The Research on AI-Empowered Project-Based Teaching Reform in Advanced Mathematics

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Abstract: *With the development of artificial intelligence technology, new technological paths have been created for the reform of teaching in Advanced Mathematics based on project-based learning. Based on the above theories, this paper will provide the theoretical basis and model for AI-assisted project-based teaching in Advanced Mathematics, and conduct studies at all three levels. The aims of this paper are to study the features of intelligent transformation in project-based teaching of advanced mathematics, explore how artificial intelligence can be applied to help students learn, and put forward a model for human-machine cooperative learning. At the level of mechanism, this paper puts forward a semantic association model for knowledge units and project themes, develops a difficulty-adaptive adjustment strategy based on student performance data, and constructs an intelligent matching path among multimodal resources and project tasks. At the level of intervention, this paper will record the process of a student's mathematical thinking, automatically detect problems in their reasoning, build a closed-loop system, and offer personalised help to motivate them to learn more. The aim of this paper is to promote the construction of data-driven, project-based teaching in Advanced Mathematics.*

Keywords: *Advanced Mathematics, Project-based Learning, Knowledge Graph, Cognitive Load, Intelligent Intervention, Adaptive Learning*

Introduction

Advanced Mathematics is the foundation for the study of science and engineering, so the goals of teaching it are to transmit knowledge and cultivate students' thinking ability. Project-based teaching is a good way to have students learn by solving problems and applying what they have learned. The first three deficiencies of the old implementation model are: first, the content of the project is based on experience-driven assumptions and does not consider changes in people's cognition; second, process monitoring is still in the form of periodic evaluation and cannot observe subtle changes in cognition; and third, resource allocation is fixed and cannot be adjusted dynamically according to changes in the task. Artificial intelligence technology has introduced a new way to solve the problems listed above. Collection and analysis of learning process data by intelligent systems can be used to make teaching decisions based on data; a knowledge graph can organise mathematical concepts and generate problems dynamically, and at the same time, a real-time feedback mechanism can quickly find out if there are any difficulties students are having in their studies and offer help. The first problem this paper will address is how to implement AI-empowered project-based teaching of advanced mathematics in an innovative way, and it will provide supporting information for the reform of teaching models by discussing related issues at the levels of theoretical reconstruction, mechanism design and process intervention.

1. Theoretical Reconstruction of Intelligent Technology in Project-Based Teaching of Advanced Mathematics

1.1 Evolution and Intelligent Turn of the Project-Based Teaching Paradigm in Advanced Mathematics

In recent years, the development of project-based teaching in Advanced Mathematics has gone from auxiliary means to structural reform. First, problem-based teaching was employed to introduce the mathematical knowledge; the design of these projects followed a fixed sequence of knowledge points, and at that time, technical tools were used sparingly, only as calculation aids or to show the results.

With the development of learning theories and the spread of digital technology, project-based teaching has gradually moved from a supportive position to an integrated one, and at the same time, the degree of integration between project themes and mathematical content has also been rising. However, the basis of the logic for instructional design is still a presuppositional system.

A good step has been taken in the construction of project-based teaching. The first is that the way new problems are created will change from fixed preparation to real-time generation; that is to say, according to the current cognitive state of the students, the intelligent system will adjust the difficulty of the problem, recommend suitable mathematical tools, and change the progressive sequence of problems accordingly. Therefore, the division mode of the teaching decision-making authority will be changed, and some functions of experience-based decision-making will be moved to a data-driven collaborative system. Therefore, project-based teaching in Advanced Mathematics is suitable for all kinds of cognitive traits of students[1].

1.2 Mechanism Analysis of Artificial Intelligence Technology in Mathematical Cognitive Construction

Application of Artificial Intelligence Technology in the Construction of Mathematical Cognition is based on the general characteristics of good mathematics learning. Advanced Mathematics Cognition is the repeated coordination of symbolic manipulation and visual imagination, and abstract concepts such as limits and continuity need to be converted into all sorts of representations for assimilation. Scaffolding cognition in the traditional classroom is limited by the teacher's own experience and the spatiotemporal constraints of the classroom, so it is difficult to carry out fine-grained tracking and intervention of learners' cognitive processes.

Intelligent technology is a type of mathematical cognition in the form of algorithms, and its development path can be shown by changes in cognitive pathways and intelligent construction of conceptual networks. Collect behaviour data of the learners while they are working on the project, build a cognitive state model in cooperation with others based on a knowledge graph, and dynamically change the order and level of abstraction of the mathematical concepts in the project tasks. Intelligent technology can take many forms and use various analogies to help students learn about abstract thinking, and thus it will be easier for them to connect symbols and learn new knowledge.

1.3 Construction of a Mathematics Project-Based Learning Ecosystem from the Perspective of Human-Machine Collaboration

The ecosystem of mathematics project-based learning in the era of human-machine collaboration is constantly changing and developing, and it includes learners, teachers, intelligent systems and mathematical knowledge resources. The construction logic of this ecosystem is that all parts work together; the learner's behaviour data can be used to improve the system, and the role of the teacher will change from knowledge transmission to guiding the learning process. To promote the healthy development of the ecosystem, an intelligent system should be able to collect information from all parts of society and solve problems promptly.

The foundation of the construction of the learning ecosystem is an organised representation of mathematical knowledge. Based on semantic parsing of the curriculum standards and deep learning of textbook content, an intelligent system is employed to construct a knowledge graph covering the main knowledge points in Advanced Mathematics and establish various associations among knowledge units and the library of project themes. During the process of project-based learning, the system will continuously observe how students solve problems and which materials they use; based on this observation, it can identify common difficulties that all students are facing, as well as individual differences among them, and then adjust the difficulty of the project, divide the tasks for different students, and promote teamwork.

2. Dynamic Generation Mechanism for Mathematics Project Content Based on Knowledge Graphs

2.1 Semantic Association Model of Knowledge Units in Advanced Mathematics and Project Themes

The system of knowledge in advanced mathematics has a strict logical hierarchy and an intricate association structure. Knowledge units have a sequence of prerequisite dependencies; for example, the limit is the basis for continuity and derivatives, but it also has lateral analogical transfer paths, and echoes of ideas and methods can be found between linear algebra in finite-dimensional spaces and functional analysis in infinite-dimensional spaces. As the carrier of mathematical knowledge, the design of project themes should accurately map the internal logic of all combinations of knowledge, maintain the authenticity and integrity of the problem environment, and allow students to organically discover the essential ideas of mathematical concepts through project exploration. The first step in the dynamic generation of project content is to construct a semantic association model for knowledge units and project themes[2].

The construction of the semantic association model is based on the formal representation of mathematical concept ontologies and their relations in knowledge graph technology. Based on the detailed study of the advanced mathematics textbooks, curriculum standards and classic project cases, this model extracts the core concept nodes of limits, derivatives, integrals, series and differential equations, along with all kinds of relationships such as definitions, theorems, properties, methods and applications, to build a knowledge network covering the foundation of the subject. Therefore, each project in the project theme library is divided into elements of the problem context and elements of the mathematical structure; the former describes the real background and features of the problem domain for the project, and the latter shows the mathematical operations, reasoning and modelling processes that are implicit in the project. Based on the analysis of semantic similarity and concept co-occurrence, many many-to-many mappings have been built between the project themes and the knowledge units in this model. The map contains the corresponding points of explicit knowledge and also the implicit associations in thinking methods, such as linking optimisation problems with both extremum theory and convex analysis; thus, project themes can have multiple dimensions of mathematical knowledge and support integrated application across units.

2.2 Adaptive Adjustment Strategy for Project Difficulty Based on Student Performance Data

The Degree of Project Difficulty Affects Cognitive Load and Motivation to Learn. Too hard will make the students feel frustrated and stop thinking; too easy will not be motivating. In the past, teachers would use their own experience to set the general difficulty of the project, but it did not suit all the students in the class. Based on the performance data of the students, the difficulty of the project will be adjusted according to how well they have been learning.

Based on the data we have collected and analysed about the students' learning progress, we will revise the teaching plan. Micro-behavioural data obtained from learners during the implementation of a project, such as the time taken to solve problems, types of errors made, frequency of asking for help, exploration paths, etc., are organised according to the cognitive diagnostic model after feature extraction to form a quantitative index of their knowledge mastery and thinking ability. Based on the results of the above representation, the system will automatically adjust the mathematical depth, step complexity and inquiry openness of the current problem. The Adjustment Mechanism is based on the Zone of Proximal Development. Without changing the basic mathematical structure of the project, one can adjust the numerical parameters to change the level of difficulty, add or remove intermediate hints, expand the scope of the problem, etc., so that the learner is always in a state of moderate difficulty.

2.3 Intelligent Matching Path of Multimodal Resources and Mathematics Project Tasks

In project-based learning for advanced mathematics, students need to know how to use all kinds of resources to solve problems and obtain learning materials, such as conceptual explanations in text handouts, reasoning demonstrations in video lectures, visual simulations via dynamic presentations, parameter exploration in interactive simulations, etc. Although there are many rich and varied learning materials available, they are also prone to information overload and selection confusion; it is often difficult for students to find the most suitable materials for their current studies at a convenient time. The aim of the intelligent matching path is to determine, based on the attributes of a project task and the current demands of learners, which suitable multimodal resources should be offered to reduce cognitive load and improve the efficiency of resource utilisation[3].

The basis of intelligent matching is that the semantic annotations of the resources and models in the user demand must be aligned bidirectionally. First, in this way, we can organise the multi-modal data and extract some metadata about the mathematical knowledge points in each piece of information, as well as related project stages, cognitive functions and expected learning results. At the same time, in the course of project work, this way can also determine the type of resource demand for learners by observing their behaviour now and identifying any confusion they may be experiencing. According to all the requirements of the task, the current knowledge of the students, their learning preferences, the characteristics of the available resources, etc., the matching algorithm will determine how well these resources meet the needs and then intelligently recommend the best order of resources from a large database to help the students complete their mathematics project tasks smoothly.

3. Intelligent Intervention in the Mathematics Project Process Under Cognitive Load Regulation

3.1 Tracking and Representing the Trajectories of Learners' Mathematical Thinking in the Project Process

The thinking activities of students in the project-based learning of advanced mathematics are not explicitly shown but can be observed through the continuous process of problem-solving, and they have the complex characteristics of dynamism, non-linearity and multi-modality. In the traditional way of teaching, teachers' knowledge of students' thinking is based on the presentation of intermediate results and short-term observations; thus, they are unable to learn about the whole process of thinking emergence and change. Precise Tracing and Systematisation of the path of mathematical thinking are needed for intelligent intervention at present. Presenting the thinking trajectory is to record the sequence of behaviour and also to externalise and map the deep structure of mathematical cognition.

Tracking of thought processes is based on the collection and integration of all kinds of behaviour data by the intelligent system in the project. All of the operations a learner performs in a mathematics project, such as entering symbols, changing formulas, drawing graphs, modifying parameters, etc., are recorded as a sequence of time-series data. Cognitive computing will be employed by the system to study the data in more detail and extract features of the thinking process, such as the choice of a way to solve a problem, the order in which an intermediate conclusion is reached, and how different representations are converted. With the addition of eye-tracking and screen-recording technology, a large amount of data has been obtained, and now we can collect patterns of gaze movement among mathematical symbols and graphics to provide more precise support for reconstructing thinking processes[4].

Based on the above, we can construct a topological structure diagram of the thinking process and show the learner's cognitive path from the initial problem to the final solution. In addition to showing the final result, this way of presentation can also show the main nodes and turns in the process of thinking, as well as good reasoning paths and poor exploration branches. Annotations of a learner's metacognitive behaviour in the representation of the thinking process include self-correction, retrospective verification and strategy modification. Outsourcing of the high-order thinking activities will offer another basis for the decisions in the next round of intervention. Cluster analysis can be applied to a large number of thinking trajectories to find the general thinking patterns of learners with different cognitive styles, and based on this, a personalised intervention model for training can be developed.

3.2 Automatic Identification of Obstacles in Mathematical Reasoning Based on Real-time Feedback

During the course of mathematics projects, the students' reasoning activities often encounter all kinds of problems, such as interruptions in thought, circular reasoning, misapplication of concepts, or logical leaps. Promptly find out if there are any problems or errors in the work and correct them early to prevent problems in the whole project and learning. An automatic recognition mechanism that can detect any change in a student's thinking at that moment will be able to point out logical errors in time. The accuracy of the diagnosis will determine how suitable and effective the next steps are.

The Operation of the identification mechanism is based on the algorithmic model of norms for mathematical reasoning. The intelligent system has a rule base for advanced mathematics reasoning and a typical error pattern base, and then it will continuously compare the learner's reasoning process with the correct path to find any problems by identifying differences. The construction of the rule base is based on the analysis of the logical system of Advanced Mathematics, and the normative requirements include the order-preserving property of limit operations, the applicable conditions for the mean value theorem of derivatives, and the discriminant criteria for series convergence. Based on the mining of historical learning data, several types of reasoning deviations have been summarised in the error pattern base, such as omitting the chain rule in the differentiation of composite functions and misjudging the direction in surface integrals.

For multi-step reasoning in complex projects, a Hidden Markov Model or a Graph Neural Network can be used to perform state transition analysis of the thinking process, and it is possible to find important places where the chain of reasoning is broken or there is circular wandering. The model knows that a person is in a thinking state and can distinguish between brief confusion and serious, prolonged problems. The results of the identification contain the location information of the obstacle points and an initial judgment on the type of obstacle, such as concept confusion, use of an improper method or errors in representation transformation. At the same time, it will also calculate the degree of recognition. Obstacle points with low confidence will still be recognised by the system, and the free movement of the learners will not be restricted in advance. Identify the relevant information and the results of the thought process to determine how to intervene[5].

3.3 Personalised Scaffolding Push and Dynamic Optimisation of Mathematics Inquiry Depth

After finding out why a student is having difficulty learning, the next step is to offer some targeted assistance to help them overcome this obstacle and study well. The "push" mode of personalised scaffolding should be based on the student's current psychological state, the type of difficulty, and the whole structure of the mathematics project; thus, it should offer specific help without being too obvious. There are many kinds of pushes, such as asking questions, giving analogy cases, step-by-step instructions and concept micro-lessons; generally speaking, they all aim to motivate students' metacognitive awareness and self-management ability. In line with the principle of gradual release in scaffolding design, the first step is to have little support, and as the length of the work increases, more support will be needed.

As I move the scaffolding, the system will continue to observe how you react next and adjust the depth of the inquiry for this project dynamically. If the student can continue to learn in a more profound way on their own with the help of support, then moderately increase the openness and difficulty of the problems. If the student is still in a state of cognitive overload, the scope of the investigation will be reduced for now, and more organised support will be offered. Dynamic optimisation of the depth of inquiry refers to changing the difficulty of tasks and altering the degree of openness in mathematical problems; at different times, one can flexibly switch between closed-form calculation and open-ended modeling according to the current situation of the learners.

Promptly provide feedback and adjust the difficulty of the problem accordingly so that the process of solving the mathematics project is at a suitable level for the students; it should be neither too easy nor too difficult. At the same time, we will also note any changes in the student's operational fluency, number of errors and frequency of asking questions to determine how mentally strained they are. If the system does not think that exploration will be helpful, it will offer assistance. When the system finds that the child is thinking, it will reduce some support to encourage independent play. All the links in the chain of intervention are closed loops of observation-diagnosis-correction-observation. First, it can prevent the stagnation of thought caused by a large amount of material and avoid superficial thinking due to oversimplification; thus, it promotes the orderly development and gradual improvement of mathematical thinking ability.

Conclusion

The three main problems in the reform of AI-enhanced project-based teaching of advanced mathematics at the three levels of theoretical reconstruction, mechanism design and process intervention will be systematically analyzed in this paper. First, we will present the theoretical basis of intelligent transformation in project-based teaching of advanced mathematics; next, we will go over the basic mechanism of artificial intelligence technology in mathematical cognitive construction; finally, we will put forward a general framework for a mathematics project-based learning ecosystem based on human-machine collaboration. At the level of mechanism, this paper builds a semantic association model for knowledge units in Advanced Mathematics and project themes, puts forward an adaptive adjustment strategy for project difficulty based on student performance data, designs an intelligent matching path between multimodal resources and mathematics project tasks, and presents a technical solution for the dynamic generation of project content. At the level of process intervention, this study observes and records the process of students' mathematical thinking during the implementation of project activities, and based on real-time feedback, it can automatically detect problems in mathematical reasoning and dynamically adjust the intensity and direction of personalised support and mathematical exploration to form a closed-loop system of observation-diagnosis-intervention-re-observation. Based on the three above, we can promote the development of project-based teaching in advanced mathematics from an experience-driven model to a data-driven model and provide theoretical support and a practical path for innovation in mathematics education in the intelligence era.

At the level of intervention, this paper will record and track students' thinking in a mathematics project over time, build an automatic obstacle detection system for mathematical reasoning based on real-time feedback, and create a closed-loop system that can offer timely help and adjust the level of mathematics exploration accordingly. Some theoretical support and technical ideas for the change in modern mathematics from experience-oriented to data-driven thinking have been put forward in previous studies. The following directions will be taken in the future: First, improve the algorithmic accuracy of the mathematical cognitive diagnosis model and strengthen the detection of complex reasoning processes; Second, increase the construction of the library for interdisciplinary project themes and deepen the integration of mathematical knowledge with engineering and science problems; Third, explore the combined application of multimodal learning analytics technology to achieve all-round perception of learners' cognitive and emotional states; Fourth, carry out long-term tracking studies on intelligent intervention strategies to verify their lasting effect on the development of students' mathematical thinking ability.

Fund Projects

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