

Artificial Intelligence and Intelligent Tutoring Systems in Differential Calculus Education: A Global Review (2019–2025)

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Abstract

Review Article

Differential calculus is a vital subject in many STEM programs, yet students often find abstract concepts like limits, derivatives, and the connection between rates of change challenging. The recent growth of artificial intelligence (AI) and intelligent tutoring systems (ITS) provides opportunities to customize calculus teaching, offer immediate feedback, and support learners outside traditional classrooms. This review compiles research from 2019 to 2025 on the use of AI—especially ITS—in college-level differential calculus. It explores technological bases, effectiveness, limitations, ethical issues, and future directions. Studies from North America, Asia, Europe, and Latin America are included to give a global view. While evidence suggests AI tutors can boost engagement and help students grasp concepts better, issues remain regarding accuracy, fairness, teacher involvement, and data privacy. Suggestions are provided for thoughtfully incorporating AI into differential calculus education.

Keywords: Artificial Intelligence (AI), Intelligent Tutoring Systems (ITS), Differential Calculus, STEM Education, Personalized Learning, Rates of Change.

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1. INTRODUCTION

Calculus has traditionally served as a barrier for many STEM fields. Students often see it as abstract and detached from real-life use, leading to anxiety and high dropout rates. Recently, artificial intelligence has become a valuable tool in education, capable of customizing lessons to individual learners, tracking progress, giving instant feedback, and creating interactive exercises. These features align well with the skills needed for calculus, which demands both procedural skills and conceptual insight (Woolf 2021; Baker and Inventado 2014). The COVID-19 pandemic further accelerated adoption of AI-enabled educational technologies, as remote learning highlighted the need for personalized, scalable support (see syntheses in (Various 2023d; Various 2023c)). Although ITS show promise, concerns persist regarding their effectiveness, how well they align with established pedagogical principles, and their influence on conventional calculus instruction (Various 2024d).

2. METHODOLOGY

The review considered peer-reviewed journal articles, conference proceedings and reports published between 2019 and early 2025. Sources were identified through academic databases (e.g., ERIC, PubMed,

arXiv), open-access portals and targeted web searches. Priority was given to studies focusing on differential calculus or closely related university mathematics. Articles on general mathematics tutoring or K–12 were included when they clarified technological foundations or limitations relevant to calculus (Aleven and Koedinger 2002; Pane *et al.*, 2014). Non-English sources were translated when necessary. The review emphasized empirical evidence while also considering theoretical perspectives and commentary (Koedinger *et al.*, 2012).

3. Technological Foundations of Intelligent Tutoring Systems

3.1. Architecture of ITS

Modern Intelligent Tutoring Systems (ITS) generally consist of four interconnected components: a domain model that encodes subject knowledge and problem-solving strategies, a student model that monitors each learner's progress and predicts future performance, a tutor model that selects instructional actions based on the domain and student models, and a user interface that enables interaction through text, diagrams, or multimedia (Woolf 2021). Adaptive systems utilize methods such as Bayesian networks and machine learning algorithms to update the student model in real-time and adjust feedback accordingly (Baker and

Inventado 2014). In the context of calculus, domain models are required to represent procedural rules (e.g., differentiation rules), conceptual relationships (e.g., the connection between limits and derivatives), and common misconceptions (Koedinger *et al.*, 2012).

3.2. Algorithms and Models

Early Intelligent Tutoring Systems (ITS) primarily relied on rule-based expert systems and knowledge tracing. However, recent advancements have integrated machine learning and natural language processing techniques. Knowledge Space Theory (KST) underpins platforms such as ALEKS by mapping prerequisite relationships among mathematical skills and deploying adaptive assessments to evaluate a learner's "knowledge state" (Various 2023a; McKeown *et al.*, 2023). Progress in deep learning, including transformer models, enables systems to interpret unstructured responses and generate natural language feedback. A study conducted in 2025 incorporated a transformer-based model into adaptive ITS to analyze student interactions, personalize feedback, and customize learning trajectories, thereby enhancing the accuracy of mathematics exercises (Various 2024b; Various 2025b). Furthermore, large language models (LLMs) such as ChatGPT and Gemini are employed to interpret open-ended prompts, provide step-by-step solutions, and develop practice problems. Although these generative models facilitate conversational interactions, they necessitate meticulous prompt design to ensure precision. (Khan Academy 2024; Education Week 2024).

3.3. Affective and Multimodal Features

Some systems incorporate affective computing to detect students' emotional states and tailor support. A Mexican project developed an Intelligent Tutoring System (ITS) that utilized facial feature extraction and neural networks to infer affective states; a fuzzy expert system subsequently adapted exercises based on cognitive and emotional data (TandF_AffectAware2022; Various 2024a). The architecture comprised presentation, server, and logic layers, underscoring the complexity of deploying real-time affective responses (researchgate.net). Multimodal interfaces—such as interactive graphing tools, dynamic animations, and voice assistants—enhance calculus learning by visualizing abstract concepts like slopes and instantaneous rates of change (Various 2023b).

3.4. Data and Ethics

Intelligent Tutoring Systems (ITS) depend on extensive student data to personalize instruction. This reliance raises concerns regarding privacy, fairness, and transparency. A comprehensive review emphasized that the development of ITS must adhere to data protection regulations (e.g., GDPR, FERPA) and incorporate fairness-aware machine learning to mitigate bias. Furthermore, it also proposed solutions that include explainability, algorithmic auditing, and secure data

storage methods, such as blockchain. Designers are advised to ensure that predictive models do not disadvantage specific demographic groups and that learners maintain agency over their educational data (Various 2025b; Various 2023c).

4. Global Case Studies in Differential Calculus Instruction

4.1. North America: ALEKS and LLM Integration

ALEKS Pre-Calculus Modules (United States) – ALEKS is an innovative Intelligent Tutoring System (ITS) rooted in knowledge space theories (McKeown *et al.*, 2023; Various 2023a). A 2023 study evaluated the completion of ALEKS pre-calculus modules by high school students before university enrollment. Enrollment in ALEKS markedly enhanced scores on the College Mathematics placement examination; however, the intervention did not significantly increase the likelihood of placing into College Algebra. The duration of time spent on the system was identified as a significant factor. The authors concluded that Intelligent Tutoring Systems can enhance mathematics curricula by offering individualized learning plans informed by knowledge space theory (Various 2023b; Education Week 2024).

4.2. Updating Calculus Teaching with AI (Canada)

A 2024 classroom study from Canada employed AI tools—namely ChatGPT, MathGPT, Gemini, and Wolfram Alpha—to enhance students' comprehension of derivatives and rates of change. Well-constructed prompts enabled students to generate exercises, verify solutions, and refine their reasoning processes. The researchers reported observed improvements in accuracy of derivative calculations and a clearer distinction between average and instantaneous rates of change. AI facilitated adaptive feedback, simulations, and interactive visualizations, thereby enriching motivation and engagement. They emphasized that AI tools should serve as a supplement rather than a substitute for instructors and advocated for strategic integration across the curriculum (Various 2024c).

4.3. Asia: Emerging LLM Tutors

Experimental deployments with LLM-enhanced tutors in STEM courses show improved mastery and positive learner sentiment when feedback is adaptive and stepwise, suggesting transferability to calculus skills (Various 2024b).

4.3.1. MathGPT and Flexi 2.0 (Philippines)

A 2024 experimental study evaluated two AI-powered tutors, MathGPT and Flexi 2.0, among preservice mathematics educators in Calculus I. Students were randomly assigned to traditional instruction or AI-enhanced tutoring. Both AI groups showed improvement from pre-test to post-test; however, users of Flexi 2.0 demonstrated greater gains. The pre-test mean scores were 12.70 (MathGPT) and 12.60 (Flexi 2.0), increasing to 18.40 and 21.00, respectively, in the post-test. Flexi 2.0 users improved by 8.40 points compared to 5.40

points for MathGPT. The authors attributed this difference to Flexi 2.0's interactive features and dynamic feedback. Concerns were raised regarding potential over-reliance on AI and unequal access to technology; they recommended training students to evaluate AI responses critically and advocated for equitable access. (Bastani *et al.*,2025).

4.3.2. Adaptive ITS with Transformers (China)

A 2025 study described an adaptive tutoring system integrating deep learning and natural language processing to personalize STEM education. Transformer-based models analyzed learner interactions and adjusted feedback. The system achieved high mastery rates—approximately 85% in programming and 78% in mathematics—among university students and reported a positive correlation between the time spent and learning gains. Students appreciated the adaptive feedback (80% positive responses). Although not specific to calculus, the study illustrates the potential of LLM-based ITS for complex domains (Villegas-Ch *et al.*,2025).

4.4. Europe: Adaptive Pre-University Maths to Calculus Pipelines

Regional initiatives building adaptive tutors aligned to local curricula illustrate the importance of knowledge tracing and collaboration networks for eventual calculus use (Carnegie Mellon University 2024).

4.4.1. BeLEARN Adaptive Tutor (Switzerland)

The Swiss project “Intelligent Tutoring System for Pre-University Mathematics” aimed to develop an adaptive system tailored to local curricula. The system used knowledge tracing to detect “blocking states” and optimal learning moments. Collaborating with high-school networks, researchers sought to create an ITS that could be adapted across subjects and ensure relevance to the Swiss educational system, belearn.swiss. Although the project focused on pre-university mathematics, its methods and collaborative approach inform future calculus-specific designs (*Intelligent Tutoring System (ITS) for Pre-University Mathematics* 2021).

4.4.2. Limited Research in European Humanities and Arts

A comprehensive review of AI-based Intelligent Tutoring Systems (ITS) noted a paucity of applications in humanities and arts compared with STEM fields. Most deployments occur in well-funded contexts; scaling to under-resourced environments remains a challenge. The authors call for broader evaluation metrics and the development of models suitable for humanistic learning, underscoring the need for diversity in subject matter and contexts. (Zerkouk *et al.*,2025).

4.5. Latin America: Affective Tutoring in Mexico

An early yet impactful project from Mexico integrated neural networks and fuzzy logic to develop an intelligent and emotionally responsive mathematics tutoring system. Facial feature analysis identified students' emotions, while a fuzzy expert system combined these affective states with cognitive data to tailor exercises (Various 2024c). The architecture employed a multi-layer design, separating presentation, server, and logic layers, and included modules dedicated to affective computing. Despite predating recent advances in large language models, this system exemplifies a comprehensive approach to addressing learners' needs that continues to influence current research (Various 2024c).

5. Effectiveness of AI and ITS in Differential Calculus Education

5.1. Learning Gains and Engagement

Evidence suggests that AI-driven tutoring can improve problem-solving and conceptual understanding when designs emphasize immediate feedback, stepwise hints, and alignment with conceptual targets (Aleven and Koedinger 2002; Pane *et al.*,2014; Various 2023d). However, not all gains transfer to proctored exams, and design choices around productive struggle and independence are critical (Bastani *et al.*,2025; Various 2024d). Time-on-task and equitable access influence outcomes in placement and readiness programs (McKeown *et al.*,2023).

5.2. Impact on Equity and Access

AI tutors offer uninterrupted availability and can support learners who lack access to human instructors, thereby potentially reducing educational disparities. However, digital divides persist; disparities in internet connectivity and device accessibility may limit the benefits for certain students. The study on MathGPT/Flexi 2.0 demonstrated that technological access remains a barrier and emphasized the importance of addressing inequities (Alvarez 2024). The ALEKS study indicated that the length of engagement with the platform influenced learning outcomes, suggesting that students with external commitments may encounter difficulties in attaining full benefit (Nehring *et al.*,2023). Achieving equitable access requires institutional support, subsidization of devices, and the provision of alternative offline educational materials.

5.3. Comparison with Traditional Instruction

Research comparing Intelligent Tutoring Systems (ITS) to traditional instructional methods yields mixed results. A systematic review of AI-driven ITS in K-12 education indicated that, while ITS generally enhanced learning outcomes, their advantages diminish when compared to non-intelligent digital tools; more prolonged interventions and larger, more diverse samples are required (Létourneau *et al.*,2025). Another review emphasized that the effectiveness of ITS depends on robust pedagogical features such as immediate

feedback, guided practice, and adaptivity, all aligned with instructional theory (Létourneau *et al.*, 2025). The ChatGPT study observed that some students relied excessively on AI, which contributed to a decline in human interaction (Serhan and Welcome 2024). These findings highlight that AI should serve as an adjunct to, rather than a substitute for, human instruction, with educators remaining integral to the design and implementation process.

5.3.1. Long Term Outcomes and Sustainability

Numerous evaluations are conducted within short-term, controlled environments, which raises concerns regarding their external validity. The arXiv review of AI-based Intelligent Tutoring Systems (ITS) emphasized that evaluations often depend on self-reported metrics, lack demographic disaggregation, and employ diverse methodologies, thereby restricting comparability and scalability (Zerkouk *et al.*, 2025). A longitudinal study of the Cognitive Tutor Algebra I in the United States indicated significant gains only following sustained implementation over a two-year period (Létourneau *et al.*, 2025). Long-term investigations into differential calculus remain limited. Furthermore, the sustainability of such interventions is contingent upon institutional support for ongoing maintenance, updates, and professional development of educators.

6. Limitations and Challenges

6.1. Technical: Accuracy, Reliability, Over-Reliance

Large language models occasionally generate inaccurate or nonsensical solutions to mathematical problems. Students participating in the ChatGPT study reported confusion when the AI provided incorrect answers. The marketing claims made by commercial AI tutoring services may overstate their capabilities, which could lead to unrealistic expectations. To ensure mathematical accuracy, it is essential to utilize robust domain models, obtain validation from expert instructors, and engage in iterative refinement of prompts (Alvarez 2024).

6.2. Adaptive Fidelity and Over-reliance

While adaptive feedback can personalize learning, it may promote passivity. The Math- GPT/Flexi 2.0 study warned that students could become too reliant on AI responses, highlighting the importance of designing activities that require critical evaluation (Alvarez 2024). Over-automation can also reduce productive struggle—an essential part of learning calculus. Tutors need to carefully adjust scaffolding to decrease support and foster independent problem-solving slowly.

6.3. Scalability and Infrastructure

Implementing Intelligent Tutoring Systems (ITS) widely requires reliable internet, sufficient computing capacity, and strong technical support. Rural or underfunded institutions often lack the infrastructure needed for AI platforms. Projects like BeLEARN

highlight the value of collaborating with local networks and tailoring systems to meet specific curricula and local needs (*Intelligent Tutoring System (ITS) for Pre-University Mathematics* 2021). Although cloud-based options can reduce hardware requirements, they introduce challenges related to privacy and costs (Various 2023b; Education Week 2024; Bastani *et al.*, 2025). Over-scaffolding may reduce durable learning if supports are not faded (Various 2024d).

6.4. Infrastructure and Scalability

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7. Pedagogical and Human Factors

7.1. Teacher Roles and Professional Development

AI tutors should support, not substitute, instructors. Teachers require training to incorporate AI into lesson plans, analyze analytics, and intervene when students face challenges. The Canadian research highlighted that AI tools enable dynamic and adaptive learning, but they work best when teachers help design prompts and foster discussion (Torres-Peña *et al.*, 2024). Without adequate training, educators might feel displaced or misjudge AI results.

7.2. Ethics, Equity and Culture

To promote responsible use, educational institutions and policymakers must establish explicit guidelines for the use of artificial intelligence in education. These should include ethical standards, oversight entities, procedures for reporting bias, and protocols for data protection. Research initiatives should involve educators, students, and ethicists to align innovation with societal values. International collaboration can facilitate the exchange of best practices and ensure that artificial intelligence benefits a diverse range of populations (Various 2023c; Various 2025b).

8. Future Directions

8.1. Integrating Large Language Models and Explainable AI

Emerging ITS increasingly incorporate LLMs to handle open ended questions, provide natural language explanations and generate new problems. Integrating LLMs with domain specific rule systems could improve accuracy. Researchers also advocate for explainable AI (XAI) features that allow students and teachers to inspect reasoning paths, fostering trust and helping learners compare their own thinking with the system's reasoningarxiv.org. For calculus, XAI could highlight

the steps used in differentiation or demonstrate how limits relate to derivative definitions.

8.2. Hybrid Human AI Tutoring Models

The most promising scenarios involve collaboration between artificial intelligence and human educators. A NORC report outlines a framework in which an AI analyzes student interactions and emotional states to tailor lesson plans, while a human tutor oversees these insights and provides targeted guidance. Such hybrid models preserve the indispensable qualities of human instructors — including empathy, contextual judgment, and motivational abilities — while utilizing AI for routine feedback and data analysis.

8.3. Focus on Conceptual Understanding and Real-World Applications

Future systems should prioritize enhancing conceptual understanding over mere procedural drills. Implementing interactive simulations that illustrate real-time rate fluctuations or depict real-world problems requiring modeling can facilitate students' perception of calculus as applicable. AI tools that generate context-rich tasks and promote exploration may render calculus less abstract. Furthermore, research should explore how Intelligent Tutoring Systems (ITS) can support interdisciplinary curricula that integrate calculus with disciplines such as physics, economics, or biology.

8.4. Ethical Frameworks and Policy Guidance

To promote responsible use, educational institutions and policymakers must establish explicit guidelines for the use of artificial intelligence in education. These should include ethical standards, oversight entities, procedures for reporting bias, and protocols for data protection. Research initiatives should involve educators, students, and ethicists to align innovation with societal values. International collaboration can facilitate the exchange of best practices and ensure that artificial intelligence benefits a diverse range of populations. (Various 2025b; Axios 2025; Institute of Education Sciences 2023; Various 2025a).

9. CONCLUSION

Artificial intelligence and intelligent tutoring systems are transforming how differential calculus is taught. Evidence from North America, Asia, Europe, and Latin America shows that AI-powered tutors can improve students' procedural skills, conceptual understanding, and engagement. Programs like ALEKS, MathGPT, Flexi 2.0, and adaptive tutors based on transformers offer personalized learning paths, instant feedback, and interactive visual tools. Nevertheless, these advantages are balanced by challenges such as accuracy issues, overdependence, limited access, and ethical questions. Long-term, detailed research is necessary to evaluate sustainability and applicability outside controlled environments. Human teachers remain essential; AI should act as an aid rather than a substitute. Future research should aim to incorporate

explainable AI, hybrid tutoring approaches, ethical standards, and culturally aware designs. With careful implementation and ongoing assessment, AI can significantly improve the accessibility, engagement, and fairness of differential calculus education for university students worldwide.

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