Paradigm Reconstruction of University Physics Experiment Teaching from the Perspective of Cognitive Science (I): Conceptual Origins and Shifts

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

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Abstract

In response to the urgent requirements for cultivating top-tier innovative talents as outlined in the national "Outline of the Planning for Building a Powerful Country in Education" and the shift in pedagogical values triggered by the development of artificial intelligence technology, and to more effectively realize the educational value of Physics Laboratory—a foundational course with extensive coverage—this paper explores in depth the fundamental paradigm reconstruction of university physics laboratory teaching.

The study elucidates the deep-seated dilemma of "explicit knowledge, implicit methodology" in current curricula, the root of which lies in the long-standing adherence to a "knowledge-centered" logic. Introducing the principle of "primacy of cognitive ability" from cognitive science, this paper systematically demonstrates for the first time the primordial logical chain of scientific development: "cognitive limitations → experimental problems → experimental methods → physical knowledge," through the analysis of classic cases.

Based on this, the research explicitly proposes that the core objective of physics laboratory teaching should shift from the transmission and verification of knowledge to the systematic training of students' ability to "break through cognitive boundaries," thereby reinterpreting physics experiments as a "strategy library and achievement repository for cognitive breakthroughs." This conceptual study provides a theoretical foundation and a brand-new logical starting point for the paradigm reconstruction of physics laboratory teaching.

Full Text

Preamble

Paradigm Reconstruction of University Physics Experiment Teaching from the Perspective of Cognitive Science (I): Concepts and Origins

LUO Chenglin, LI Youzhen, SUN Xiliang, ZHENG Xiaojuan, KONG Deming, XU Fuxing (School of Physics, Central South University, Changsha, Hunan 410083, China)

Abstract

In response to the urgent requirements for cultivating top-tier innovative talents outlined in the national *Outline of the Planning for Building a Powerful Country in Education* and the shift in educational values triggered by the development of artificial intelligence, this paper explores a fundamental paradigm reconstruction for university physics experiment teaching. The study elucidates the deep-seated dilemma of "explicit knowledge, implicit methods" in current curricula, rooted in a long-standing "knowledge-centered" logic. By introducing the cognitive science principle of the "primacy of cognitive ability" and analyzing classic cases, this research systematically demonstrates, for the first time, the fundamental logic chain of scientific development: "cognitive limitations → experimental problems → experimental methods → physical knowledge." Based on this, the study proposes shifting the core objective of physics experiment teaching from the transmission and verification of knowledge to the systematic training of students' ability to "break through cognitive boundaries." Consequently, physics experiments are redefined as a "repository of strategies and outcomes for cognitive breakthroughs." This conceptual study provides a theoretical foundation and a new logical starting point for the paradigm reconstruction of physics experiment teaching.

Keywords: PMT (Perception-Manipulation-Thinking) system; Cognitive Science; Physics Experiment; Experimental Method; Teaching Paradigm; Artificial Intelligence

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The national *Outline of the Planning for Building a Powerful Country in Education (2024-2035)* explicitly proposes establishing and improving mechanisms for discovering and cultivating top-tier innovative talents, emphasizing the creation of "high-quality courses that strengthen foundations, nourish the soul, and enhance wisdom." Concurrently, as artificial intelligence rapidly penetrates society, scientific research, and education, basic knowledge and skills are increasingly being replaced by machines. This shift has led to a relative decline in the instructional value of rote knowledge, moving the focus of educational content toward higher-order levels such as methodology, thinking, and ability.

A core consensus has emerged in current educational reform: teaching must shift from pure knowledge transmission to the cultivation of core competencies and innovative capabilities. Innovation is essentially the ability to propose and solve new problems in novel contexts. This ability is not acquired through the simple accumulation of knowledge but through learning how to reorganize knowledge using new strategies and methods. Consequently, methods—rather than knowledge—should occupy the central position in teaching aimed at fostering innovation [?, ?, ?]. However, many physics experiment courses still organize content around physical knowledge or skill training. The first impression these courses give to both teachers and students is often the knowledge itself, while the methods inherent in the experiments are left for students to intuit. Even when explanations exist, they are often scattered across various experimental projects and processes without a systematic framework; occasional thematic discussions are disproportionate in depth and quantity to the importance of experimental methods [?, ?].

This existing system, characterized by explicit knowledge and implicit methodology, can no longer meet the demands of modern education. University physics experiments require a reconstruction that makes experimental methods explicit while using physical knowledge as a supporting framework. This is a major goal of current physics experiment curriculum reform. Fundamentally, physics experiments exist to solve problems regarding human cognition of material composition and the laws of motion in the natural world. Cognitive science, which studies the human mind to reveal its structure and cognitive laws, is thus intimately related to physics experiments.

The fundamental tenet of cognitive science is that cognitive ability is primary, while knowledge is secondary; the latter is a product of the former rather than a prerequisite [?]. Following this concept, this study uses in-depth case analysis to clarify the generative relationship between "limitations of cognitive ability," "experimental problems," and "experimental methods." Furthermore, it systematically organizes the corresponding genealogy of experimental problems to construct a curriculum system that takes cognitive limitations as its logical starting point, makes experimental methods explicit, and treats physical knowledge as both support and outcome. This research aims to drive a paradigm shift in physics experiment teaching: from teaching knowledge and skills to systematically training the cognitive abilities that serve as the engine of innovation.

1 Dilemmas and Demands: The Reality of Physics Experiment Method Teaching

Literature [?] categorizes methods for understanding the objective natural world into three levels of universality: first, research methods unique to specific disciplines (e.g., amplification, balance, compensation, and controlled variables in physics); second, general research methods applicable across disciplines (e.g., observation, mathematical modeling, and logical reasoning); and third, philosophical methods (e.g., contradiction analysis and practice). Specifically, within physics experiments, numerous research results have summarized various experimental methods from different perspectives and levels [**?**, **?**]. However, these studies share common deficiencies:

1. **Incomplete Systems**: While these works summarize various methods, they fail to clarify whether these summaries cover the full breadth of physics experiment content, leaving the problem of systemic completeness unresolved.
2. **Chaotic Logical Architecture**: The relationships between methods are often muddled. For instance, are "amplification" and "transformation" coordinate or subordinate? Transformation, as a meta-method, actually encompasses amplification as a sub-category, yet textbooks frequently list them as parallel concepts [**?**].
3. **Loose Connections**: A single experiment often employs different methods at different steps, and the same method may appear in different projects. However, textbooks rarely explain which experimental problems require which methods, nor do they specify the physical knowledge used to implement a given method.
4. **Weak Practicality**: Even if students understand the definition of a method, they often struggle to apply it flexibly to specific experimental problems, relying instead on "inspiration." Students may "know the method" but do not know "how to use the method."

Because experimental methods have not been systematized and lack an objective theoretical basis, curriculum design often retreats to the "mature" framework of physical theory despite repeated reforms. Therefore, the primary task in establishing a system where experimental methods are explicitly presented is to create a method system with clear classification, defined functions, and sufficient completeness. To achieve this, we must trace the logical starting point of experimental methods.

2.1 Re-examining Classic Experimental Cases

Case 1: Observation of Microscopic Objects. Under ideal conditions, the minimum resolution angle of the human eye is approximately 1 arcminute; at a distinct vision distance (approx. 25 cm), the smallest detail distinguishable is about 0.08 mm. However, research objects in physics are often much smaller. To observe these objects (which exceed sensory perception limits), researchers use the principles of convex lens refraction (physical knowledge) to create microscopes. The key step is using imaging knowledge to achieve angular magnification of light, solving the problem of the naked eye' s inability to see detail. Thus, the experiment employs the **amplification method**.

Case 2: Temperature Measurement. Humans can perceive heat and cold through touch, but this is limited; for example, touching a 100°C object causes injury, and touch alone cannot precisely calibrate temperature. Because physics research involves temperatures far beyond human sensory range, researchers use principles like the thermal expansion of gases (physical knowledge) to create thermometers. The key step is using thermal expansion to convert temperature changes into volume changes visible to the eye. Thus, the experiment employs the **transformation method**.

Case 3: Measurement of Minute Electric Charges. Basic instruments cannot measure minute charges. To measure the charge of an electron, Millikan used the balance between electric and gravitational forces, as well as the balance between air resistance and gravity for oil droplets moving at constant speed (physical knowledge) to create the Millikan oil-drop apparatus. This converted the measurement of minute charges into other physical quantities measurable by basic instruments. Thus, the experiment employs the **balance method**.

These cases share a common logical sequence: (1) the object of study exceeds natural human perception or current instrumental limits, creating an experimental problem; (2) researchers use physical knowledge to break through these cognitive limitations, solving the problem and gaining new knowledge; (3) the effective experience gained in breaking through these barriers is condensed into an experimental method, often named after the key step, tool, or knowledge feature used.

2.2 Tracing the Origin: Redefining the Essence of Experimental Methods

As shown above, experimental methods are essentially procedural knowledge derived from effective problem-solving experiences. This gives them several key characteristics:

1. **Procedural and Purposeful**: They describe "how to do" something to provide strategic guidance for solving similar problems, differing from declarative physical knowledge which describes "what is."
2. **Subjective and Hierarchical**: Methods are cognitive strategies actively constructed by the analyst. The same experiment can be categorized under different methods depending on the level of abstraction. For example, the Millikan oil-drop experiment uses the "balance method" (based on its implementation steps) or the "transformation method" (based on converting difficult measurements). Conversely, the same method can appear in different experiments.

Because methods possess these subjective and hierarchical traits, they can appear less "objective" than physical knowledge. This has led to a methodological error: in pursuit of objectivity, previous research often stripped methods from their problem contexts, classifying them instead by the physical knowledge that supports them. This creates a logical break: people need methods because they encounter problems, yet teaching often hides the problem itself. This is akin to studying a key in isolation while ignoring the lock it was meant to open.

Therefore, a thorough logical return is necessary: methods originate from problems and serve as the condensation of effective experience. Knowledge is merely the supporting material for the method. To use an analogy: the problem is the lock, the method is the shape of the key, and knowledge is the material of the key. Whether the lock opens depends on the shape of the key. While the material (knowledge) is essential, it is not the decisive factor. Experimental methods should be governed and defined by “experimental problems” rather than physical knowledge. A systematic method system must be built around a systematic problem system.

3 Theoretical Foundation: Cognitive Science Origins of Experimental Problems

The analysis of typical cases shows that physics experiments often begin with difficulties in perception or measurement. This reveals a universal root: the contradiction between the existing boundaries of human cognitive ability and the need to explore the unknown world. Cognitive science provides a profound explanation for this.

Cognitive science points out that the entire knowledge system (including physics) is a product of cognitive operations [?]. However, native human cognitive ability is limited by sensory thresholds and “cognitive load” constraints like attention span and working memory capacity [?]. The tension between limited cognitive ability and the infinite complexity of the world constitutes the fundamental drive of cognitive activity. Cognitive psychology defines a “problem” as a situation where obstacles exist between the current state and a goal [?]. We can infer that these “obstacles” are essentially the boundaries of human cognitive ability.

In the context of physics experiments, we argue that an experimental problem is a specific situation that arises when unknown physical content exceeds the boundaries of current human cognitive ability (including the extension provided by scientific instruments). Instruments are not external tools but functional extensions of human sensory and thinking organs [?]. The “observability principle” in physics requires that physical quantities eventually be perceived in some way, reflecting the isomorphism between instrument-extended cognitive ability and native human perception.

4 Integration and Reconstruction: The Fundamental Logic Chain and Paradigm Blueprint

From the perspective of cognitive science, the development of physics experiments follows this logic: (1) contradictions between cognitive limitations and the complexity of the world produce physical problems; (2) researchers reorganize information and instruments to break through cognitive boundaries through internal (thinking) and external (action) operations, solving the problem and acquiring new knowledge; (3) experimental methods are the experiential summaries of this breakthrough; (4) physical knowledge supports the implementation of these methods and serves as the product of the breakthrough.

The invention of the microscope confirms this: it did not originate from a specific scientific question (like observing cells) but from the universal cognitive need to "see small things." Breaking this boundary produced the amplification method and lens knowledge. The value of the microscope lies not just in solving one problem but in enabling scientists to observe crystal dislocations and bacteria, driving further research.

Based on this, we reposition physics experiments: they are not mere carriers of theoretical knowledge, but a repository of strategies and outcomes for breaking cognitive boundaries. A new system should be built on cognitive science—specifically the limitations of human cognition—rather than on physical theoretical systems.

Comparison between the Current and New Teaching Paradigms

Feature	Current System (Old)	Cognitive Science-Based System (New)
Theoretical Basis	Physical theory; emphasizes systematic knowledge	Cognitive science; focuses on cognitive limits and breakthrough strategies
Core of Construction	Knowledge points or theoretical modules	Experimental problems (derived from cognitive limits)
Logical Sequence	Knowledge-oriented: Theory → Experiment → Verification	Ability-oriented: Cognitive limits → Problems → Methods → Knowledge
Teaching Goals	Mastery of knowledge, verification of theory, skill training	Enhancing cognitive ability, mastering scientific methods, fostering transferability
Role of Experiments	"Carrier" or "Assistant" to theory	Repository of strategies and outcomes for cognitive breakthroughs

5.1 Summary of Research

This paper addresses the fundamental challenges of talent cultivation in the AI era by critically re-evaluating the logic of university physics experiment teaching. We identified the "knowledge-explicit, method-implicit" dilemma as a result of the "knowledge-based" traditional paradigm, which inverts goals (ability) and means (knowledge). By analyzing the logic chain of "cognitive limitations → experimental problems → methods → knowledge," we have redefined physics experiments as practical activities that systematically extend human capabilities. This repositioning shifts the focus from "generating knowledge" to "expanding ability,” liberating physics experiments from their subordinate status as mere verification tools.

5.2 Future Work

As the first part of a series, this paper addresses the “why” and “where” of conceptual change. Subsequent research will follow these paths:

System Construction (Part II): We will build an operational “PMT”(Perception, Manipulation, Thinking) curriculum framework. By using the limitations of these three cognitive dimensions as a primary framework, we will systematically derive core experimental problem types and integrate corresponding experimental methods.

Practical Verification (Part III): We will design and implement teaching experiments based on the PMT system to evaluate its effectiveness in improving students’ methodological thinking, problem-solving, and cross-contextual transfer abilities. This will complete the transition from theoretical construction to practical validation.

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

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