Curriculum and Teaching Methodology (2025)
Clausius Scientific Press, Canada

DOI: 10.23977/curtm.2025.080522
ISSN 2616-2261 Vol. 8 Num. 5

The Impact of AI-Based Intelligent Assistance Systems on Student Learning: A Case Study of the Equations of Mathematical Physics Course

Xinxin Jia[1,2,a], Xiaofeng Li[1,2,b], Lei Kou[1,2,c], Jingya Wen[1,2,d], Yongjie Ma[1,2,e], Huibin Yu[1,2,f,*]

[1]Institute of Oceanographic Instrumentation, Qilu University of Technology (Shandong Academy of Sciences), Qingdao, Shandong, China
[2]State Key Laboratory of Physical Oceanography, Qingdao, 250353, Shandong, China
[a]Jiaxinxin@ qlu.edu.cn, [b]cactusimp@163.com, [c]koulei1991@qlu.edu.cn, [d]wjy8110@qlu.edu.cn, [e]aurora_execution@163.com, [f]binbinyu@163.com
[*]Corresponding author

Keywords: Equations of Mathematical Physics, Intelligent Tutoring System, Learning Motivation, Educational Reform

Abstract: The Equations of Mathematical Physics course frequently engenders student anxiety and diminished motivation due to its highly abstract content and complex solution structures. Traditional teaching methods—characterized by knowledge spoon-feeding, delayed feedback, and disconnection from practical applications—further constrain learning efficacy. To address these challenges, this study implemented the Intelligent Tutoring System (ITS) "Xuetang-Cloud" as an intervention tool. The system constructs a structured knowledge graph for precise learning diagnostics and dynamically generates adaptive learning pathways based on real-time student performance data. Through continuous progress tracking and management, it enables dynamic personalized instruction. Empirical results demonstrate that the ITS's personalized incentive mechanisms—including real-time progress visualization and targeted resource recommendations—significantly enhance student motivation and self-directed learning. Research has shown that intelligent transportation system interventions that address learning anxiety in a timely manner can enhance students' confidence; Through case studies of embedded engineering, we aim to bridge the gap between theoretical application and ultimately achieve a synergistic improvement in students' knowledge internalization efficiency and STEM literacy.

1. Introduction

The Equations of Mathematical Physics course confronts core pedagogical challenges stemming from its highly abstract and complex content—particularly solution techniques for wave equations, heat conduction equations, and Laplace's equations—where students frequently develop learning apprehension due to tedious theoretical derivations, intricate solution structures, and specific conceptual obstacles including unified treatment approaches for nonhomogeneous equations, operational difficulties in Laplace transform inversion, and deficient comprehension of Green's function method's physical significance; concurrently, traditional instruction exhibits three critical limitations characterized by a knowledge-spoon-feeding tendency that prioritizes formula derivation over applied guidance (creating a schism between cognitive development and knowledge transmission), compressed schedules with delayed feedback, and unmet engineering practice requirements, collectively necessitating targeted pedagogical reform(2005)[1].

An Intelligent Tutoring System (ITS) is an artificial intelligence-based computational framework that delivers personalized instructional functions—such as exercise recommendation by Liu X(2025)[2], Song X(2024)[3], real-time feedback, and learning path adaptation—through dynamic modeling of students' cognitive states; its core modules encompass: (1) Knowledge Mapping & Learning Diagnostics, which constructs structured knowledge repositories via educational data mining to identify knowledge gaps in real-time; (2) Adaptive Learning Pathways that dynamically recommend resources and provide interactive feedback based on diagnostic outcomes, employing Natural Language Processing (NLP) to elucidate complex concepts—exemplified by stepwise decomposition of d'Alembert's formula derivations for wave equations; and (3) Learning Progress Management that tracks behavioral data to generate diagnostic reports, empowering instructors to refine pedagogical strategies; in educational contexts, particularly within STEM disciplines such as mathematical physics equations, ITS proves exceptionally suited for personalized intervention due to their rigorous logical frameworks and high algorithmic model ability.

2. Applications and Educational Value of Intelligent Tutoring Systems

As a mature application of artificial intelligence technology in education, Intelligent Tutoring Systems (ITS) derive their core value from enabling precise and dynamic personalized pedagogical interventions through systematic architectural frameworks by Xavier C(2025)[4].

Commencing with knowledge mapping and real-time learning diagnostics as its logical foundation, the system deconstructs disciplinary knowledge into structured networks through educational data mining, continuously analyzing student behavioral data to precisely identify individual knowledge gaps—thereby establishing the cognitive basis for personalized interventions. Building upon these diagnostic outcomes, the system activates its adaptive learning pathway engine, dynamically adjusting instructional content and sequencing via intelligent algorithms; for instance, upon detecting student deficiencies in Fourier transform applications, it autonomously delivers targeted micro-lectures and gradient exercises to achieve directed remediation of knowledge deficiencies—functionally operationalizing cognitive diagnostic results(2025)[5]. During knowledge transmission, the real-time interactive feedback module leverages Natural Language Processing (NLP) to construct conversational tutoring environments, exemplified by stepwise deconstruction of d'Alembert's formula derivations when students solve wave equations, providing immediate corrective guidance for reasoning errors—simultaneously enabling dynamic pathway calibration and deepening conceptual understanding. Pervading throughout, the learning progress management system tracks multidimensional metrics (e.g., task completion duration, temporal error rate patterns) to generate visualized diagnostic reports, empowering instructors to optimize pedagogical design at scale and establishing a synergistic human-AI intelligence loop. These four modules constitute an organically integrated architecture: knowledge mapping furnishes the cognitive framework, learning diagnostics locates problem coordinates, the adaptive engine generates solutions, real-time feedback ensures implementation efficacy, and progress management completes assessment-strategy iteration—collectively forming an educational enhancement loop of "diagnosis-intervention-feedback-optimization." This technological architecture demonstrates ITS's irreplaceable value in STEM education: disciplines like mathematical physics equations exhibit high logical rigor (with explicit deductive chains between concepts) and strong modelability (where problem-solving decomposes into discrete cognitive steps), perfectly aligning with ITS's rule-based reasoning and data-driven mechanisms. The system not only pinpoints cognitive blind spots in solving differential equations but also transforms abstract mathematical principles (e.g., method of characteristics) into individualized scaffolded training sequences through personalized pathway design, while its instantaneous feedback mechanism effectively addresses differentiated needs unattainable in traditional classrooms(2023)[6].

Ultimately, Intelligent Tutoring Systems (ITS) transform educational processes into computable, regulatable, and predictable cognitive optimization models, significantly enhancing the cultivation efficiency of higher-order thinking skills while reducing instructors' mechanical workload burdens—thereby providing foundational technological paradigm support for overcoming pedagogical bottlenecks in complex disciplines, such as Table 1.

Table 1: Teaching Challenges and ITS-Specific Solutions

Challenge Categories	Specific Manifestations
High Interdisciplinary Integration	Integration of Mathematical Analysis and University Physics Concepts
Elevated Theoretical Abstraction	Conceptual Difficulties in Bessel Functions, Green's Functions, and Related Constructs
Deficient Prerequisite Knowledge	Student Conceptual Blockage Due to Deficient Calculus and Ordinary Differential Equation Foundations
Insufficient Learning Motivation	Prevalent Spoon-Feeding Pedagogy Resulting in Exceptionally High Course Failure Rates

2.1. Conceptual Consolidation for Knowledge Deficits

The core strategy of the intelligent tutoring system for mathematical physics equations lies in constructing a closed-loop intervention framework of "detection-remediation-verification," which addresses the core teaching challenges through a dynamic and precise knowledge gap remediation mechanism. The course heavily relies on the continuity of the mathematical knowledge system and the physical conceptual system, as any gaps in prerequisite knowledge can lead to subsequent learning breakdowns. The system employs a three-tier diagnostic mechanism: embedding mathematical tool assessments at chapter entry points, analyzing physical concepts during problem-solving processes, and real-time monitoring of symbolic operations. When a student fails to derive the d'Alembert formula, the system automatically traces back to their mastery of the characteristic line method for hyperbolic PDEs and triggers targeted diagnostic tests.

The intervention process utilizes intelligent closed-loop knowledge points to preset diagnostic triggers at critical junctures, continuously analyze homework error patterns, and establish virtual experiment monitoring points. Following each intervention, the system dynamically generates verification test questions. If students meet proficiency standards when solving regenerated variable-coefficient ODE problems, advanced content such as spherical harmonics is unlocked; if they fail to meet the threshold, alternative learning pathways are activated for continued study. Throughout this process, the personal knowledge topology map is updated in real-time, while tracking mechanisms are embedded within subsequent learning activities.

2.2. Visualization of Abstract Concepts

To address the core challenges in the Equations of Mathematical Physics course—such as the abstract structure of partial differential equation solutions, the obscure physical interpretation of boundary conditions, and the difficulty in understanding special functions—the Intelligent Tutoring

System (ITS) employs an AI-driven dynamic visualization intervention strategy. First, it utilizes a parametric simulation engine to transform analytical and numerical solutions of wave equations, heat conduction equations, and others into spatiotemporal-evolving 3D dynamic fields (e.g., temperature distribution cloud maps, vibration surfaces, velocity vector diagrams). This engine supports real-time modification of initial/boundary conditions and uses sensitivity heatmaps to intuitively reveal the solution's dependence on these conditions. Second, it leverages function deconstruction tools to generate 3D geometric models for Bessel functions, Legendre polynomials, and similar special functions, linking them to physical scenarios like standing waves and spherical harmonic oscillations. Through dynamic synthesis animations, it demonstrates the convergence process of separation of variables for series solutions. This strategy transforms abstract mathematical entities into manipulable objects, bridging the traditional disconnect between symbolic derivation and physical intuition. It establishes a tripartite cognitive framework integrating "mathematical formalism, physical behavior, and geometric representation," ultimately shifting the learning paradigm from symbolic computation to spatial reasoning and from static solving to dynamic experimentation. This cultivates students' intuitive insight into mathematical-physical equations and empowers them to visually internalize theories through mathematical tools.

2.3. Improvement of Learning Motivation

To enhance learning motivation in the Equations of Mathematical Physics course, a dual-track approach integrating real-time Q&A and gamification design is implemented: first, a millisecond-response multimodal Q&A system is constructed, where formula derivation stalls or calculation errors trigger a circuit breaker mechanism to suppress frustration at its inception; simultaneously, learning paths are restructured through a scientific-narrative framework, continuously infusing motivation via a dynamic achievement system, instant incentive feedback, and social competition mechanisms. Based on real-time motivation heatmaps, strategies are personalized—activating point-based duels for competitive learners and triggering equation Easter eggs for exploratory types. This transforms abstract knowledge into a "research expedition," ultimately elevating core metrics of classroom engagement in high-threshold mathematical physics courses as Figure 1.

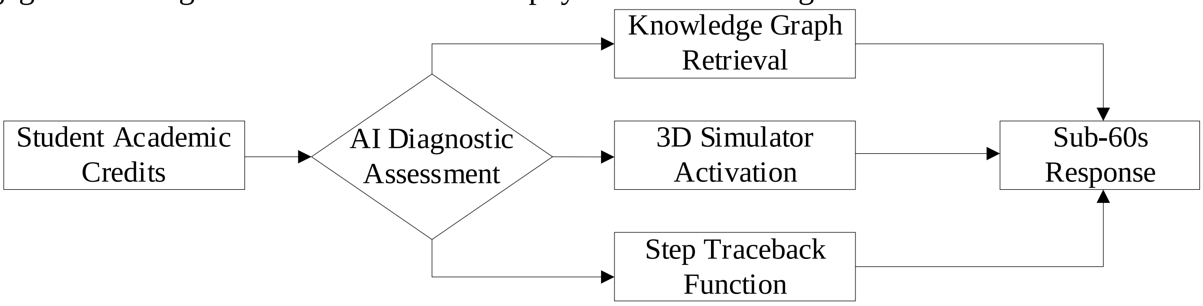

Figure 1: Intrinsic Motivation Amplification

3. Typical Application Scenarios and Empirical Results

3.1. Personalized Experimental Teaching

To enhance students' ability to bridge mathematical theory and engineering practice, a personalized programming experiment scheme is designed using tiered tasks: starting with 1D wave equation FDM solutions and advancing to 2D wave equation solutions. Students implement dynamic visualization through Python/C, integrating parameter sensitivity analysis and boundary condition design. By transforming abstract concepts—such as separation of variables and traveling wave solutions—into interactive wave animations, and structuring the learning process into pre-class micro-lectures, in-class debugging, and post-class extensions, the approach enables 86% of students to verify that "simulation demonstrations concretize abstract equations," effectively dismantling cognitive barriers between theoretical mathematics and engineering applications as Figure 2.

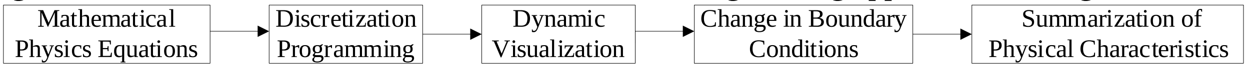

Figure 2: Personalized Pedagogical Experiment

3.2. Introduce Problem-Based Learning (PBL)

In the reform practice, the course effectively addresses the core issues of traditional teaching—such as the disconnect between theory and practice and low student engagement—by integrating AI-assisted topic selection. Through collaborative group projects that combine wave equation theory with engineering cases (e.g., forward modeling and inverse problem research in oil exploration), and leveraging AI tools for automated code generation and derivation support, the approach lowers barriers to numerical computation as Figure 3. This significantly enhances students' engineering practical skills, innovative thinking, and interdisciplinary application comprehension, demonstrating the model's efficiency and scalability in promoting the integration of "theory-tools-application" in STEM education.

Figure 3: Problem-Driven Instructional Process

4. Quantitative Comparison of Learning Outcomes

A comparison of final examination scores between the course using the Intelligent Tutoring System (ITS) group and the traditional teaching group, with a sample size of n=201, revealed that the ITS group demonstrated significantly higher learning outcomes compared to the traditional instruction group as table 2.

Table 2: Score Comparison

Group	Mean Score	Total Learning Time	Standard Deviation
ITS Experimental Group	85.3	96	6.8
Traditional Group	78.5	120	10.1

Based on the experimental comparison, the ITS experimental group achieved a significantly higher final average score (85.3) than the traditional teaching group (78.5) despite less total study time, representing an improvement of 13.8 points; analysis of standard deviation further indicates that all students in the ITS group exhibited upward performance trends. By dynamically adjusting learning paths, the ITS system implements precision teaching that reduces study time while enhancing outcomes as Table 3.

Table 3: Comparison of Teaching Effectiveness

Comparison Aspect	Traditional Mode	ITS-Assisted Teaching	Innovative Essence
Knowledge Delivery	One-way transmission	Personalized recommendations, on-demand learning	Student-centered approach
Abstract Problems	Teacher-provided	AI dynamically generated	Multimodal cognitive model
Feedback Timeliness	2-3 days for assignment grading	Second-level response, instant error correction	Closed-loop learning reinforcement
Personalized Learning	Holistic analysis	Individual mastery profile	Individual knowledge mastery feedback

5. Conclusion

Addressing the abstract nature and complex solution methods in the Equations of Mathematical Physics course that foster student apprehension and low motivation, along with traditional teaching issues including one-way knowledge transmission, delayed feedback, and theory-practice misalignment, this study introduces the Intelligent Tutoring System "Xuetang Cloud" as a core pedagogical intervention. The system constructs structured knowledge graphs to enable precise learning diagnostics and dynamically generates adaptive learning pathways based on real-time performance feedback.

The study demonstrates that the system effectively enables tracking and management of student learning processes, facilitating dynamic implementation of personalized instruction; personalized motivational mechanisms such as real-time progress visualization and targeted resource recommendations provided by the ITS significantly enhance students' learning motivation and self-regulated learning capabilities; the intelligent tutoring system successfully alleviates academic apprehension and strengthens learning confidence; by strategically embedding engineering practice cases, it bridges the gap between theoretical knowledge and practical application. The implementation of this tutoring system not only substantially improves students' cognitive assimilation efficiency of core knowledge but also fosters synergistic development of STEM literacy, thereby providing an effective pathway and empirical evidence for resolving pedagogical challenges in advanced abstract STEM courses.

Acknowledgements

Funding: Qilu University of Technology (Shandong Academy of Sciences), Educational Reform Project (Project Numbers: 2024yb36).

Disclosure statement

The authors declare no conflict of interest.

References

[1] Shapiro J A. An algebra subsystem for diagnosing students' input in a physics tutoring system[J]. International Journal of Artificial Intelligence in Education, 2005, 15(3): 205-228.

[2] Liu X. Application and Challenges of Artificial Intelligence in Education: Current Status, Issues, and Future Directions[J]. International Journal of Social Science and Education Research, 2025, 8(6): 150-159.

[3] Song X. Physical education teaching mode assisted by artificial intelligence assistant under the guidance of high-order complex network[J]. Scientific Reports, 2024, 14(1): 4104.

[4] Xavier C, Rodrigues L, Costa N, et al. Empowering Instructors With AI: Evaluating the Impact of an AI-Driven Feedback Tool in Learning Analytics[J]. IEEE Transactions on Learning Technologies, 2025.

[5] Wang H, Wang C, Chen Z, et al. Impact of AI-agent-supported collaborative learning on the learning outcomes of University programming courses[J]. Education and Information Technologies, 2025: 1-33.

[6] Ley T, Tammets K, Pishtari G, et al. Towards a partnership of teachers and intelligent learning technology: A systematic literature review of model-based learning analytics[J]. Journal of Computer Assisted Learning, 2023, 39(5): 1397-1417.