

Paradigm Reconstruction and Practical Pathways of AI-Enabled Physical Chemistry Teaching

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Abstract: Physical chemistry is a core course for chemistry-related majors. Its teaching faces problems such as abstract concepts, complicated mathematical deductions, and disconnection between theory and practice, making it difficult to improve teaching quality. Generative artificial intelligence offers new solutions to these teaching difficulties. This paper proposes strategies to reduce cognitive barriers, reshape classroom models, and optimize evaluations. Besides, it also puts forward risk prevention measures for “cognitive outsourcing” and “AI hallucinations”. This research holds that the essence of AI-enabled physical chemistry teaching lies in realizing the paradigm shift from unified content supply to the construction of an educational ecosystem through technology, and its effectiveness depends on consistently prioritizing the cultivation of students’ higher-order thinking abilities.

Keywords: Artificial intelligence; Physical chemistry; Human-AI collaboration; Teaching reform

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1. Introduction

Physical chemistry is an important foundational course for chemistry, chemical engineering and materials-related majors. It applies physical principles and mathematical methods to interpret chemical laws and bridges fundamental theories and engineering practice. It plays a crucial role in cultivating science and engineering talent ^[1]. However, its teaching still faces ongoing challenges. Abstract concepts are difficult to understand, and the numerous formulas and complex derivations impose a heavy burden on students. Insufficient linkage between theoretical knowledge and practical application weakens students’ capacity for knowledge transfer and innovative practice. These challenges thus render the reform of physical chemistry teaching a long-standing problem.

Generative artificial intelligence brings new opportunities for curriculum innovation ^[2,3]. Large language models, intelligent knowledge graphs and teaching assistants can optimize teaching resources, classroom

activities, learning modes and assessment systems. Domestic universities have explored preliminary AI-assisted physical chemistry teaching practices and verified their practical value^[4,5]. However, many existing applications merely overlay technology onto traditional teaching. AI is merely regarded as a content generation tool, without reconstructing the underlying teaching relationships. Against this background, this paper explores two core issues. What core value does AI bring to physical chemistry teaching and how can deep integration be realized while avoiding emerging risks. Based on the requirements of high-quality higher education development, this study constructs a feasible AI-enabled teaching framework. It explores reconstruction paths and risk prevention strategies, and provides references for intelligent reform of science and engineering courses.

2. The paradigm reconstruction and logical foundation of AI-enabled physical chemistry teaching

2.1. Obstacles in physical chemistry teaching and solutions based on AI

Common problems in physical chemistry teaching include abstract concepts, complex mathematical derivations, and the disconnection between theory and practice. These problems mainly arise from the cognitive mismatch between the discipline's rigorous, hierarchical knowledge system and students' gradual cognitive development from concrete to abstract thinking. Traditional classrooms lack the intermediate medium that connects academic knowledge with students' cognition. Therefore, contradictions can hardly be eliminated, resulting in the solidification of cognitive barriers and restricting the improvement of teaching quality. Generative AI functions as an adaptive cognitive mediator to alleviate the difficulties in traditional teaching^[6]. Instead of simply presenting knowledge, it transforms, classifies and decomposes academic knowledge according to students' progress and thinking habits, bridging the gap between academic logic and cognitive logic^[7]. Its enabling value is mainly reflected in three aspects.

Firstly, cognitive barriers can be eliminated through multi-dimensional language adaptation. Physical chemistry involves professional terms, mathematical symbols and theoretical formulas, which often create learning obstacles for students. Generative AI can freely convert among different forms of knowledge. It can visualize obscure formulas and stratify condensed theories, building a bridge connecting the professional disciplinary discourse with students' cognitive thinking. Secondly, the cognitive chain can be improved through dynamic knowledge supplementation. Students often forget previous and associated knowledge. Traditional teaching can hardly fill knowledge gaps instantly and leads to cognitive disconnection. AI can respond to learning needs in real time, compensate for knowledge deficiencies, build consistent learning sequences, and prevent fragmented learning. Thirdly, it cultivates disciplinary abilities through interactive dialogue to drive learning. Different from the one-way output of traditional teaching aids, AI supports multi-round interactive dialogue and problem-solving, forming a deep learning cycle of "question-response-further inquiry". It dynamically adjusts explanations and depth based on students' actual performance, transforming teaching from simple knowledge delivery to collaborative cognitive construction, effectively promoting students' higher-order thinking and subject awareness.

2.2. From auxiliary tools to reconstruction of teaching ecosystem

Given the challenges in current teaching and the value of generative AI as a flexible cognitive mediator, the genuine empowerment of AI for physical chemistry teaching requires breaking narrow tool-oriented thinking

and promoting teaching innovation from the perspective of an integrated teaching ecosystem.

At present, most teaching applications are still at the level of tool assistance, regarding AI merely as an instrument to facilitate teachers' instruction. Such patterns use AI to accelerate teaching processes such as knowledge explanation and content delivery, yet essentially optimize and inherit the conventional teacher-centered teaching mode without altering underlying teaching logic. In contrast, the ecology-oriented application model no longer confines AI to a mere auxiliary tool, but regards it as the core medium for reshaping the overall learning relationship. The focus shifts from improving teachers' efficiency to supporting students in organizing knowledge, building reasoning, and developing cognition, so as to realize a fundamental transformation of teaching mode. In short, tool-based application pursues efficiency optimization of teachers' teaching, while ecosystem-oriented empowerment focuses on promoting students' deep learning and cognitive upgrading.

3. Implementation pathways and risk prevention of AI-enabled physical chemistry teaching

3.1. Knowledge visualization for resolving cognitive barriers

Abstract theories and complex mathematical derivations are the main obstacles in the learning process of physical chemistry. By using visualization technology, the obscure theoretical expressions and intricate mathematical relationships can be transformed into intuitive and perceptible visual materials such as images and animations, thereby eliminating students' cognitive barriers and helping them establish effective connections between their existing knowledge and the new learning content ^[8].

Firstly, dynamic knowledge graphs are constructed to help students develop a systematic understanding ^[9]. Teachers can use the map tool to organize knowledge points and build dynamic knowledge graphs with hierarchical and logical correlations. The graphs not only present the core concepts of each chapter but also mark the connections between knowledge points, enabling students to jump to relevant modules based on their own level, conduct targeted gap-filling and personalized review, and guide students to gradually build a complete knowledge framework and form a clear cognitive system. Secondly, the interactive simulation resources are employed to clarify the relationship between physical and chemical processes and variables. Many students can apply formulas to complete calculation exercises, but they can only perform mechanical substitution calculations and fail to comprehend the physical connotation behind these formulas. By using interactive animations and adjustable parameter simulation programs, inquiry-based teaching can be conducted on physical and chemical scenarios. Taking the Carnot cycle as an example, the interactive animation sequentially demonstrates the four reversible processes of isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression, visually presenting the changes in temperature, pressure, and volume at each stage. Students can independently adjust the temperatures of the heat sources through the program and observe the dynamic changes of the p-V curve and the efficiency of the heat engine in real time. The teacher can guide students to establish the connection between the formulas and the cycle process by asking questions and conducting group discussions, thereby deepening their understanding of the course content.

3.2. Reconstructed learning scenarios: from dual “teacher-student” mode to tripartite “teacher-AI-student” collaboration

The traditional “teacher-student” one-way teaching mode applies unified teaching supply to diverse learning

conditions, further aggravating misalignment between disciplinary logic and individual cognitive logic. The introduction of AI breaks such structure and constructs a tripartite collaborative educational scenario of “teacher-led, AI-empowered and student-centered”, which improves both teaching and learning.

The tripartite structure facilitates role transformation of teachers. AI undertakes routine work such as question-and-answer (Q&A), resource sorting, and basic marking. Teachers evolve from “knowledge transmitters” into “learning designers, thinking guides and learning diagnosticians”, focusing on activity design, targeted guidance and in-depth discussions to cultivate students’ higher-order thinking abilities^[10].

AI maintains an auxiliary positioning and provides hierarchical support throughout the whole teaching process^[11]. Before class, it assists in learning diagnosis and preview to help students attend class with clear questions. During class, its intervention boundary is strictly controlled. Teachers dominate the deduction of core concepts and explanation of key difficulties. After class, AI supports personalized error analysis and targeted training to address learning deficiencies and form a complete teaching support system.

The new teaching model also strengthens students’ central role. Even though AI can quickly provide answers, students should first think independently before seeking help. They need to transform vague confusion into clear and specific questions, which is the key to achieving deep learning. Besides, students should learn to judge whether the output from AI is reasonable and sufficient, discover the flaws in AI replies, raise questions and request revisions. Through questioning and using AI for verification, this helps to refine their thinking abilities.

The three participants form a dynamic and cyclic collaborative mechanism. Teachers optimize the teaching design according to the learning data provided by AI. Students generate high-quality classroom questions with the support of AI. Cognitive gaps that appear during discussions are addressed precisely by AI afterward.

3.3. Transformation of the evaluation system: from summative assessment to process-oriented construction

The traditional physical chemistry assessment mainly relies on summative examinations, which have obvious limitations. It focuses on the results rather than the process, fails to reflect students’ cognitive development and thinking growth, and may even encourage the kind of rote learning, deviating from the goal of cultivating comprehensive qualities. Moreover, AI can easily complete standardized test tasks, seriously impairing the reliability and validity of traditional assessments. This makes it an inevitable requirement for teaching reform to transform the evaluation system.

Firstly, a process-oriented student learning diagnosis is achieved through the application of AI. With the support of AI-powered natural language understanding and automatic question generation, personalized diagnostic tests can be generated after each teaching unit, and the difficulty can be dynamically adjusted based on the student’s previous learning performance. Beyond the scores, the test results can also generate a visual “cognitive profile”, which helps identify conceptual misunderstandings, thinking weaknesses, and learning obstacles. On this basis, teachers can carry out targeted teaching intervention, and students can conduct targeted remedial learning, thus forming a positive teaching and learning cycle.

Secondly, the quality of AI interaction processes is included in evaluation. As students’ conversations with AI become an important part of their learning, conversation quality itself serves as valuable learning evidence. Teachers can require students to attach excerpts of their interactions with AI in some assignments to demonstrate the questions they raised, the content generated by AI, and their judgment and screening process

of the information. This kind of metacognitive reflection not only records the actual learning process but also prevents students from overusing AI. At the same time, the quality of the questions raised by students and their critical thinking will be evaluated, which helps them transform from passive recipients of answers to active proposers of high-quality questions.

Thirdly, open-ended task evaluations are adopted to assess students' higher-order thinking. In the context of AI-enabled learning, assessment emphasizes not only knowledge memorization but also students' ability to apply knowledge to solve practical problems. Open-ended tasks are designed, such as the electrochemical performance test of materials in practical applications and the analysis of test results. AI tools can be used for information retrieval and preliminary analysis. Students conduct analysis of the reaction process and results, submit a summary report, and give a group presentation. The assessment focuses on whether students can extract the core physical and chemical mechanisms behind the problems, verify the AI output content based on professional knowledge, and explain the experimental results in terms of physical and chemical connotations. These evaluations focus on the high-level thinking abilities that AI cannot replace, which align with the core training goals of the physical chemistry course.

3.4. Prevention of cognitive outsourcing risks

Introducing AI into teaching brings about a significant risk of cognitive outsourcing, which cannot be ignored^[12]. If students completely delegate core cognitive tasks such as concept analysis, mathematical derivation, and logical reasoning to AI, the scientific thinking training inherent in physical chemistry teaching will lose its effectiveness. Unlike obvious academic cheating, the negative impacts of cognitive outsourcing are often concealed. It may seem to improve learning efficiency, but in essence, it deprives students of the opportunity to develop independent thinking and weakens the fundamental educational goals.

Multi-dimensional prevention strategies are proposed to reduce the risks of cognitive outsourcing. At the teaching design level, teachers should clearly define the boundaries for the use of AI, distinguishing between learning tasks that can be assisted by AI and those that must be completed independently. For example, in the core formula derivation process, students are required to independently derive the formulas throughout the process and are not allowed to use AI. The educational value of formula derivation does not lie in obtaining the final result, but in training students' physical logic and mathematical reasoning abilities. For conceptual judgment and analysis exercises, a learning process of "first independent thinking, then AI verification and expansion" is established. This guides students to form their own judgments first, and then use AI to check the thinking and supplement knowledge. At the classroom implementation level, a separate independent thinking session without AI intervention is specially set up. Teaching activities such as blackboard demonstrations, classroom discussions, and group presentations strictly limit the use of AI tools, enabling students to fully experience the entire process of problem analysis and logical reasoning. In terms of evaluation methods, a process-based and diverse evaluation approach that AI cannot replace is adopted. Classroom discussion performance and oral reasoning are included in the assessment to truly measure the students' thinking development level, avoiding evaluation solely based on written assignments and standardized answers. Furthermore, teachers need to cultivate students' awareness of self-regulation. Over-reliance on AI will gradually reduce students' willingness and ability to think independently. Teachers should guide students to establish a correct view of AI tools. AI is a learning assistant and cannot replace one's own thinking. Such guidance helps reduce students' passive reliance on tools and encourages them to mobilize their own thinking when facing learning challenges actively.

3.5. Critical thinking training for identifying AI hallucinations

AI is not a completely reliable source of authoritative knowledge. The results generated by large language models are based on statistical probabilities rather than rigorous and logical reasoning. Therefore, they are prone to producing seemingly reasonable and fluent information, but in reality, they contain errors. This phenomenon is called “AI hallucinations”. In physical chemistry teaching, these hallucinations manifest as incorrect formula writing, inaccurate descriptions of conceptual relationships, and even fabricated citations of literature. This misleading content may cause cognitive confusion and form incorrect knowledge systems. Besides, the biases present in training data may cause AI to tend to support certain theories while ignoring other reasonable viewpoints, which also requires attention.

Through targeted teaching design, these risks can be transformed into valuable teaching resources. During the teaching process, regular training on information discrimination and critical thinking should be conducted. Students need to fully understand the limitations of AI tools and verify the content generated by AI. Teachers can deliberately introduce typical AI error cases and design targeted identification and correction tasks. Students are required to identify the errors and correct the incorrect content based on scientific principles. This practice not only helps to strengthen professional knowledge, but also enables students to develop rigorous scientific literacy and critical thinking skills.

4. Conclusion

AI-enabled physical chemistry teaching is not just adding technology to the classroom. Instead, it represents a systematic teaching innovation that aligns with the trend of higher education reform. Its core lies in breaking away from the old routine of traditional cramming-style teaching and superficial use of AI tools, and reconstructing the teaching and learning relationships from the perspective of the educational ecosystem. Knowledge visualization helps to reduce cognitive barriers, tripartite collaborative scenarios revitalize classroom teaching, and process-oriented evaluation optimizes the entire teaching system. These approaches effectively solve major problems in teaching and promote the transformation of courses from knowledge transfer to literacy cultivation.

The intelligent teaching reform should adhere to the essence of education, balancing the empowerment of technology with the cultivation of students’ thinking abilities. Establishing a dual risk prevention and control system can effectively reduce cognitive outsourcing and information deviations. Future practices will further optimize implementation paths, closely aligning with the training goals, and cultivating high-quality innovative science and engineering talents.

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