
AI translation · View original & related papers at
chinaxiv.org/items/chinaxiv-202604.00170

Paradigm Reconstruction of University Physics Experiment Teaching from the Perspective of Cognitive Science (III): Teaching Practice and Paradigm Revolution

Authors: Luo Chenglin, Li Youzhen, Sun Xiliang, Zheng Xiaojuan, Deming Kong, Fuxin Xu, Luo Chenglin, Deming Kong

Date: 2026-04-11T20:03:57+00:00

Abstract

As the closed loop of this series of studies, this paper aims to verify the effectiveness of the concepts and systems constructed in the previous sections through pedagogical empirical research, and thereby position its significance in terms of paradigm innovation. The study first designed a teaching model centered on the main line of “anchoring cognitive limitations → exploring methodological strategies → supporting knowledge generation,” and provided a representative lesson plan. A quasi-experimental study involving 535 students found that the experimental group adopting the new system significantly outperformed the traditional teaching group in core dimensions such as “experimental methodological thinking awareness” and “transfer application awareness.” After verifying the empirical effects, this paper elucidates, through a systematic comparative analysis of paradigms, that the work in this series achieves a profound transformation from a “knowledge verification paradigm” to a “cognitive development paradigm.” Its fundamental transition lies in shifting the starting point of instructional design from external knowledge structures to the learner’s internal cognitive development process. This study ultimately completes a comprehensive demonstration of “concept-system-practice-evidence,” providing an empirically tested physics laboratory course solution for cultivating irreplaceable innovative capabilities in the era of artificial intelligence.

Full Text

Preamble

Paradigm Reconstruction of University Physics Experiment Teaching from the Perspective of Cognitive Science (III): Teaching Practice and Paradigm Innovation

Luo Chenglin, Li Youzhen, Sun Xiliang, Zheng Xiaojuan, Kong Deming, Xu Fuxin (School of Physics, Central South University, Changsha 410083, Hunan Province)

摘要

As the concluding part of this research series, this paper aims to verify the effectiveness of the previously constructed concepts and frameworks through pedagogical empirical research and to define its significance in terms of paradigmatic innovation. The study first designs a teaching model centered on the progression of “anchoring cognitive limitations → exploring methodological strategies → supporting knowledge generation,” providing a representative lesson plan as a reference.

A quasi-experimental study involving 535 students was conducted. The results indicate that the experimental group, which utilized the new system, performed significantly better than the traditional teaching group in core dimensions such as “experimental methodological thinking” and “transfer application awareness.” Following the verification of these empirical effects, this paper employs a systematic comparative analysis of paradigms to clarify that the work presented in this series achieves a profound transformation from a “knowledge verification paradigm” to a “cognitive development paradigm.”

The fundamental shift lies in moving the starting point of instructional design from external knowledge structures to the internal cognitive development process of the learner. This research ultimately completes a comprehensive demonstration spanning “concept-system-practical evidence,” providing an empirically tested solution for physics laboratory courses designed to cultivate irreplaceable innovative capabilities in the era of artificial intelligence.

关键词

Abstract

The PMT (Perception-Manipulation-Thought) framework; Instructional design; Innovation capability; Integrated education; PBL teaching; Artificial Intelligence. CLC Number: G642

1. Introduction

With the rapid advancement of Artificial Intelligence (AI) and robotics, the demand for interdisciplinary talents possessing both theoretical depth and practical innovation capabilities has become increasingly urgent. Traditional pedagogical models often struggle to bridge the gap between abstract conceptual perception, hands-on technical manipulation, and high-level critical thinking. To address these challenges, this paper proposes the PMT (Perception-Manipulation-Thought) framework as a structured approach to instructional design. By integrating Project-Based Learning (PBL) with a focus on innovation-driven integrated education, the PMT system aims to cultivate a comprehensive skill set in students, enabling them to navigate the complexities of modern technological landscapes.

2. The PMT Framework: Perception, Manipulation, and Thought

The PMT framework is designed as a holistic educational architecture that synchronizes three critical dimensions of learning:

2.1 Perception (P)

Perception serves as the foundational layer, focusing on how students acquire and interpret information from their environment and theoretical domains. In the context of AI and robotics, this involves understanding sensor data, recognizing patterns, and grasping fundamental scientific principles. The goal is to move beyond passive reception toward an active, multi-sensory engagement with the subject matter.

2.2 Manipulation (M)

Manipulation represents the transition from theory to practice. This dimension emphasizes the development of technical proficiency, including programming, hardware assembly, and system integration. By engaging in “learning by doing,” students internalize abstract concepts through the physical or digital manipulation of tools and systems, fostering a robust technical intuition.

2.3 Thought (T)

Thought constitutes the highest level of the framework, encompassing critical thinking, algorithmic logic, and creative problem-solving. It requires students to reflect on their perceptions and manipulations to derive new insights, optimize existing systems, and innovate original solutions. This stage is crucial for transforming technical laborers into visionary innovators.

3. Instructional Design and PBL Integration

The implementation of the PMT framework is best realized through Project-Based Learning (PBL). Unlike traditional lecture-based methods, PBL provides a natural vehicle for the PMT cycle to flourish.

[Figure 1: see original paper]

In a PMT-based PBL environment, students are presented with real-world challenges that require

Paradigm Reconstruction of University Physics Experiment Teaching from the Perspective of Cognitive Science (3): Teaching Practice and Paradigm Innovation LUO Chenglin, Li Youzhen, Sun Xiliang, Zheng Xiaojuan, Kong Deming, Xu Fuxing (School of Physics, Central South University, Changsha, Hunan 410083, China)

Abstract

As the concluding part of the series, this paper aims to empirically validate the effectiveness of the previously proposed concept and system, and thereby establish its paradigm-innovation significance. A teaching model following the thread of “identifying cognitive limitations → exploring method strategies → constructing knowledge support” was first designed, with a typical lesson plan provided. A quasi-experimental study involving 535 students then revealed that the experimental group using the new system significantly outperformed the control group on core dimensions such as “awareness of experimental methods” and “awareness of transfer application.” After confirming the empirical effects, a systematic paradigm comparison was conducted, demonstrating that the series accomplishes a profound shift from a “knowledge-verification paradigm” to a “cognitive-development paradigm.” The fundamental transition lies in moving the starting point of instructional design from external knowledge structures to the learner’s internal cognitive-development process. This study thus completes the full “concept-system-practice-evidence” argument, offering an empirically tested solution for physics experiment courses aimed at cultivating irreplaceable innovative ability in the age of artificial intelligence.

Keywords

PMT (Perception-Manipulation-Thinking) Framework; Instructional Design; Innovation Ability; Articulation Education; Problem-Based Learning (PBL); Artificial Intelligence

As the concluding work of this research series, this paper aims to address a core question: Do the “cognitive breakthrough” concept established in the first paper [?] and the PMT content system developed in the second paper [?] possess the expected educational efficacy within authentic teaching contexts?

This inquiry constitutes the necessary closed loop transitioning from theoretical construction to practical validation. Accordingly, this study designed and implemented a quasi-experimental research project to test the pedagogical effectiveness of the PMT system. We first developed a teaching model centered on the progression of “anchoring cognitive limitations → exploring methodological strategies → knowledge support and generation.” Using the Millikan oil drop experiment as a case study, we demonstrate the distinctions between this approach and conventional instruction. Through a comparative pedagogical experiment involving 535 students, the teaching effectiveness of the new system was evaluated across three dimensions: learning interest, methodological and strategic awareness, and transfer application awareness. Building upon these results, this paper employs a systematic paradigmatic comparative analysis to position this series of work within the evolutionary context of four experimental teaching paradigms. Ultimately, we elucidate its fundamental transition from a “knowledge verification paradigm” toward a “cognitive development paradigm.”

1 Research Design: Teaching Model and Empirical Scheme Based on the PMT System

1.1 教学模式设计：以密立根油滴实验为例

This study conducted an empirical analysis of the teaching effectiveness of physics experiments based on the PMT system. A total of 22 teaching classes and 535 students were included, of which 11 classes (270 students) served as the control group using traditional teaching methods, and 11 classes (265 students) served as the experimental group using the PMT system framework for instruction.

Taking the Millikan oil drop experiment as an example, the teaching for the control group followed conventional steps: (1) defining the core objective as measuring the elementary charge; (2) explaining the experimental principles by analyzing the forces and motion of oil drops between two plates to derive the formula for calculating charge; (3) introducing the instrument structure and operational procedures; and (4) guiding students to use the greatest common divisor method to process charge data and obtain the electron charge value. In contrast, the experimental group used the PMT system as a guide to restructure the teaching logic: (1) Anchoring the problem to stimulate interest: Teachers and students jointly analyzed the problem, pointing out that measuring the electron charge is essentially an “observation of microscopic quantities,” a universal challenge in subsequent studies and scientific research. Redefining the core objective as “exploring a new method for measuring microscopic quantities” gave the experiment significant broader meaning. (2) Strategy design to present an overall problem-solving framework: By reviewing existing measurement methods for microscopic quantities (such as amplification and superposition), and using the case of measuring paper thickness via superposition, students were inspired to understand the design logic behind oil charging (superposition) and

the greatest common divisor method, thereby determining the overall problem-solving strategy. (3) Solving the precision measurement problem: Discussing how to accurately measure the charge of an oil drop led to the design scheme of using equilibrium states (the equilibrium method) and the correction of Stokes' Law. (4) Addressing the interval control problem to analyze operational principles: Explaining the principle of controlling oil drop motion by manipulating the voltage between the plates (the field control method). (5) Summary and transfer: Systematically reviewing the solutions for each stage, introducing other strategies for similar problems, and encouraging students to design alternative experimental schemes and transfer the learned methods to new contexts.

Compared with the control group, the teaching in the experimental group abstracted general methods from the case of measuring paper thickness via superposition. This provided a holistic conceptual framework for the experiment and resolved a long-standing question in Millikan oil drop experiment pedagogy: How did Millikan think of using oil drops for the experiment in the first place? This question is often neglected in conventional teaching that emphasizes operation, but it is a fundamental and unavoidable issue in teaching that prioritizes design and innovation.

However, this only reflects the PMT system's capacity for analyzing experimental content. Its deeper value lies in the fact that, by restructuring teaching logic, it deeply resonates with the "4C" teaching model proposed by Zhong Baichang et al., which aims to cultivate students' innovative abilities [?]. The 4C model reveals a four-stage cognitive path for innovation cultivation: Clustering (starting with specific problems), Conceptual Extraction (generalizing essential laws), Relational Internalization (establishing cognitive structures), and Transfer/Innovation (achieving far transfer). Examining the Millikan oil drop experiment under the guidance of the PMT system: (1) "Anchoring the problem" corresponds to "Clustering" in 4C theory—placing the electron charge measurement experiment within a universal category of "microscopic quantity observation" problems, alongside measuring paper thickness and microscopic deformation.

- (2) Strategy design reveals the essence of the superposition method and the greatest common divisor method, corresponding to "Conceptual Extraction." The superposition method involves stacking microscopic objects to solve the problem of measurement tools lacking sufficient sensitivity for tiny physical quantities. From this, one can further understand that the greatest common divisor method and the general superposition method for calculating averages are essentially both methods of "calculating components from a total after superimposing equal elements." (3) Introducing other strategies for similar problems during the experimental review—such as the amplification and transformation methods for measuring microscopic quantities—corresponds to "Relational Internalization" in 4C theory. This allows students to build a knowledge and methodological network for measuring microscopic quantities. In fact, the multiple steps

of the experiment and the experimental problems corresponding to each step can be mapped to fourteen categories of cognitive limitation problems—for example, the step of measuring oil drop charge corresponds to the “precision measurement problem,” while controlling oil drop motion corresponds to the “interval control” problem.

During the experiment, students gradually establish a broad and clear cognitive network framed by the PMT system. (4) “Summary and Transfer” directly corresponds to “Transfer and Innovation” in 4C theory—encouraging and training students to apply the learned methods to new situations.

It is evident that the PMT system not only provides a classification framework for experimental content but also possesses a spiritual core based on the authentic cognitive development of physical experiments and scientific research. This allows it to naturally realize the cultivation of innovative abilities as revealed by the 4C model within the instructional process.

1.2 教学效果实证：基于 535 名学生的准实验研究

Numerous indicators exist for evaluating the effectiveness of teaching models [?, ?]. Based on the fundamental philosophy and core objectives of the PMT (Physical Method-Thinking) system, this study simplifies these complexities by focusing on three core dimensions: learning interest and sense of achievement, experimental methods and thinking awareness, and transfer application awareness. The rationale for selecting these three indicators is as follows: (1) Interest is the best teacher; it serves as both a critical condition for ensuring learning effectiveness and a result of the learning process itself [?]. The sense of achievement represents the learner’s intuitive perception of their own learning outcomes. Together, these two elements constitute the emotional dimension for measuring teaching effectiveness. (2) The core pedagogical goal of the PMT system is to resolve the deep-seated dilemma in current curricula where “knowledge is explicit while methods remain implicit” [?], thereby shifting student attention from isolated knowledge points to methodological thinking. Consequently, awareness of methods and thinking necessarily becomes a core indicator of teaching effectiveness, reflecting shifts in the students’ rational cognitive level. (3) According to the innovation capability cultivation theory proposed by Zhong Baichang et al., transfer ability is a key indicator for measuring the effectiveness of innovation cultivation in teaching [?]. Since the PMT system identifies the cultivation of student innovation capability as its core objective, transfer application awareness must be included as a primary indicator.

The “Experimental Summary” section of student laboratory reports served as the text for analysis. As these summaries are written freely by students, they authentically reflect their psychological states, learning gains, and cognitive focus, thereby avoiding the interference of leading questions often found in questionnaires. Without providing any prompts, we calculated the number of students who mentioned content related to the three core indicators. The quantitative

metric used was the percentage of students in each group who mentioned each category. The statistical results are shown in [Figure 1: see original paper].

Interest and Sense of Achievement

Methods and Thinking

Regarding interest and the sense of achievement, approximately 20% of the students in the control group reported gaining something from the course, which is consistent with routine observations. In contrast, this figure reached approximately 50% in the experimental group. Many students explicitly expressed a newfound appreciation for the value of physics experiments, indicating a significant enhancement in their learning experience.

In terms of experimental methods and thinking awareness, only about 10% of the students in the control group mentioned experimental methods; the majority remained focused on specific knowledge points contained within the experiments rather than the underlying methodology. In the experimental group, this figure approached 70%, showing a clear shift in attention toward the methodological level and cognitive processes.

Regarding transfer application awareness, fewer than 5% of the students in the control group could associate the material with potential applications in other fields, and their descriptions were relatively vague (e.g., noting that experiments require care or that data processing must be rigorous). In the experimental group, nearly 50% of the students were able to consciously extrapolate experimental methods to different disciplines or practical problems.

The aforementioned data indicate that instructional design based on the classification system of cognitive capacity limitations can effectively guide students to focus on experimental methods, strengthen cognitive training, and enhance learning motivation and transfer capabilities.

1.3 成效归因分析：PMT 体系何以提升教学效果

This system is easily understood and accepted by both teachers and students, significantly enhancing teaching effectiveness due to the following three reasons. First, the experimental philosophy based on cognitive science is intuitive and stimulates learning interest. The concept of cognitive limitations is directly related to human perception and thinking experiences, requiring no specialized professional knowledge of cognitive science from teachers or students; for instance, expressions such as “the limited resolution of the human eye” align with common sense, making them easy to understand and relate to. Furthermore, university students generally focus on the relevance of experimental courses to their majors and future development. Traditional experimental teaching, organized around knowledge points, often creates distinct disciplinary boundaries that lead students to feel a disconnect between physics experiments and their own fields—for example, electronics students often struggle to understand the

necessity of fluid mechanics experiments. In contrast, this system uses the breakthrough of cognitive limitations as its main thread, highlighting the universal value of experiments in methodological training and mindset shaping. This allows students to intuitively see how physics experiments provide common support for solving various professional problems, thereby effectively stimulating their interest in learning.

Second, by adopting “Problem-Method-Knowledge” as the logical thread, the system provides experimental teaching with an inherent “soul.” When organizing teaching according to this philosophy, the limitations involved in the experimental project are explained first, followed by a clear description of the experimental methods. Specific experimental projects are then used to demonstrate the process of applying these methods to solve concrete experimental problems. Consequently, the teaching unfolds clearly around the sequence of “cognitive limitation problem -solution method -physical knowledge support and discovery.” Students no longer experience a fragmented collection of knowledge points and operational steps, but rather a complete problem-solving process. This process naturally and vividly restores the basic logic of scientific exploration, where methods and knowledge are deeply integrated within the context of problem-solving. The tight integration of experimental problems and methods gives the latter a clear direction for application, highlighting their connotation and value while providing a live demonstration of how to flexibly apply relevant knowledge. It also clarifies the origin and development of new knowledge. As a result, students acquire “living” methods and knowledge, naturally shifting their focus from mere rote memorization to the comprehension and transfer of methodology and thinking.

Third, the strong transferability and openness of the system directly support the development of innovation capabilities. By classifying experiments according to the cognitive problems they solve, this system blurs disciplinary boundaries and emphasizes the cross-domain versatility of methods.

Once experimental projects are categorized by cognitive problems, they are primarily distinguished into foundational and comprehensive types. There is no need for a separate “design and innovation experiment” category because the teaching of every experiment serves as a demonstration of multiple solution strategies for a specific problem, inherently containing training in innovative thinking. During their studies, students both accumulate strategies for various types of problems and witness multiple solution paths for the same problem, thereby establishing a cognitive mapping between “problems” and “method sets.” This structure not only stimulates interest in innovative exploration by showcasing the diversity of solution paths but also helps students rapidly invoke relevant methods across different fields in the future. This structured “problem-method” mapping allows innovative activities to shift from relying on individual inspiration to systematic exploration that follows recognizable patterns and can be advanced collaboratively, thus lowering the threshold for innovation and improving its quality.

The three attributions of teaching effectiveness mentioned above precisely corroborate the mechanisms for cultivating innovation capabilities revealed by Zhong Baichang et al. Their research points out that the contradiction between “narrow caliber” and “high requirements” in conventional education stems from neglecting conceptual extraction and thinking training [?]. Through the logical thread of “Problem-Method-Knowledge,” the PMT system places “conceptual extraction” and “thinking training” at the core of teaching. Its “strong transferability” directly responds to the 4C model’s identification of “transferable innovation” as the ultimate goal of innovation capability cultivation.

2 范式比较：从知识传递到认知发展的演进路径

To clearly demonstrate the fundamental breakthroughs of the PMT system relative to traditional paradigms, we present a paradigmatic positioning analysis across eight core dimensions, comparing it with common physics laboratory curricula [?] (Table 1):

System A: Subject Knowledge-Oriented

System B: Knowledge + Methodological Topics

System C: Competency-Layered

PMT System: Cognitive Problem-Methodology Framework

Physics theoretical system; Objectivist epistemology.

Physics theory + Preliminary scientific methodology; remains knowledge-centered.

Educational psychology (Competency Stage Theory); Constructivist learning theory.

Cognitive science (Primacy of cognitive ability); Constructivism and problem-solving.

Verification and subordination of theory; serves to understand and consolidate theoretical knowledge points. Focuses on training students in knowledge comprehension, instrument operation, and basic data processing skills.

Dual carrier of theory and method; attempts to balance knowledge verification with methodological awareness.

A training ground for competencies; fosters students’ comprehensive practical abilities and preliminary innovation through progressive tasks.

A strategy and achievement repository for breaking cognitive boundaries; aims to systematically train cognitive abilities and cultivate underlying scientific thinking and transferable creative skills.

Parallel modules with clear boundaries: divided by branches of physics (mechanics, electromagnetism, thermodynamics, modern physics, etc.).

Patchwork structure: adds an independent “Experimental Methods” introductory module onto the foundation of System A.

Pyramidal structure: layered by experimental complexity and competency progression (Basic - Comprehensive - Design - Innovative).

Tree-like or parallel structure with clear boundaries: divided according to the specific cognitive limitation problems that need to be resolved.

Experimental Methods and Knowledge Integration

Knowledge is the starting point and end goal of the experiment; methods are implicit and scattered, left for students to discern on their own.

Knowledge remains the primary content; methods are explicit but isolated, with weak links to knowledge, leading to students knowing the methods but being unable to apply them.

Knowledge serves as a tool for completing tasks at various levels; methods lack systematic organization and are largely summarized by students themselves.

Methods are explicit and systematic, corresponding directly to cognitive problems; knowledge supports problem-solving and serves as the medium for cognitive breakthroughs.

Instructional Logic

From known theory to experimental verification.

A logic of merging knowledge and method, though the relationship between the two is often superficial.

Overall progression based on task difficulty; specific teaching often reverts to the logic of System A.

A logic of problem-solving and knowledge construction following the sequence: “Cognitive Limitation - Experimental Problem - Experimental Method - Related Knowledge.”

Teacher-Student Roles

Teacher: Authoritative lecturer; Student: Passive verifier. The process is fixed, emphasizing imitation and replication.

Teacher: Lecturer of knowledge and methods; Student: Learner. Methodological learning often becomes decoupled from experimental application.

Teacher: Project coach; Student: Gradually autonomous practitioner. Autonomy increases in higher-level tasks.

Teacher: Cognitive coach and problem guide; Student: Active problem-solver and cognitive pioneer.

Strong disciplinary systematicity; aligns closely with theoretical courses; easy to implement.

Awakens methodological awareness beyond mere knowledge transmission.

Aligns with the intuition of competency growth; higher-level stages can stimulate student initiative.

Targets the source of ability; possesses strong logical cohesion and high transferability; truly achieves the goal of “teaching one how to fish.”

Prone to the separation of knowing and doing; suppresses inquiry instincts; weak in thinking training; difficult to cultivate innovative capacity. Disciplinary boundaries are rigid, resulting in weak transferability and poor links between basic and professional courses.

Similar to System A; even with methodological chapters, it easily falls into “abstract talk,” where theory and method become “two separate skins,” and students still lack the flexibility to apply them.

Basic experiments may still be confined to the old paradigms of Systems A and B; competency layering lacks a unified internal cognitive thread.

At the current stage, it requires a reconstruction of teaching materials and evaluation systems; places high demands on the cognitive science literacy of course designers and teachers.

Experimental project division can be subjective, leading to competency leaps. High-level training is time-consuming and difficult to scale.

System A (Knowledge Verification) represents the traditional subject-centered paradigm; System B (Methodological Patch) is a preliminary correction to A but does not touch the underlying logic; System C (Competency Progression) achieves a shift in perspective from “knowledge” to “competency,” though the definition of competency remains too macro-level. In contrast, the PMT System (Cognitive-Problem) achieves a fundamental paradigmatic leap: it shifts the focus from external “knowledge” or “tasks” to the learner’s internal “cognitive process” itself.

The core of this paradigmatic shift lies in transforming the primary question of instruction from “What should students know?” to “What types of problems do students need to solve, and what cognitive strategies should they develop for this purpose?” This is not merely about “how to teach” but fundamentally reconstructs “what to teach.” It allows experimental teaching to return from being the “back garden” of theoretical verification to the “original site” of scientific discovery, providing a systematic and operational curricular solution for cultivating the design and innovative thinking that remains irreplaceable in the age of artificial intelligence.

3 结论与展望

Based on cognitive science, this study constructs a new physical experiment system centered on the main axis of “cognitive limitations -experimental prob-

lems -experimental methods.” The objective is to facilitate a transformation in university physics experiment teaching from “knowledge presentation” to “methodological explicitness.” This system categorizes human cognitive abilities into three dimensions—perception, manipulation, and cognition—and extracts fourteen types of cognitive limitation problems. Around these dimensions, a complete logical chain of “cognitive limitations → experimental problems → experimental methods → typical experimental projects” is established, forming a curriculum structure where methods are explicit and supported by knowledge. Teaching practice demonstrates that this system effectively guides students to focus on experimental methods and scientific thinking, significantly enhancing learning interest and transferability, thereby validating its pedagogical effectiveness.

In concluding this paper, it is necessary to further elaborate on the theoretical contributions, innovative breakthroughs, and application prospects of this work, as well as the limitations of the current research process.

3.1 理论贡献：实验科学本源价值的回归

This research treats cognitive ability as the logical foundation for conducting physical experiments, which represents a substantive return to the essence of experimental science. Historically, physical experiments originated from human curiosity and the exploration of nature within the constraints of our own cognitive limitations. As knowledge accumulated, physical theory—due to its systematic advantages—gradually became the primary thread for organizing experimental content. However, this has created a logical “inversion”: experiments should provide the factual basis for theory and verify its correctness through the process of enhancing cognitive ability, rather than serving as a mere appendage to theory. This misalignment has led students to frequently misunderstand experimental teaching as a secondary step for “understanding theory,” thereby obscuring its core value in enhancing cognitive capacity and methodological training. This study aims to rectify these misconceptions and reconstruct the value recognition of experimental teaching, centering it on “problem-solving and the enhancement of cognitive ability.”

3.2 核心突破：以完备性问题框架统摄方法体系

Historically, the failure to establish an experimental system centered on problem-oriented inquiry can be attributed to two primary factors. First, previous research has frequently discussed methodologies in isolation from the specific problems they aim to solve, leading to a misalignment in research direction. Second, physical problems are inherently diverse and seemingly disorganized, lacking a concise framework capable of systematizing them while demonstrating theoretical completeness.

By conducting an in-depth analysis of the relationship between cognitive limitations, experimental problems, and methodologies, this study establishes a

fundamental principle: experimental problems must serve as the core for governing and classifying experimental methods. From this foundation, we extract fourteen basic dimensions—six pertaining to perception, six to manipulation, and two to cognition (thinking). These dimensions form a comprehensive classification framework that encompasses all types of experimental problems and has been rigorously demonstrated to be complete. This analysis, which originates from the basic principles of cognitive science and extends to the very essence of physical experimental problems, provides an objective, stable, and open framework for the systematic organization of disciplinary content.

3.3 应用前景：支撑 PBL、贯通培养、项目式教学及跨学科迁移

Looking ahead, the PMT (Problem-Method-Theory) system not only provides a new paradigm for physics experiment teaching but also offers significant implications for broader educational and scientific research scenarios: (1) Supporting Problem-Based Learning (PBL) [?]: This system clarifies that “problems originate from cognitive limitations” and constructs a complete logical chain of “cognition—method—knowledge” around these problems. By reproducing the authentic process of scientific exploration, it provides a solid theoretical basis and clear design coordinates for problem-oriented instruction. (2) Facilitating integrated curriculum design [?]: Currently, experimental courses across different educational stages suffer from issues such as repetitive content and gaps in competency development.

The PMT system provides a top-level design logic that transcends the mere listing of knowledge points, focusing instead on “competency progression” as the main thread. This helps achieve continuity in thinking training from basic education to higher education, and even from higher education to scientific research practice. (3) Empowering Project-Based Learning (PBL) and scientific innovation [?]: This system can decompose complex project goals into several problems rooted in cognitive limitations. This allows students or researchers to “follow the map” to invoke or transfer corresponding methodological strategies, thereby reducing design difficulty and enhancing the systematic nature and innovative quality of solutions. Further expansion into other scientific research fields could help form a common paradigm for interdisciplinary methodological exchange. (4) Extension to other STEM courses: The design philosophy of “categorizing methods centered on problems and enhancing competency through methods” can serve as a reference for curriculum reforms centered on competency cultivation. As shown in the previously mentioned Millikan oil drop experiment case, the PMT system resonates deeply with the 4C teaching model proposed by Zhong Baichang et al.: while the 4C theory specifies the developmental process of innovative ability during teaching (four stages), the PMT system clarifies the content direction of cognitive development in physics experiments (the three dimensions of perception, manipulation, and cognition).

In this sense, the PMT framework can be regarded as the contextualization and operationalization of the 4C model within the field of physics experiments.

Together, they outline a clear path for the cultivation of innovative capabilities.

In summary, this study not only proposes a new physics experiment teaching system with a clear structure and defined functions but also returns to the fundamental values of experimental science in its philosophy. Methodologically, it provides a transferable and scalable framework for competency-oriented educational innovation, thereby effectively responding to the curriculum design direction of “cultivating the soul and enhancing wisdom.”

3.4 研究局限及未来工作

This study has several limitations that warrant further investigation. First, the empirical research is primarily based on the textual analysis of student laboratory reports; future studies could introduce more objective competency assessment tools—such as performance tests evaluating the ability to design experimental protocols—to enhance the robustness of the conclusions. Second, long-term tracking of teaching effectiveness has yet to be conducted to verify the persistence and stability of transferrable skills. Third, the application cases of the PMT system in other science and engineering courses need to be expanded to further test its cross-disciplinary generalizability.

Looking forward, we are committed to translating the PMT system into specific textbooks and curriculum resources, promoting its pedagogical practice on a broader scale, and continuously tracking its long-term impact on the cultivation of innovative talents. Ultimately, this research aims to provide a systematic response—from conceptualization to practice—rooted in physics laboratory education for higher engineering and science education in the era of artificial intelligence.

References: [1] Luo Chenglin, Li Youzhen, Sun Xiliang, et al. Paradigm Reconstruction of College Physics Experiment Teaching from the Perspective of Cognitive Science (I): Origin and Shift of Concepts. (ChinaXiv) <https://chinaxiv.org/abs/202604.00075V1> (DOI:10.12074/202604.00075). [2] Luo Chenglin, Li Youzhen, Sun Xiliang, et al. Paradigm Reconstruction of College Physics Experiment Teaching from the Perspective of Cognitive Science (II): Construction of the PMT System Framework. (ChinaXiv) <https://chinaxiv.org/abs/202604.00120V1> (DOI:10.12074/202604.00120). [3] Zhong Baichang, Liu Xiaofan. The Theoretical Mechanism of Innovation Ability Cultivation and the Construction of 4C Teaching Model [J]. *Modern Distance Education Research*, 2021, 33(4): 20-32. [4] Liu Jinqiu, Qiu Wenxu, Zhao Chaojun, et al. Practical Research on “6E Model + Regular Hexagon Evaluation Method” in University Physics Experiments [J]. *Physics and Engineering*, 2025, 35(4): 198-255. [5] Xie Yuxia, Bi Mengxia, Sun Yuhang, et al. Research on Blended Teaching and Diversified Assessment Models for University Physics Experiments [J]. *Physics and Engineering*, 2025, 35(3): 134-137. [6] Zhang Junpeng. *Psychology of Physics Learning* [M]. Beijing: Peking University Press, 2022. [7] Hu Yangyang, Xing Hongjun, Gu Yahui.

Research on the Presentation of Scientific Methods in Physics Textbook Writing [J]. Curriculum, Teaching Material and Method, 2016, 36(9): 63-67. [8] Xu Fuxin, Xie Ding, Peng Yongyi. University Physics Experiment Course [M]. 2nd Edition. Changsha: Central South University Press, 2022. [9] Wen Xiaoyan, Li Xiaoqiang. New University Physics Experiments [M]. Beijing: Peking University Press, 2022. [10] Zhang Zengming. University Physics Experiments [M]. Beijing: Higher Education Press, 2024. [11] Li Jinhuan, Wang Xiaojun, Wang Qingyong. Practical Exploration of PPBL Teaching Model in Optics Teaching [J]. Physics Experimentation, 2015, 35(08): 10-14.

[12] Zhou Xiaohong, Zeng Weiyu, Mao Shuzhe, et al. Investigation on the Current Situation of the Connection between High School Physics Experiments and University Physics Experiments and Research on Optimization Paths [J]. Physics Bulletin, 2023(01). [13] Ni Chen, Li Yuying, Fang Kai, et al. Research on Project-based Experimental Teaching from the Perspective of Subject Competitions [J]. Laboratory Research and Exploration, 2022, 41(8): 256-262.

(Corresponding Author 1: Kong Deming, E-mail: csu-kdm@163.com) (Corresponding Author 2: Luo Chenglin, E-mail: chlluocsu@csu.edu.cn)

Author Contribution Statement: Luo Chenglin: Proposed the research concept, constructed the PMT theoretical framework, designed the pedagogical experiments, collected and analyzed data, and drafted the initial and final versions of the manuscript.

Li Youzhen: Participated in partial discussions and assisted in proofreading the manuscript. Sun Xiliang: Participated in partial discussions and assisted in proofreading the manuscript. Zheng Xiaojuan: Participated in partial discussions and assisted in proofreading the manuscript.

Kong Deming: Provided research resources and platform support, guided the overall research direction, and reviewed the manuscript. Xu Fuxin: Participated in partial discussions, guided the overall research direction, and revised the manuscript.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.