniform problem-solving methods without opportunity for conceptual exploration limited learners' independence and creativity.

Need for Relatedness: Creating a gap between abstract mathematical concepts and tangible real-world phenomena led to a sense of meaninglessness and a lack of personal connection to the learning material.

This failure to satisfy basic psychological needs led to a decrease in intrinsic motivation and the formation of a persistent negative attitude towards calculus concepts [37]. This phenomenon was clearly evident in the statement of one participant who reported "having a bad feeling towards these concepts since high school." These results are consistent with findings on the negative impact of purely computational instruction on students' attitudes towards mathematics and science [22].

Alignment with the Existing Body of Knowledge:

The findings of this study broadly overlap with and reinforce the existing body of knowledge in this field. For example, the "integral = antiderivative" misconception identified in this study confirms classical findings on integral misconceptions [6]. Also, the incomplete and intuitively flawed understanding of concepts like instantaneous velocity and acceleration demonstrated by some participants is entirely similar to challenges reported in students' understanding of motion graphs, which led to the development of diagnostic tools like the TUG-K [13]. Furthermore, the frequent suggestions from pre-service teachers for conceptual teaching, the use of visual tools, hands-on activities, and connecting concepts to real life directly support research emphasizing the effectiveness of constructivist teaching strategies in fostering conceptual change [35]. These strategies, including problem-based learning, computer simulations, and conceptual change texts, can help create more accurate and stable mental models [38].

In summary, it can be concluded that the pre-service physics teachers in this study, while possessing the procedural knowledge necessary to solve standard and familiar problems, lack the deep, flexible conceptual knowledge required to explain the physical principles, engage in qualitative reasoning, and create meaningful connections between different mathematical representations (algebraic, graphical, numerical, and verbal) [39,40]. This deep gap is rooted in ineffective learning experiences, persistent misconceptions, and negative attitudes formed throughout their education. These findings sound an alarm for curriculum planners and instructors of physics and mathematics, indicating the urgent necessity for a fundamental revision of teaching approaches, an emphasis on conceptual understanding alongside computational skills, and the enrichment of learning environments to satisfy the psychological needs of learners.

Conclusion:

This phenomenological study has illuminated the profound challenges physics student-teachers face in understanding and applying the mathematical concepts of derivatives and integrals within kinematics. The findings reveal a persistent and critical gap between procedural fluency and deep conceptual understanding among future educators. This gap manifests primarily as a tendency to reduce powerful mathematical ideas to mere algorithms, particularly the prevalent misconception of interpreting integration solely as the inverse of differentiation, while neglecting its physical meaning as accumulation.

These results strongly align with and extend the established body of research in physics and mathematics education. The observed procedural-conceptual divide corroborates the classic findings of Orton [6], on integration and Zandieh [9], on derivative understanding. Furthermore, the identified weakness in translating between graphical, algebraic, and physical representations echoes the challenges diagnosed by instruments like the Test of Understanding Graphs in Kinematics (TUG-K) [13], confirming that this issue persists at the teacher preparation level.

The study also underscores the significant role of prior learning experiences in shaping knowledge structures and attitudes. The reported negative impact of formula-focused, teacher-centered instruction on motivation and conceptual growth is consistent with the principles of Self-Determination Theory Deci & Ryan [36], and prior research on science teaching anxiety, Gómez-Zwiep, [37]. Conversely, the participants' own advocacy for intuitive, context-rich, and conceptually-driven teaching methods directly supports the effectiveness of constructivist and inquiry-based pedagogical strategies, as demonstrated in studies by Resbiantoro & Setiani [35], and Korganci et al. [38].

In summary, this research not only validates existing concerns about mathematical preparation in physics education but also amplifies them by highlighting their lived reality for those destined to become teachers. It confirms that the cycle of superficial, algorithmic understanding risks being perpetuated unless actively interrupted. Therefore, the findings necessitate a decisive shift in teacher education programs toward an integrated, concept-first approach that explicitly bridges mathematics and physics, prioritizes multiple representations, and addresses both the cognitive and affective dimensions of learning. Investing in such a transformation is essential for cultivating a future generation of physics teachers equipped with the deep, flexible understanding required to foster genuine scientific literacy.

Suggestions:

It is essential that the curriculum for pre-service physics teacher training programs and university foundation courses move towards integrated mathematics-physics education. In this approach, the concepts of derivatives and integrals should be introduced not as abstract mathematical tools, but as the language for describing physical phenomena. Teachers and professors should employ strategies based on constructivism and discovery learning, instead of focusing exclusively on solving computational problems. The use of graphs, computer simulations, laboratory activities, and real-world examples can help build correct mental models. Instruction should explicitly address the identification and correction of common misconceptions (such as reducing the integral to an antiderivative). Creating educational situations where pre-service teachers are required to explain the reasons behind relationships and articulate concepts in their own words can be very effective. Finally, investing in fostering this deep understanding in future teachers will not only improve the quality of physics teaching in schools but is also a fundamental step towards nurturing a generation with scientific and analytical thinking.

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