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Research and Practice of a Knowledge Graph-Driven Inquiry-Construction Double-Helix Teaching Model in High School Mathematics

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Abstract: In the context of the "Two New" initiatives, high school mathematics instruction still grapples with three interlocking problems: knowledge fragmentation, limited cultivation of higher-order thinking, and weak alignment among teaching, learning, and assessment. To counter these challenges, we propose an Inquiry–Construction Double-Helix model that uses a domain-specific knowledge graph as its cognitive spine. The model interweaves two mutually reinforcing strands—student-driven inquiry and systematic knowledge construction—into a double-helix trajectory analogous to DNA replication. The Inquiry Strand is launched by authentic, situation-based tasks that shepherd students through the complete cycle: question → hypothesis → verification → reflection. The Construction Strand simultaneously externalizes, restructures, and internalizes core disciplinary concepts via visual, hierarchical knowledge graphs. Within the flow of a lesson, the two strands alternately dominate and scaffold each other, securing the co-development of conceptual understanding, procedural fluency, and mathematical literacy. Empirical evidence demonstrates that this model significantly enhances students' systematic knowledge integration, problem-solving transfer ability, and core mathematical competencies, offering a replicable and operable teaching paradigm and practical pathway for deepening high school mathematics classroom reform.

Keywords: Knowledge graph; Inquiry-construction; Teaching model; High school mathematics

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1. Introduction

The application of knowledge graphs in education is gradually shifting from resource organization toward enhancing instructional processes. At the technical level, researchers are exploring how knowledge graphs can optimize learning paths and cognitive processes. Chen *et al.* [1] proposed dynamically modeling learners' cognitive states using knowledge graphs and generating personalized learning paths through deep reinforcement learning. The Knewton team [2] integrated knowledge graphs with item response theory to develop an adaptive recommendation system that links concepts, test items, and learning behaviors. The Chinese research community has also made significant progress in this area. For example, the Tsinghua University Basic Education Knowledge Graph Project [3] and the CN-DBpedia Project [4] provide foundational support for the systematic organization and precise retrieval of educational resources.

Notably, research is expanding from static knowledge bases to dynamic interactive tools. Zhao *et al.* [5] attempted to embed knowledge graphs into teaching workflows, but their functions remain primarily focused on assisting lesson preparation and diagnosing learning conditions, not yet fully developed into cognitive tools supporting teacher-student co-creation in the classroom. In recent years, some studies have begun exploring the direct use of knowledge graphs for inquiry and construction processes within classrooms. For example, Wang and Liu [6], through high school mathematics case studies, preliminarily verified the potential of knowledge graphs in supporting students' conceptual connections and problem inquiry, providing useful references for deep integration at the classroom level.

Overall, existing research often positions knowledge graphs as "background technology" for optimizing resource allocation and path recommendation. However, it has yet to systematically address a key instructional question: within the "inquiry-construction" classroom process, how can knowledge graphs be utilized in real-time by teachers and students, dynamically evolved, and continuously optimized to deepen the cognitive interaction of teaching and learning?

At the level of teaching methodology, the integration of inquiry-based and constructivist teaching has become an important trend. Bybee *et al.* [7] proposed the 5E instructional model comprising five phases: Engagement, Exploration, Explanation, Elaboration, and Evaluation. Schoenfeld [8] advocated for a "doing mathematics" practical framework centered around "conjecturing, representing, justifying, and reflecting," emphasizing students' active construction of knowledge meaning within complete cognitive processes. In China, under the background of the new curriculum standards, there is an active promotion of the integration of contextualized teaching and collaborative inquiry. However, in practice, further exploration is still needed regarding how to balance the openness of inquiry with the systematicity of knowledge, and the authenticity of situations with the depth of concepts [9,10].

A key challenge in current teaching practice is the certain disconnection between inquiry activities and knowledge construction: the inquiry process can easily deviate from objectives due to a lack of conceptual anchors, while the construction process often struggles to deepen due to the absence of authentic problem drives. Therefore, it is necessary to construct a mechanistic teaching framework that enables inquiry and construction to alternately support and synergistically evolve like a double helix, achieving the organic integration of the teaching process.

2. Research content, objectives, and problems

2.1. Research content

Serving as the foundational framework for this study, the high school mathematics knowledge graph is constructed with emphasis on scientific rigor, pedagogical relevance, structural coherence, and interactive capacity. Moving beyond verifying the disciplinary accuracy of concepts, theorems, and formulas, this research delineates their multidimensional connections within instructional logic: vertically, concepts advance through progressively challenging cognitive levels; horizontally, knowledge points maintain translatability across different modules; externally, mathematics establishes application links with real-world contexts such as physics and economics. The resulting dynamic network—simultaneously hierarchical and interconnected—provides teachers and students with a navigable "cognitive map" that supports zooming, panning, and rotational views, thereby establishing a solid foundation for transforming classroom engagement.

The "Inquiry-Construction Double-Helix" teaching model employs the DNA structure as its central metaphor, dividing the learning process into two complementary strands: the "Inquiry Strand," connecting the phases of question, conjecture, verification, and conclusion; and the "Construction Strand," progressing through association, integration, systematization, and internalization. Functioning like molecular base pairs, the knowledge graph bridges these strands by dynamically translating inquiry outcomes into structured disciplinary knowledge while simultaneously transforming its abstract frameworks into launching points for further investigation. This interaction generates a self-reinforcing cycle: inquiry initiates construction, which then raises deeper questions, and collaboratively developed solutions are continuously incorporated into the knowledge graph, enabling organic expansion of the knowledge network. This integrated process effectively addresses the dual challenges of superficial inquiry and fragmented knowledge.

To operationalize the Double-Helix teaching model, this paper designs a "Four-Phase, Six-Step" classroom procedure. The four instructional phases are:

Phase I: Pre-class anchoring and perception

Phase II: In-class exploration and discovery

Phase III: In-class construction and integration

Phase IV: Post-class transfer and innovation

The six instructional steps are distributed across these phases:

(1) Scenario anchoring (Phase I): The teacher creates authentic scenarios based on the knowledge graph and releases guided tasks, allowing students to gain an initial perception of the core issues and knowledge background.

(2) Problem focusing (Phase II): Through teacher-student interaction, the core problems to be investigated are jointly identified, clarified, and precisely located on the knowledge graph.

(3) Collaborative inquiry (Phase II): In small groups, students engage in deep exploration activities—such as conjecturing, reasoning, and verification—relying on the associative pathways suggested by the knowledge graph.

(4) Systematic modeling (Phase III): The teacher facilitates whole-class discussion, analysis, and integration of fragmented inquiry findings, guiding students to systematically structure new knowledge within the framework of the knowledge graph, forming a sound cognitive network.

(5) Transfer application (Phase IV): Students apply the newly constructed knowledge system and the knowledge graph tool to solve novel, more complex situational problems, achieving far transfer of knowledge.

(6) Reflection and optimization (Phase IV): Students are guided to compare their own thinking paths with the systematic structure of the knowledge graph, engaging in metacognitive reflection to optimize their cognitive strategies and learning methods.

Following the Double-Helix model, a quasi-experimental study was conducted over one semester with established experimental and control classes across two high schools. The research employed a comprehensive multi-source data collection approach, incorporating concept map analysis, open-ended tasks, academic achievement measures, classroom observations, student interviews, and platform log data. This methodology enabled simultaneous assessment of knowledge systematization, inquiry capabilities, and affective attitudes.

Cross-validation through mixed methods revealed that experimental class students demonstrated not only significantly enhanced comprehensive problem-solving abilities but also more networked and self-regulated learning pathways. Utilizing the knowledge graph, teachers effectively identified students' "conceptual breakpoints" and implemented targeted differentiated instruction. Consequently, this study provides both a replicable implementation framework and compelling empirical evidence supporting the efficacy of the "Inquiry-Construction Double-Helix" teaching model.

2.2. Research objectives

This study aims to achieve a triple objective—theoretical innovation, practical leadership, and empirical support—through the construction, practical testing, and effective dissemination of the "Knowledge Graph-Driven Inquiry-Construction Double-Helix Teaching Model for High School Mathematics."

In theoretical construction, it seeks to break away from the limitations of traditional teaching, where inquiry and construction are often disconnected. By elucidating the core driving role of the knowledge graph as the "cognitive foundation" and the internal mechanism enabling the synergistic ascent of the double helix—comprising the "question-conjecture-verification-conclusion" inquiry strand and the "association-integration-systematization-internalization" construction strand, the study aims to establish a mature teaching model that is theoretically sound, rigorously structured, and practically operable.

In practical application, the goal is to translate the theoretical model into replicable practical outcomes. This involves developing a series of exemplary teaching cases, supporting learning resources, and teacher guidance materials covering core high school mathematics content (e.g., Functions, Analytic Geometry). These resources will form demonstrative practice packages, providing direct references for frontline teaching.

In validation and dissemination, through rigorous teaching experiments and multi-faceted evaluation, the study intends to scientifically verify the model's effectiveness in enhancing students' knowledge systematization, mathematical inquiry capabilities, and core mathematical literacy. Building on this, it will systematically summarize the key implementation strategies, applicable conditions, and potential challenges of the model, forming valuable practical reflections. Ultimately, this will provide a comprehensive, empirically validated, and scalable solution for deepening high school mathematics classroom reform.

2.3. Key problems to be addressed

To ensure the "Knowledge Graph-Driven High School Mathematics Inquiry-Construction Double-Helix Teaching Model" possesses both theoretical foresight and practical feasibility, this study is committed to addressing core challenges at three levels.

At the technical tool level, the problem is how to transcend the current limitation of knowledge graphs, often serving as static repositories. The focus is on designing and constructing a mathematics knowledge graph that is genuinely suitable for the dynamic needs of high school classroom teaching. The core challenge lies in ensuring this graph not only accurately represents the structured relationships of disciplinary knowledge but also possesses strong interactivity, capable of responding to real-time queries and path exploration by teachers and students, thereby becoming a "live" cognitive tool that drives student inquiry and supports knowledge construction.

At the instructional process level, the key issue is to reveal the micro-level interaction mechanism between the "Inquiry Strand" and the "Construction Strand" in teaching practice. This requires clearly explaining how these two strands specifically alternate dominance and act as mutual causes and effects within the classroom context. Specifically, it involves clarifying how inquiry activities provide fresh material for knowledge construction, and how systematic knowledge construction, in turn, offers a framework for subsequent inquiries and enhances their quality of thinking, thereby forming a synergistically ascending spiral progression path.

At the effectiveness evaluation level, traditional assessment methods are inadequate for capturing the deep learning and systems thinking advocated by this model. Therefore, it is essential to design and implement a matching multi-faceted teaching evaluation system. This system must be capable of scientifically measuring students' value-added outcomes in areas such as the integrity of knowledge network construction, the transfer ability in complex problem-solving, and the comprehension level of mathematical thinking methods, thereby providing solid and reliable empirical evidence for the model's effectiveness.

3. Reform program design and problem-solving approaches

The central objective of this reform initiative is to develop and implement a "Knowledge Graph-Driven High School Mathematics Inquiry-Construction Double-Helix Teaching Model." Structured around the "Inquiry-Construction" double-helix interaction and powered by the knowledge graph as its cognitive foundation, this systematically designed paradigm aims to develop students' core mathematical competencies while addressing the persistent divide between knowledge acquisition and competency development.

3.1. Overall model architecture: Constructing the "Double-Helix" teaching model

Guided by the "Double-Helix" as its core theoretical metaphor, this model's architecture features a rigorously structured framework with tightly interconnected components. At its heart lies the continuous development of students' core mathematical literacy, serving as the central axis around which two primary strands spiral upward in synergistic progression. The Inquiry Strand advances through the sequence of "Question → Conjecture → Investigation → Conclusion," emphasizing knowledge generation through active exploration. Simultaneously, the Construction Strand progresses through "Association → Integration → Systematization → Internalization," focusing on the structural processing and cognitive integration of knowledge. Bridging these strands, the knowledge points and their associative networks within the knowledge graph function as connecting rungs—much like the base pairs in DNA—providing both the foundational basis for inquiry and the structural framework for construction at each instructional node. This integrated system operates within a supportive environment orchestrated by the teacher (as facilitator and designer) and enabled by information technology platforms, collectively forming a dynamic, symbiotic teaching ecosystem.

3.2. Solutions and pathways for core problems

In knowledge graph construction, a collaborative development path of "expert leadership, teacher participation, and technical implementation" is adopted, committed to creating an interactive cognitive tool truly suitable for teaching scenarios. Based on the curriculum standards and textbooks as the fundamental framework, it deeply integrates implicit knowledge dimensions like mathematical thinking methods. Utilizing graph database technology, a dynamic knowledge system possessing both visualization and reasoning capabilities is constructed. This knowledge graph, by establishing multi-level associative networks for nodes such as "Function," "Equation," "Inequality," and "Graph," provides a structured navigational scaffold for teachers and students to conduct inquiry activities and knowledge construction, transforming static knowledge resources into a cognitive tool that supports deep thinking.

In classroom teaching implementation, to solve the problem of the integration mechanism between inquiry and construction, a complete "Four-Phase, Six-Step" teaching procedure is designed. This procedure begins with the pre-class "Anchoring and Perception" phase, where the teacher creates learning scenarios based on the knowledge graph to activate students' prior knowledge. Entering the in-class "Exploration and Discovery" phase, students rely on paths suggested by the graph to conduct independent or collaborative inquiry, experiencing the complete process of conjecture and verification. Subsequently, in the "Construction and Integration" phase, the teacher guides students to deeply discuss and analyze the inquiry findings, achieving systematic organization of knowledge within the framework of the knowledge graph. Finally, through the post-class "Transfer and Innovation" phase, students apply the newly constructed knowledge and the graph tool to solve novel situational problems, completing the internalization and transfer of knowledge. This procedure clearly demonstrates the alternating presentation and spiral ascent of inquiry activities and knowledge construction across the various teaching stages.

Regarding the construction of the teaching evaluation system, a mixed-methods approach is adopted to comprehensively assess the model's effectiveness in promoting deep learning and systems thinking. Quantitative evaluation involves collecting data through pre- and post-test score comparisons, along with questionnaires measuring inquiry skills and systems thinking. Qualitative evaluation comprehensively utilizes methods such as inquiry report analysis, mind map assessment, and in-depth student interviews. Particularly crucial is leveraging the technological platform to record and analyze students' learning paths within the knowledge graph. This process data provides direct and reliable evidence for evaluating students' thinking trajectories and the level of their knowledge network construction.

This reform plan, encompassing the theoretical model, tool development, process implementation, and evaluation feedback, forms a closed-loop, operable teaching practice system. It provides comprehensive assurance for the model's effective implementation and outcome validation.

4. Innovation and feasibility analysis of teaching reform

4.1. Innovation of teaching reform

The principal innovation of this teaching reform resides in its systematic reimagination across theoretical, methodological, and practical domains, establishing an integrated pedagogical system that leverages technology to empower thinking and embeds mechanisms to ensure depth.

Theoretical innovation: Introducing the "Inquiry-Construction Double-Helix" as a central metaphor reconceptualizes the dynamic interplay between teaching and learning. This model transcends conventional linear instruction by framing inquiry and knowledge construction as an organic, interdependent system characterized by mutual reinforcement and synergistic development. Within this architecture, the inquiry process serves as the "engine" of knowledge construction, perpetually generating authentic experiential input, while the construction process functions as a "navigational system," supplying conceptual frameworks and cognitive tools that guide inquiry. This structured yet dynamic theoretical lens not only offers a new paradigm for understanding deep learning mechanisms but also reorients instructional design from mere "process orchestration" toward the intentional "cultivation of a cognitive ecosystem."

Methodological innovation: The knowledge graph evolves from a "static knowledge repository" into a "dynamic cognitive engine." It transforms from a passive content carrier into an active cognitive instrument for deep engagement. Functioning as an architectural framework, it simultaneously externalizes the discipline's essential structure—making mathematical concepts visually accessible—while its interactive and inferential capabilities enable real-time responsiveness to student inquiry, thereby dynamically scaffolding the knowledge construction process. This reconception fosters a new pedagogical paradigm of "technology-facilitated deep thinking," fundamentally aligning digital tools with the development of students' higher-order cognitive capacities.

Practical innovation: At the implementation level, the "Four-Phase, Six-Step" instructional procedure translates the double helix principle into an actionable roadmap—guiding educators through Anchoring and Perception, Exploration and Discovery, Construction and Integration, and Transfer and Creation—effectively providing a practical "implementation blueprint." Complementing this, the novel application of knowledge graph-based learning analytics renders implicit cognitive processes visible and measurable by tracking and interpreting students' navigation patterns and conceptual associations within the graph. This process-focused assessment approach, working in concert with traditional outcome-based evaluation, yields more scientific and precise measurement of teaching efficacy, thereby ensuring the model's operational viability, assessability, and potential for scalable adoption.

4.2. Feasibility analysis

Grounded in established educational theories, this initiative draws on constructivist principles for its "Construction Strand" and inquiry-based learning models for its "Inquiry Strand." The "Double-Helix" framework represents both a systematic integration and innovative extension of these foundations, ensuring theoretical soundness while advancing pedagogical design.

Technically, the model leverages increasingly accessible knowledge graph technologies. Mature open-source tools and visualization libraries have substantially reduced implementation barriers, while improved school infrastructure under national digitalization initiatives provides the necessary operational environment.

For implementation, a phased strategy ensures manageable adoption. Initial pilots in selected classrooms or units will generate refined exemplars and develop teacher expertise. This is supported by comprehensive professional development, detailed teaching resources, and reusable knowledge graph components—creating a sustainable "strategy-resources-training" ecosystem that enables effective scaling while maintaining quality.

5. Conclusion

This study addresses enduring challenges in high school mathematics—such as knowledge fragmentation, superficial inquiry, and the disconnection between knowledge and skill development—by proposing a knowledge graph-driven "Inquiry-Construction Double-Helix" teaching model. Repositioning the knowledge graph as a dynamic cognitive engine, the model establishes a "technology-empowered deep thinking" paradigm, where interactive knowledge structures support systematic inquiry and knowledge construction. Through a well-defined "Four-Phase, Six-Step" instructional procedure and learning-path analytics, the approach visualizes and measures deep learning processes. By integrating theoretical innovation with practical implementation, it not only bridges the gap between inquiry and construction but also demonstrates significant effectiveness in fostering knowledge systematization and higher-order thinking. The research offers a scalable, replicable framework that contributes to intelligent and competency-focused reform in mathematics education.

Disclosure statement

The authors declare no conflict of interest.

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