Educational Research Advances Vol.1, No.2, p. 124-139, 2026

Original article

From Knowledge Carrier to Cognitive Engine: A Triadic Framework for Smart Textbooks

Xiaotong Wang*, Xinyi Lv, Hanchang Wang

Naval Aviation University, Qingdao Campus, Qingdao 66041, *P. R. China*

Received: January 16, 2026
Revised: June 1, 2026
Accepted: June 14, 2026
Published: June 24, 2026

Cited as:
Wang, X. T., Lv, X. Y., & Wang, H. C. (2026). From knowledge carrier to cognitive engine: A triadic framework for smart textbooks. *Educational Research Advances, 1*(2), 124-139. https://doi.org/10.46690/era.2026.02.06

Abstract: With the advancement of educational digitalization strategies, core educational resources like textbooks are undergoing unprecedented transformations as traditional static, unidirectional, and rigid models fail to meet demands for personalized learning and higher-order competency cultivation. This study establishes a systematic theoretical framework through interdisciplinary perspectives of philosophy, pedagogy, and psychology to analyze the ontological nature of smart textbooks (STs), revealing a paradigm shift from “knowledge carriers” to “cognitive engines” through three dimensions: ontologically, transitioning from static entities to dynamic cognitive ecosystems; epistemologically, evolving from unidirectional transmission to collaborative knowledge construction; and axiologically, advancing from instrumental rationality to educational rationality. Furthermore, the research deconstructs four driving cognitive mechanisms (generation-adaptation-collaboration-evolution) underlying STs operations, aiming to clarify their core characteristics and operational logic to provide theoretical foundations and practical guidelines for digital-era educational innovation that transcend limitations of traditional pedagogical models.

Keywords: Smart Textbooks; Cognitive Engine; Educational Digitalization; Ontology; Epistemology; Axiology; Cognitive Logic

1. Problem Statement: The Paradigm Shift Challenge from "Knowledge Carrier" to "Cognitive Engine"

In the era of digital transformation, the education sector is undergoing profound changes. The 2022 initiation of the National Educational Digitalization Strategic Action by the Ministry of Education marks the entry into a new phase where digital technology serves as the core driving force. In this macro context, textbooks as the most fundamental educational resources have become critical nodes for educational quality enhancement and talent cultivation model innovation. Traditional paper-based textbooks, while instrumental in knowledge dissemination and educational equity, exhibit inherent limitations characterized by "static, closed, and unidirectional" attributes. These features increasingly hinder the development of personalized, contextualized, and lifelong learning paradigms. Thus, advancing textbook digitalization and intelligence upgrading has become an indispensable component of educational digitalization strategies.

From print to electronic to current smart textbooks (STs), textbook evolution synchronizes with technological innovation and pedagogical advancements. STs represent not mere technological integration but fundamental reconceptualization of textbook ontology and functionality. This paradigm shift from "knowledge carrier" to "cognitive engine" responds to the era's fundamental demands. Philosophical hermeneutics posits that understanding emerges through "fusion of horizons" between subject and text in historical contexts. The multimodality, interactivity, and generativity of STs reshape the scene and mechanisms of understanding, expanding it from singular textual interpretation to multi-dimensional dialogues with technology, environment, and community.

1.1 Major Research Focuses in Current Literature

With deep integration of AI and educational sciences, research on STs and intelligent learning environments has entered rapid growth. Based on systematic literature review of five-year span, current research clusters around three core dimensions:

*Correspondence author.
E-mail: 315146470@qq.com (X. Wang); xinyilv@163.com (X. Lv); lovexue199075@163.com (H. Wang)

Yandy Scientific Press
ISSN: 3106-3632

1.1.1 *Technical Path Exploration*

Driven by computer science and educational technology scholars, this line focuses on core technologies enabling "intelligent" textbooks. Early studies emphasized multimedia integration and basic interactivity, while recent research prioritizes advanced AI applications. Yu et al. (2025) demonstrated knowledge graph and learning object technology's capacity to represent disciplinary knowledge structures, combined with learner response data for real-time diagnostic assessment to inform personalized recommendations. Hwang et al. (2020) highlighted the paradigm shift from auxiliary tools to "adaptive mentors" through NLP and deep learning for precise learner intent recognition and feedback. Abdelrahman et al. (2023) systematically reviewed deep knowledge tracing models, identifying graph neural network-based algorithms' superior capability in capturing implicit knowledge associations for personalized path recommendations. Liu et al. (2021) explored intelligent technologies' role in educational assessment, advocating for STs' dynamic intervention capacity through knowledge graph-enabled semantic association and push mechanisms.

1.1.2 *Pedagogical Application Research*

This direction examines DIT implementation in authentic educational contexts, seeking practice paradigms aligned with new teaching models and empirically verifying their effectiveness. Researchers no longer treat STs as mere traditional classroom supplements but as core elements reconstructing pedagogical workflows. Zhu and Hu (2022) argued that new textbooks are critical components for constructing high-quality education systems, effectively supporting student-centered pedagogies like flipped classrooms and project-based learning (PBL). Gui et al.'s (2023) meta-analysis confirmed that adaptive digital textbooks significantly enhance STEM learners' academic performance, particularly benefiting low-achieving learners. Sosnovsky et al. (2025) emphasized that deep interactive digital resources improve higher-order thinking skills only when technical functions and pedagogical design achieve organic integration rather than simple aggregation.

1.1.3 *Content Design and Presentation*

This research line focuses on DIT user interfaces, interaction design, and user experience, optimizing designs to enhance attractiveness, usability, and immersion. Drawing from human-computer interaction, cognitive psychology, and design theories, scholars explore cognitively-aligned information visualization. Sailer and Homner's (2020) meta-analysis revealed that gamification elements (immediate feedback loops, challenge mechanisms) significantly boost behavioral engagement and emotional satisfaction. Koć-Januchta et al. (2022) proposed an "optimal flow experience" design framework from embodied cognition perspectives, demonstrating that moderate interaction intensity and immersive contexts (VR/AR integration) enhance concentration and presence. Chiu (2022) extended self-determination theory, showing that STs satisfying learners' autonomy and competence needs through technological means can significantly reduce cognitive load. Crompton and Burke (2023) focused on metaverse and extended reality (XR) applications, asserting that immersive interaction design promotes embodied cognition by transforming abstract concepts into perceivable experiences.

1.2 Deep-Rooted Challenges

Despite significant progress in DIT development and application, current research practices exhibit "technology prioritization over theory" and "data emphasis at the expense of humanities", facing crises of instrumental rationality overshadowing educational rationality.

1.2.1 *Disconnection Between Technology Application and Educational Goals*

Many DIT developments fall into "functionalism" traps, equating "intelligence" with technological feature stacking. Rich media resources (video, animation, VR/AR) are often embedded primarily for visual appeal rather than deep thinking integration. Li (2024) critically challenged the "technology supremacy" paradigm in educational informatization, arguing that media-rich but cognition-agnostic approaches may lead to "technological encroachment on education". Zhai et al. (2021) found that while AI integration is widespread, many applications remain confined to auto-scoring or simple content pushing, lacking substantive support for creativity and critical thinking development.

1.2.2 *Instrumentalization of "Data-Driven" Approaches*

While data-driven approaches aim to enable personalized learning through learning analytics, practical implementations often devolve into "dataism". Overemphasis on tracking, quantifying, and predicting learning behaviors risks oversimplifying learners' complex inner worlds, reducing active, emotional subjects to algorithm-analyzed objects. Yang (2023) warned against "dataism traps" in educational digitalization, stressing the need to preserve intangible qualities like emotions, attitudes, and values that resist algorithmic capture. Williamson et al. (2020) critiqued "data colonialism" in educational platforms, noting algorithm-dominated path planning may cause "algorithm dependency", depriving learners of autonomous exploration and reflective opportunities.

1.2.3 *Systematic Theoretical Framework Deficiency*

Compared to rapid technological advancements, systematic DIT theoretical construction lags significantly. Current research exhibits fragmentation, focusing on specific technologies (learning analytics) or scenarios (smart classrooms) without holistic perspectives. Bearman and Ajjawi (2023) noted the lack of systematic theoretical exploration on human-machine relationships in technology adoption. Most developments rely on behaviorist or simplistic cognitivist assumptions, resulting in "high-tech, low-efficiency" phenomena. Heidegger's "enframing" concept proves particularly relevant here (Zhang & Zhang, 2025). He argued modern technology constructs coercive frameworks shaping our worldviews. Current practices unwittingly fall into this enframing trap, prioritizing "technical feasibility" over "educational purpose", failing to transcend instrumental rationality.

1.3 The Inevitable "Cognitive Turn"

To overcome these challenges and return to educational essence, DIT research must undergo profound paradigm shifts: from technology-centric to education-centric approaches, from external functions to internal cognition focus, achieving a complete "cognitive turn" - shifting focus from technical forms to cognitive processes and development mechanisms.

This turn requires re-examining human-machine relationships. Järvelä et al.'s (2025) "hybrid intelligence" concept provides theoretical support, advocating for graded automation mechanisms that dynamically adjust and enhance human-machine cognition rather than replace it. This signals DIT research shifting from "automated instruction" to "collaborative cognition". Huang et al.'s (2023) research supports this, emphasizing AI's role as "social scaffolding" rather than command issuers in collaborative learning to support higher-order thinking.

In this context, STs should transcend static knowledge carriers to become dynamic cognitive engines. Chen et al.'s (2022) "educational new infrastructure" perspective inspires future textbooks to construct open cognitive ecosystems through data flow connecting learners, teachers, and intelligent platforms into distributed cognitive networks. This shift demands multidisciplinary philosophical, pedagogical, and psychological explorations of fundamental questions:

Ontological Questions: What essentially constitutes STs? What distinguishes them from traditional and electronic textbooks? Are they mere knowledge carriers or integral learning environments?

Epistemological Questions: How have knowledge acquisition and meaning construction fundamentally changed with STs? How are human-human and human-technology relationships reconfigured?

Axiological Questions: What is STs' ultimate educational value? How should we measure their effectiveness in achieving educational objectives?

Based on these considerations, this study establishes a three-dimensional philosophical framework integrating ontology, epistemology, and axiology to systematically explore STs' deep connotations, clarify their core transformations from knowledge objects to cognitive ecosystems, unidirectional transmission to collaborative construction, and instrumental rationality to educational rationality. Furthermore, it deconstructs their intrinsic cognitive logic to reveal mechanisms supporting learners' cognitive development.

2. Ontological Connotations: The Fundamental Shift from Knowledge Object to Cognitive Ecosystem

Ontology addresses the core question of "what exists," and ontological exploration of STs essentially answers the fundamental question of "what are STs?" STs have fundamentally reconstructed the essence of textbooks, transforming them from isolated objects into dynamic and open "cognitive ecosystems." This transformation not only alters the logic of knowledge presentation and organization but profoundly reshapes the interactive relationships between learners and textbooks, technology and knowledge.

2.1 From "Entity" to "Ecosystem": The Reconstruction of Textbook Ontological Positioning

STs have transcended the entity limitations of traditional textbooks, no longer existing as isolated "objects" but as cognitive ecosystems formed by elements including learners, digital intelligence technology, and knowledge content. Their core function extends beyond knowledge delivery to creating, regulating, and expanding supportive environments that enable and develop cognition.

2.1.1 *Transformation of Existential State: From Static Objects to Dynamic Environments*

Traditional textbooks are material entities characterized by clear physical boundaries, fixed content, and linear structures. They conform to the classical ontological view articulated by Aristotle: "An entity is an independent existence that bears all attributes," treating knowledge as an objective entity separable from cognitive subjects. In contrast, STs transcend this "present-at-hand state" (Heidegger's Vorhandenheit) to approach the "ready-to-hand state" (Zuhandenheit). STs are no longer external, distanced "objects" but are integrated into learners' cognitive activities as extensions of their thinking, exploration, and knowledge construction. This implies that the existential significance of textbooks is no longer solely defined by physical properties or fixed content but is generated and validated through specific learning interactions. STs transition from self-contained, static "objects" to supportive environments that continuously evolve with learner needs and contextual changes.

2.1.2 *Reconstruction of Systemic Relationships: From Isolation to Deep Integration*

Traditional textbooks represent a relatively clear, unidirectional subject-object relationship between knowledge and learners. In STs' cognitive ecosystem, three elements form an organic whole:

(1) Learners as the most agentic core actors;

(2) Digital-intelligent technologies as supportive frameworks and feedback mechanisms;

(3) Knowledge as flowing, flexibly accessible interactive media.

Through interactive feedback loops, these elements create a closed-system dynamic:

Technologies adaptively present knowledge in multimodal formats;

Learners actively construct cognition through deep engagement with technology and knowledge;

Knowledge itself becomes continuously enriched, optimized, and reorganized during this process (Li et al., 2025).

This triadic integration transcends traditional dichotomies (subject/object, content/tool) by establishing a symbiotic relationship where each component mutually constitutes and transforms the others.

2.2 From "Prescribed" to "Generative": Evolution of Knowledge Presentation

Traditional textbooks follow a "prescriptive" closed logic in knowledge organization, viewing knowledge as predetermined, authoritative, and linearly arranged fixed content. While this facilitates systematic knowledge transmission, it also presets learning paths, implicitly compressing space for learners' active exploration and critical thinking. In contrast, the essential breakthrough of STs lies in the "generative" shift in knowledge representation – knowledge is no longer passively given but dynamically constructed and evolved through continuous interaction with learners, technology, and the environment, manifested in:

2.2.1 *Dynamic Evolution and Improvement of Content*

Leveraging artificial intelligence, big data, and learning analytics, STs capture disciplinary advancements, societal developments, and learners' real-time needs from interactions. They update, supplement, and localize knowledge content accordingly. For instance:

Social Science Textbooks: Integrate real-time policy interpretations, typical case studies, and social hotspot analyses to synchronize theoretical learning with contemporary contexts. This maintains knowledge freshness and explanatory power through temporal resonance with societal dynamics.

STEM Disciplines: Automatically incorporate emerging research findings (e.g., breakthroughs in quantum computing or biomedical engineering) and adaptive problem sets reflecting current technological challenges.

This dynamic updating mechanism transforms textbooks from static knowledge repositories into living systems that evolve with disciplinary progress and learner engagement.

2.2.2 *Personalized Adaptation and Generation of Learning Paths*

Through continuous diagnostic analysis of learners' cognitive foundations, interest preferences, learning styles, and progress states, STs employ intelligent algorithms to dynamically plan differentiated learning pathways. They generate tailored explanations, practice tasks, and assessment feedback. Specific implementations include:

Foundational Learners: The system provides additional explanatory scaffolds, guided practice modules, and incremental complexity tasks with immediate error correction mechanisms.

Advanced Learners: Automatically recommends extended readings (e.g., seminal research papers), open-ended inquiry projects, and higher-order thinking challenges (e.g., interdisciplinary problem-solving scenarios requiring synthesis across multiple domains).

This adaptive path generation is powered by multimodal learning analytics frameworks that integrate:

(1) Real-time Interaction Data. Eye-tracking, response latency, and error patterns during learning activities.

(2) Longitudinal Cognitive Profiles. Historical performance metrics and metacognitive indicators across multiple learning sessions.

(3) Contextual Factors. Temporal variables (e.g., learning duration, device type) and environmental conditions (e.g., ambient noise levels for speech-based interactions).

2.3 From "Tool" to "Partner": The Qualitative Shift in Human-Technology Interaction

Traditionally, textbooks are seen as passive tools, with their value entirely dependent on the user's intent and capability. However, through deep human-technology interaction, STs are evolving into "cognitive partners" for learners. This new relationship has two distinctive features:

2.3.1 *Embodied Interaction*

STs serve not merely as information providers but as extensions and external supports for learners' cognitive activities. Utilizing virtual reality (VR), speech recognition, gesture sensing, and haptic feedback technologies, they create immersive, embodied learning scenarios. Learners engage with knowledge through multimodal interactions—speech dialogue, gesture operations, and virtual experiments—rather than merely visual decoding and abstract thinking. Specific manifestations include:

Language Learning: Real-time pronunciation correction via phonetic analysis algorithms and AI-driven conversational partners for oral practice.

Physics Education: Virtual laboratory environments enabling tactile manipulation of abstract principles (e.g., simulating electromagnetic field interactions through gesture-controlled 3D models).

This paradigm shifts learning from "disembodied" symbolic decoding to "embodied" contextual experiences, enhancing conceptual understanding and memory retention through sensorimotor integration (Li & Liu, 2024).

2.3.2 *Social Construction*

STs transcend isolated learning by embedding collaborative tools and community functions that connect educators, learners, and domain experts. They support synchronous/asynchronous discussions, project collaborations, and knowledge sharing through:

(1) AI-Mediated Peer Networks. Intelligent matchmaking systems that form study groups based on complementary skill profiles and learning goals.

(2) Expert Crowdsourcing. Platforms enabling domain specialists to annotate content with real-world applications and emerging research insights.

(3) Collective Knowledge Mapping. Co-constructed concept graphs where learners collaboratively tag relationships between ideas through voting and consensus mechanisms.

This transformation aligns with Vygotsky's sociocultural theory: higher mental functions originate from social interaction. By constructing multidimensional interaction networks (human-machine, human-human, human-machine-human), STs provide abundant "social scaffolds," enabling learners to transcend individual cognitive limits through interactions with "more knowledgeable others" (both human peers and AI partners), advancing toward the Zone of Proximal Development.

In conclusion, the ontological transformation of STs marks a fundamental shift in understanding "textbooks" as basic educational elements—from a mechanical, material entity perspective to an organic, ecosystemic perspective. This paradigm shift constitutes the logical starting point for comprehending subsequent epistemological and axiological transformations. It redefines educational materials not as static knowledge containers but as dynamic cognitive ecosystems that adapt, interact, and co-evolve with learners and technologies.

3. Epistemological Connotations: The Paradigm Shift from Unidirectional Transmission to Collaborative Construction

Epistemology addresses the nature, origin, and acquisition of knowledge. Epistemological exploration of STs fundamentally answers the question: "How do learners acquire knowledge through STs?" Grounded in constructivist epistemology, STs have achieved a fundamental paradigm shift — from unidirectional knowledge transmission to collaborative cognitive construction. This transformation brings profound changes to knowledge paradigms, cognitive theories, and thinking frameworks.

3.1 Evolution of Knowledge Paradigms: From Objectivism to Constructivist Foundations

The epistemological core lies in knowledge paradigms, which determine our understanding of knowledge's nature and acquisition pathways. The fundamental difference between traditional textbooks and STs originates from their contrasting epistemological presuppositions.

3.1.1 *Transmitting Existing Knowledge: Objectivist Presuppositions of Traditional Textbooks*

Traditional textbooks operate under objectivist epistemology with the core principle of "transmitting existing knowledge." Knowledge is conceptualized as objective entities independent of learners, representing accurate world representations that can be transmitted and replicated through standard carriers. This perspective stems from Descartes' subject-object dichotomy, positioning learners and knowledge in opposition.

Under this paradigm, traditional textbooks function as "knowledge containers" with pre-defined content by subject experts. Learners' primary task is passive reception, memorization, and reproduction of knowledge. Instruction simplifies to a linear information chain: knowledge (objective existence)→textbook (encoding)→teacher (transmission)→learner (decoding and reception). Educational success is measured by learners' ability to accurately recall textbook content. Herbart's "teacher-centered, textbook-centered, classroom-centered" theory exemplifies this model, which effectively transmits classical knowledge systems but disconnects knowledge from learners' subjective experiences and contextual relevance. This approach suppresses active exploration and innovative thinking, failing to meet the demands of rapidly evolving digital knowledge ecosystems (Wang & Zheng, 2023).

3.1.2 *Constructing Unknown Knowledge: Generative Knowledge Paradigm of STs*

STs transcend objectivist limitations by adopting social constructivism rooted in Piaget's and Vygotsky's theories. They establish a "constructing unknown" knowledge logic, emphasizing knowledge as dynamically constructed meaning networks through learner-environment-technology interactions.

This means that the core function of STs is no longer "transmitting the known", but rather creating conditions, providing scaffolding, and building an ecosystem for "constructing the unknown". Its "generative" nature is mainly reflected in promoting three key transformations in learning methods:

(1) From Answer Presentation to Problem Exposure. STs present cognitive conflicts, open-ended questions, and real challenges, placing learners in problem-solving contexts rather than answer-memorization scenarios.

(2) From Information Provision to Contextualization. Immersive environments created through VR/AR technologies provide concrete scenarios for knowledge construction, enabling learners to design experiments, operate virtual equipment, and analyze data independently.

(3) From Rigid Structures to Exploratory Support. Hypertext and knowledge graphs organize content to stimulate active exploration through open-ended questions and interdisciplinary tasks, guiding personalized knowledge construction.

3.2 Expansion of Cognitive Paradigms: From Individual Cognition to Distributed Cognition

Epistemology necessarily addresses "where cognition occurs"—the cognitive paradigm. Traditional pedagogical paradigms implicitly confine cognition entirely within the learner's internal processes, while STs reconstruct the boundaries of cognition, shifting learning from the closed "individual information processing" paradigm to an open, collaborative "distributed cognitive construction" paradigm. Within this ecosystem, cognitive outcomes originate not only from learners' independent mental processing but also from cognitive extensions catalyzed by human-technology interaction and the collective intelligence emerging from collaborative learning communities.

3.2.1 *Limitations of Individual Cognitive Processing*

Traditional textbooks' cognitive paradigm centers on "individual cognitive processing," conceptualizing cognition as an internal information processing mechanism within learners. This paradigm is deeply influenced by early information processing theories that analogize the brain to an isolated "information processor," positing that learning involves the input, encoding, storage, and retrieval of external information (textbook content) within individual minds. Cognition is strictly constrained within individuals, with textbooks, environments, and others serving merely as passive information sources or contextual backgrounds.

Under this paradigm, textbook use becomes an isolated process of reading, memorizing, and comprehending knowledge without effective interaction with others or environments. For instance, in language learning, solitary reading and exercise completion hinder the acquisition of diverse interpretive perspectives through peer interaction; in mathematics, individual derivation of formulas and problem-solving lacks collaborative dissection of complex issues through group analysis.

3.2.2 *Open Collaboration in Distributed Cognition*

STs transcend individual cognitive limitations by establishing a human-technology collaborative distributed cognitive system based on distributed cognition theory, achieving a paradigm shift in cognitive epistemology. This theory posits that cognition exists not solely within individual brains but is distributed across systems comprising individuals, technological tools, and sociocultural environments, where cognitive processes emerge from systemic interactions.

Based on distributed cognition theory, STs transcend the traditional concept of limiting cognition to the individual interior, and construct an open and collaborative "human-machine - interpersonal" distributed cognition system. Distributed cognition theory points out that cognition not only occurs within the individual, but is also distributed across the overall system composed of individuals, technological tools, socio-cultural environments, and their interactive relationships. By organically integrating the aforementioned diverse elements, STs achieve a reasonable allocation and dynamic collaboration of cognitive tasks and cognitive loads.

(1) Externalization and Sharing of Cognitive Load. STs assume numerous mechanical, repetitive low-order cognitive tasks such as rapid information retrieval and complex data visualization. This liberates learners from burdensome extraneous cognitive load, enabling concentrated investment of limited cognitive resources into higher-order thinking activities (analysis, evaluation, creation), thereby enhancing cognitive efficiency and depth.

(2) Enhancement and Amplification of Cognitive Processes. Through embedded cognitive scaffolds like mind maps and structured argumentation frameworks, STs provide "thinking scaffolds" that not only assist learners in completing cognitively demanding tasks but also promote metacognitive development by explicitly externalizing thinking processes. These scaffolds gradually recede as learners' capabilities improve, facilitating a smooth transition from scaffolded learning to autonomous knowledge construction.

(3) Extension and Expansion of Cognitive Capabilities. Embedded intelligent tools (e.g., adaptive recommendation algorithms, virtual laboratory platforms) function not as passive information carriers but as "cognitive partners" sharing cognitive load. They deliver personalized support based on learners' real-time states, such as precisely identifying knowledge gaps through diagnostic feedback, thereby substantially extending and enhancing learners' overall cognitive capabilities.

3.3 Transformation of Thinking Frameworks: From Linear Logic to Systems Thinking

Epistemology not only focuses on "what knowledge is" and "how cognition occurs", but also profoundly influences our "how to think". This perspective on thinking determines the basic mode of analyzing and solving problems in the learning process. Traditional textbooks often embed and reinforce a linear way of thinking, while STs, with their structural, dynamic, and associative designs, effectively promote the systematic upgrading of thinking paradigms.

3.3.1 *Linear Thinking in Traditional Textbooks*

Traditional textbooks universally adhere to a "linear logic"-centered thinking framework in content organization and cognitive guidance. This paradigm is deeply influenced by mechanistic materialism reductionism, which tends to decompose complex wholes into mutually independent components and organizes learning along a single path from simple to complex and cause to effect. Under this framework, textbooks typically present a fixed sequence of "concept-principle-application-exercise," packaging knowledge into discrete modules that guide learners along a predetermined progressive path.

While this linear thinking model aids learners in mastering logical connections between foundational knowledge points, it restricts cognitive horizons and fails to cultivate the ability to analyze problems from holistic perspectives or grasp intrinsic connections between phenomena. This approach inadvertently shapes a cognitive habit of seeking single deterministic solutions. When confronted with real-world complex problems characterized by multifactorial interdependencies, uncertainties, and dynamic evolution, the limitations of this mindset become particularly pronounced, rendering it inadequate for meeting the demands of the digital age for systemic cognition and complex problem-solving capabilities (Wu et al., 2023).

3.3.2 *Systems Thinking Activation in STs*

STs transcend linear thinking limitations by embedding systems theory principles at their core, specifically designed to cultivate learners' systemic thinking capabilities. Systems theory emphasizes holistic analysis, focusing on interactions among system components, dynamic equilibrium, and evolutionary patterns. Leveraging technological empowerment, STs utilize their networked, interactive, and multidimensional characteristics to help learners comprehend intrinsic knowledge relationships from an integrated perspective.

(1) Networked Knowledge Structures. Through technologies such as knowledge graphs and concept maps, STs organize knowledge points into interconnected node networks. Learners can initiate exploration from any concept, following multiple pathways to intuitively visualize multifaceted connections between concepts. This presentation mode breaks traditional chapter boundaries, enabling learners to construct three-dimensional, interconnected knowledge systems that reveal systemic "ripple effects throughout the system" when any single element is altered.

(2) Interactive Simulation Exploration. In disciplines involving complex systems, learners engage in interactive simulations to observe system operations firsthand—for example, adjusting variables in ecological or economic models and observing real-time chain reactions, including unpredicted "emergent phenomena." This immersive experience helps learners transcend simplistic linear causality logic, fostering profound understanding of dynamic complexity.

(3) Multidimensional Perspective Presentation. For complex socio-technical issues, STs integrate perspectives and evidence from diverse disciplines and stakeholders, visualizing argumentation structures. This enables learners to compare underlying assumptions, evidence, and logical chains across viewpoints, thereby comprehending problem complexity and multidimensionality while cultivating critical and dialectical thinking skills.

In conclusion, STs transform the learning process from a passive "single-track journey" into an active "constructive exploration in complex networks." Rather than delivering deterministic knowledge endpoints, they establish a dynamically connected exploration field that encourages learners to adopt holistic and relational perspectives toward problem-solving, grasp dynamic complexity, and achieve cognitive upgrades from fragmented understanding to systemic cognition.

4. Axiological Implications: The Value Transition from Instrumental Rationality to Educational Rationality

Axiology addresses the core question of "for what purpose." Axiological analysis of STs fundamentally answers: "What educational goals do STs aim to achieve?" This positioning marks a paradigm shift where STs transcend the instrumental rationality of efficiency and knowledge acquisition, returning to the educational rationality of promoting comprehensive, free human development—a fundamental value leap.

4.1 Core Value: Dialectical Unity of Standardized Instruction and Personalized Development

The most significant value breakthrough of STs lies in achieving the dialectical unity between the "efficiency logic of standardized instruction" and the "humanistic logic of personalized development" within mass education. Rather than negating standardization, STs use technology as a lever to ensure educational quality and equity while creating space for individual growth.

4.1.1 *Efficiency Logic of Standardized Instruction and Its Limitations*

Since the industrialization era, modern education systems have relied on "standardization" as the core logic for mass knowledge dissemination and formal educational equity. This logic, dominated by Max Weber's concept of instrumental rationality, pursues predefined, quantifiable teaching objectives through standardized curricula, textbooks, and assessments.

Under this value orientation, traditional textbooks function as key carriers of standardized knowledge by:

Fixing uniform knowledge points, instructional sequences, and practice tasks.

Ensuring content stability and repeatability, enabling batch knowledge transmission and significantly improving efficiency in large-scale instruction.

However, the excessive expansion of instrumental rationality leads to profound drawbacks:

Learners are treated as "products" to be uniformly processed, neglecting individual uniqueness, potential, and developmental rhythms.

"One-size-fits-all" textbook designs fail to meet advanced learners' need for exploration or basic learners' demand for reinforcement.

Suppressed individual development prevents the realization of holistic growth (Yu & Liu, 2022).

4.1.2 *Humanistic Logic of Personalized Development and Technological Realization*

Education's ultimate purpose should be the liberation, growth, and self-actualization of every individual. This humanistic value rationality requires education to respect and adapt to learners' individual differences. Yet, under traditional technological conditions, personalized education relied on scarce teaching resources and high costs, making large-scale implementation difficult.

STs provide unprecedented technological possibilities to resolve the contradiction between standardization and personalization, achieving their dialectical unity:

(1) Macro-Level Standardization.

STs strictly follow national curriculum standards.

Ensure systematic mastery of core knowledge, key competencies, and fundamental values.

Safeguard education's public nature, foundational role, and equity—serving as the "main highway" of education.

(2) Micro-Level Personalization.

Exploration "Side Paths": Leveraging learning analytics, AI, and big data, STs create personalized learning pathways for each student.

Dynamic Learner Profiling: Continuous diagnostic assessments generate real-time learner profiles.

Adaptive Support: Tailored resources, path planning, and instant feedback align with individual rhythms, interests, and potentials.

Thus, STs transform the ancient educational ideal of teaching according to individual aptitude from a "pedagogical art" dependent on teachers' personal wisdom and experience into a scalable "educational science." While upholding equity as the educational baseline, STs dramatically expand the upper limits of learner individuality, achieving a value leap from instrumental rationality to educational rationality.

4.2 Practical Value: The Capability Transformation from Knowledge Memorization to Situational Response

The transformation of practical value represents a critical dimension of STs' value leap—the core shift from the instrumental orientation of traditional textbooks ("abstract rule memorization") to the competence-oriented orientation of "complex situational response." This transformation aligns with modern educational concepts centered on core competence cultivation, deeply integrating knowledge acquisition with practical application to overcome the traditional dilemma of "disconnection between learning and application."

4.2.1 *Traditional Value Orientation: Abstract Rule Memorization*

In traditional pedagogical paradigms, textbooks' practical value primarily manifests in helping learners memorize and understand abstract disciplinary knowledge, concepts, and rules. Learning is perceived as preparation for future application, where "application" is often reduced to solving well-structured, single-answer problems in standardized tests. This value orientation creates a severe disconnect between learning and practice.

Learners may master the mathematical formulas of Newton's Three Laws of Motion yet struggle to explain everyday mechanical phenomena; they may recite extensive English vocabulary and grammar rules but fail to engage in effective cross-cultural communication. This type of knowledge, termed "inert knowledge," can only be retrieved in specific testing contexts but cannot be flexibly applied in real-world, complex situations.

At its core, this value orientation severs the intrinsic connection between knowledge and practice. It treats knowledge as context-independent symbolic systems and equates practical competence with the mere recall and application of existing rules. This approach fails to cultivate learners' core competencies and cannot meet the demands of the digital age for higher-order thinking and practical innovation capabilities.

4.2.2 *Competence-Oriented Value of Complex Situational Response*

Contemporary educational reforms are undergoing a structural shift from knowledge mastery to competence cultivation. Competence fundamentally refers to an individual's integrated capacity to effectively mobilize cognitive resources, practical skills, and value judgments when facing authentic, uncertain situations. STs' practical value precisely aligns with this competence-oriented transformation. They transcend the mere goal of making learners "know what" to developing their abilities to "know how to do" and "know why to do," echoing Bloom's Taxonomy of Cognitive Objectives and advancing learning from lower-order "remembering" and "understanding" to higher-order "analyzing," "evaluating," and "creating."

(1) Realization of Contextualized Learning. Leveraging virtual reality (VR) and augmented reality (AR), STs embed abstract knowledge into highly realistic, complex problem scenarios. Learners transition from passive observers to active participants who must advance situations through hands-on operations, data analysis, and strategic decision-making. This establishes effective connections between knowledge and reality through "learning-by-doing."

(2) Cultivation of Transferable Competencies. By providing diverse, variant problem scenarios, STs guide learners to transfer knowledge and strategies acquired in one context to new, different contexts. This promotes deep conceptual understanding and flexible knowledge transfer.

(3) Systematic Development of Higher-Order Thinking. When confronting complex situations, learners must engage in critical analysis, solution creation, and continuous reflection. STs systematically support these skills through:

Open-Ended Inquiry Tasks: Designing problems with multiple valid solutions.

Cognitive Scaffolding: Providing just-in-time hints, expert modeling, and metacognitive prompts.

Collaborative Platforms: Facilitating peer feedback and cross-perspective discussions through AI-moderated forums.

Process-Oriented Feedback: Offering granular, actionable insights based on multimodal learning analytics.

In conclusion, STs re-anchor learning from "knowledge storage for exams" to "competence cultivation for the future," marking a fundamental transformation in practical value-from inert knowledge memorization to dynamic situational response. This shift not only addresses the longstanding "transfer problem" in education but also establishes a scalable framework for nurturing 21st-century competencies in the digital age.

4.3 Humanistic Value: Resolving the Conflict Between Instrumentalization and Subjectivity Manifestation

The transcendence of humanistic value represents the ultimate pursuit of STs' value leap—the core challenge of overcoming the "instrumentalization of humans" potentially caused by technology, with the ultimate goal of achieving learners' subjectivity manifestation. This pursuit profoundly reflects education's critical transcendence over instrumental rationality, reaffirming that education is an axiological activity fundamentally concerned with cultivating "humanity."

4.3.1 *Risks of Technological Instrumentalization and Erosion of Humanistic Care*

Technology is inherently a double-edged sword. While STs offer tremendous potential, they also carry profound value risks: the instrumentalization tendency of technology may erode education's humanistic essence. This risk manifests in three critical dimensions:

(1) Dataism and Algorithmic Bias. Over-reliance on quantified data and algorithmic decision-making risks falling into the "measurementism" trap. It may reduce complex learning processes to measurable metrics, neglecting learners' emotions, attitudes, and values—humanistic qualities resistant to quantification. For instance, algorithmic grading systems might prioritize test scores over creativity or ethical reasoning.

(2) Over-Control and Erosion of Subjectivity. Excessively "intelligent" adaptive systems may predetermine all learning pathways, depriving learners of rights to explore, make mistakes, and choose. According to Self-Determination Theory in psychology, autonomy is the cornerstone of intrinsic motivation. Excessive external control undermines learners' agency and responsibility, transforming them into passive recipients of algorithmic prescriptions.

(3) Technological Alienation and Emotional Detachment. Education is fundamentally an intersubjective dialogue and resonance. If human-machine interaction excessively displaces authentic interpersonal interactions, it weakens emotional connections between teachers and students, and among peers, depriving education of warmth and humanistic care (Holmes et al., 2022).

4.3.2 *Subjectivity Manifestation: The Humanistic Value Destination of STs*

A truly "intelligent" textbook transcends technical sophistication by rooting in educational wisdom that repositions learners as autonomous, emotionally rich, and value-diverse individuals rather than singular nodes in knowledge transmission. This value shift is essential for STs to align with educational rationality and construct profound ethical significance.

(1) From "Adaptation" to "Empowerment". STs should transcend merely adapting learners to preset pathways by empowering them as self-directed learners. Systems must provide diverse resource choices and pathway possibilities, enabling learners to set personalized goals, lead inquiry processes, and reflectively adjust strategies.

(2) From "Efficiency" to "Experience". Beyond optimizing efficiency, STs must prioritize qualitative learning experiences. Designers should craft activities that stimulate curiosity, induce "flow" states, and foster deep engagement, transforming learning into a joyful, meaningful existential experience.

(3) From "Human-Computer Interaction" to "Human-Human Connection". STs should function as catalysts for social interaction rather than substitutes. They must integrate robust collaboration tools to facilitate group discussions and project-based teamwork, positioning technology as a bridge for strengthening interpersonal bonds.

(4) Ethical Care and Value Guidance. Humanistic concerns and ethical values must be embedded in content design and algorithmic logic. Systems should guide learners to critically engage with social justice, ethical responsibility, and cultural heritage, cultivating holistic personality development and civic literacy.

In the final analysis, the ultimate value of STs lies in harmonizing technological rationality with humanistic spirit. They serve knowledge but ultimately pursue wisdom; they employ technology but ultimately aim for humanity. Only when STs can activate learners' potential, respect their choices, enrich their emotions, and elevate their moral horizons can they truly complete the value leap from instrumental rationality to educational rationality, becoming a transformative force for human freedom and holistic development.

5. Cognitive Logic: The Internal Operating Mechanism of STs

If ontology, epistemology, and axiology collectively form the "philosophical core" of STs, then cognitive logic constitutes their "technical engine" for dynamic operation. Unlike traditional textbooks' static information presentation, STs integrate cognitive science theories with digital technologies to construct a learner-centered, cognition-driven operational framework. This framework achieves the transformation from knowledge transmission to competence construction through four interlocking logic l oops: generation, adaptation, collaboration, and evolution.

5.1 Generative Logic: Problem Spaces and Cognitive Dissonance

Learning does not originate from passive information reception but from emergent authentic problems and disrupted cognitive equilibrium. Thus, STs' primary cognitive logic lies in creating environments that stimulate intrinsic inquiry motivation.

5.1.1 *Multidimensional Design of Problem Spaces*

Problem spaces function not only as cognitive scaffolds but as arenas for mental activity. By integrating real-world complexity with virtual technology's expansibility, STs construct concrete, hierarchical, and open-ended inquiry environments. This multidimensional design is philosophically grounded in constructivist learning environment theory, aiming to reconstruct the complex contexts of knowledge production and application to fundamentally ignite learners' curiosity, problem awareness, and sustained inquiry drive.

(1) Hybrid Reality and Cross-Domain Integration. Leveraging virtual reality (VR), augmented reality (AR), and digital twin technologies, STs transcend physical spatiotemporal constraints:

Real-World Anchoring: Real-time big data integration embeds contemporary social hotspots and industry frontiers into pedagogical scenarios.

Immersive Simulation: Reconstructing inaccessible micro/macro/hazardous environments to design interdisciplinary tasks that foster holistic, divergent thinking beyond single-discipline boundaries.

(2) Dynamic Balance of Challenge and Support. Guided by Vygotsky's Zone of Proximal Development (ZPD), STs implement gradient structures from foundational to advanced levels:

Optimal Challenge: Problems positioned at the edge of learners' current capabilities to stimulate exploration without inducing helplessness.

Gamified Engagement: Narrative-driven tasks and instant feedback systems that encourage non-standard solutions, transforming extrinsic motivation into intrinsic engagement through immersive experiences.

5.1.2 *Precision-Triggered Cognitive Dissonance*

Cognitive conflict is the core intrinsic driving force behind the reorganization and development of cognitive structures. According to Piaget's theory of cognitive development, true learning is not merely the accumulation of information, but rather a dynamic process where individuals adjust their existing schemas through the "accommodation" mechanism to restore cognitive balance when the assimilation of new experiences fails. One of the core capabilities of STs lies in leveraging intelligent algorithms to transform this psychological mechanism into a designable and intervenable technological teaching process.

(1) Pre-Instructional Diagnostics. Deployment of diagnostic tasks to expose and challenge learners' misconceptions, followed by:

Contradictory Stimuli: Introduction of counterexamples, logical paradoxes, or heterogeneous perspectives.

Targeted Disruption: Forcing learners to confront the limitations of prior experiences, creating strong cognitive disequilibrium that triggers intrinsic motivation for schema revision.

(2) Progressive Cognitive Tension. During learning, STs introduce viewpoints/cases slightly beyond current cognitive levels. This necessitates deep analysis, integration, and self-explanation.

(3) Constructive Threshold Control. A graduated mechanism ensures cognitive tension remains within the ZPD:

Stepped Progression: Incremental problem sequences dynamically adjusted by real-time performance analytics.

Zone Maintenance: Balancing disruption and achievability to sustain active cognitive engagement, ultimately achieving substantive knowledge internalization and transfer through deep analysis and self-explanation (Zhang et al., 2021).

5.2 Adaptive Logic: Learner Modeling and Cognitive Scaffolding

When cognitive dissonance occurs, learners enter a critical period where external support must be timely and appropriate to prevent dissonance from escalating into cognitive failure and interrupting the learning process. The core of adaptive logic lies in constructing dynamic, precise, and withdrawable cognitive scaffolding to help learners cross the Zone of Proximal Development (ZPD), enabling successful transition from potential developmental levels to independent problem-solving capabilities.

5.2.1 *Dynamic Construction of Learner Models*

Adaptive instruction requires precise representation of learners' states. STs transcend traditional "accuracy-only" metrics through multimodal learning analytics, constructing a learner model integrating knowledge states, cognitive processes, metacognition, and affective-motivational factors.

First, structured knowledge representation leverages dynamic knowledge graphs and Bayesian knowledge tracing to map not only mastery probabilities of discrete concepts but also internal knowledge architectures. This enables system differentiation between conceptual gaps and structural disconnections.

Second, cognitive trajectory tracking captures micro-level interactions (e.g., dwell time on critical information, tool usage sequences, page-switching frequency) to reconstruct learning pathways. These paradata identify whether learners operate under efficient strategies or trial-and-error loops, revealing cognitive bottlenecks.

Third, holistic modeling of metacognition and affective factors incorporates self-assessment modules for monitoring regulation capacity and employs affective computing to quantify motivation, academic emotions, self-efficacy, and cognitive styles.

Integrated via machine learning, these heterogeneous data enable real-time model updates: each interaction triggers iterative refinements, ensuring the system's representation evolves in synchrony with learners' cognitive development rather than lagging behind.

5.2.2 *Self-Adaptive Adjustment of Cognitive Scaffolding*

STs enable algorithm-driven, intelligent scaffolding based on learner models. This goes beyond linear resource delivery to encompass adaptive interventions in scaffolding type, timing, intensity, and evolutionary logic.

First, scaffolding types differentiate dynamically:

Conceptual scaffolding (e.g., ontology mapping, analogical explanations, attribute highlighting) reduces intrinsic cognitive load for conceptual difficulties.

Procedural scaffolding (e.g., task decomposition, algorithmic guidance) addresses problem-solving barriers.

Strategic scaffolding (e.g., mind maps, heuristic questions) combats cognitive rigidity.

Metacognitive scaffolding (e.g., progress monitoring prompts, reflection triggers) enhances learner agency.

Second, timing prioritizes "on-demand activation" to preserve "flow" states. Systems monitor cognitive states in real-time, intervening only when anomalies occur (e.g., inaction stagnation, high-frequency invalid attempts). Algorithms weigh historical success rates and task difficulty to deliver timely, non-intrusive support.

Third, intensity adjusts dynamically via gradient modulation:

Novices receive explicit, step-by-step guidance.

Proficient learners get prompting clues or reflective questions to encourage autonomy.

Fourth, scaffolding evolves through gradual withdrawal, transferring responsibility from STs to learners. As proficiency increases, systems reduce prompt visibility, delay response timing, or remove scaffolding entirely.

The evolutionary logic simulates the role of a mentor in traditional apprenticeships: transitioning from initial "hands-on" demonstrations, to "side-by-side" collaboration, to "you do, I watch" supervision, and ultimately achieving "hands-off" independence. This process ensures that learning challenges are always maintained within the learners' zone of proximal development, avoiding anxiety caused by overly high difficulty levels and preventing cognitive laziness caused by excessive reliance on assistance (Xie et al., 2025).

In summary, the construction of a differentiated cognitive scaffold under adaptive logic is essentially a dialogue between technology and humanity. It utilizes the rationality of algorithms to precisely calculate the distance between teaching and learning, and employs the warmth of education to provide just the right support at every moment when cognition is blocked. This mechanism truly achieves precision and personalization in teaching according to students' aptitudes in a large-scale teaching environment, opening up a new technological path for learners to deepen their understanding and cultivate their independent personality.

5.3 Collaborative Logic: Cognitive Division of Labor and Dual Feedback Loops

In the digital field constructed by STs, learning agents expand into a human-machine distributed cognition system comprising learners and intelligent systems. This relationship transcends traditional subject-object dualism, advancing toward deep collaboration based on cognitive division of labor and bidirectional feedback, thereby driving learning to deeper cognitive levels.

5.3.1 *Cognitive Division of Labor: Offloading and Complementary Strengths*

The foundation of collaboration lies in precise identification and rational allocation of human-machine cognitive advantages. According to Distributed Cognition Theory, STs should implement cognitive offloading mechanisms—reducing learners' internal information processing load to liberate higher-order thinking potential.

(1) Role Definition of Intelligent Systems. Machines possess inherent advantages in symbolic processing, data analysis, and rule application. STs act as a "cognitive prosthesis" by:

Pattern Recognition: Detecting trends in large-scale datasets (e.g., error patterns in physics problem-solving).

Real-Time Simulation: Modeling dynamic systems (e.g., climate change scenarios with parameter adjustments).

Automated Retrieval: Instant access to structured knowledge repositories (e.g., historical precedents in legal case analysis).

Precision Computation: Performing repetitive high-load tasks (e.g., matrix operations in machine learning algorithms).

These low-order but high-load cognitive tasks would otherwise saturate working memory and hinder deep reasoning if handled solely by humans.

(2) Core Domains of Human Learners. With mechanical tasks offloaded to machines, learners refocus on human-unique cognitive domains:

Non-Monotonic Reasoning: Commonsense inference beyond rigid logical rules (e.g., resolving contradictory historical sources).

Ambiguous Decision-Making: Ethical choices in complex contexts (e.g., trade-offs in medical triage scenarios).

Creative Synthesis: Cross-domain innovations (e.g., designing sustainable energy systems by integrating ecology and engineering).

Critical Evaluation: Assessing evidence validity in misinformation-rich environments.

Value-Laden Judgments: Balancing technological progress with cultural preservation in AI ethics debates.

Therefore, the ideal cognitive division paradigm is as follows: STs undertake the "process support" function, responsible for the automated organization, presentation, calculation, and preliminary processing of information, freeing learners from the complex and mechanical cognitive load; while learners focus on "meaning imposition", concentrating on proposing hypotheses, designing inquiry plans, interpreting complex results, and engaging in critical integration and creative application. This division of labor makes the overall cognitive efficiency of "human + machine" far exceed the sum of either party alone, achieving the enhancement of intelligence.

5.3.2 *Dual Feedback Loops: Recursive Feedback and Co-Evolutionary Optimization*

Human-machine collaboration is not a static juxtaposition but a dynamic cybernetic process characterized by continuous action-feedback-adjustment recursion. This process forms a dual feedback loop mechanism, where human cognition improves and machine intelligence evolves simultaneously.

(1) Primary Feedback Loop. When learners initiate cognitive actions in STs, the system captures these behaviors and generates feedback that transcends behaviorist "correct/incorrect" judgments to deliver epistemologically meaningful guidance:

Explanatory Feedback: Instead of directly providing answers, the system traces error root causes through causal chain analysis and dynamically links to relevant knowledge graphs, facilitating conceptual assimilation and accommodation. For example, in physics problem-solving, it might highlight misapplied force vectors in Newtonian mechanics.

Visualized Feedback: Leveraging data visualization techniques, the system overlays learners' reasoning trajectories against expert models or ideal paths. This visual contrast triggers metacognitive monitoring, enabling learners to explicitly perceive their cognitive gaps.

Heuristic Feedback: Through Socratic questioning or strategic hints, the system converts passive reception into active inquiry. Learners then refine mental models and adjust strategies for iterative actions, completing knowledge internalization (Hudson, 2021).

(2) Secondary Feedback Loop. This distinguishes STs from traditional teaching aids. While learners adjust strategies, their interaction data streams—including hesitation duration, help-seeking patterns, and post-correction accuracy—recursively feed into STs'base-layer algorithms:

Learner Model Calibration: Real-time updates to cognitive ability estimation and preference inference.

Algorithmic Self-Optimization: Usage-driven optimization of scaffolding policies through reinforcement learning—identifying which feedback types most effectively reduce learners' cognitive dissonance in specific contexts.

This "usage-driven optimization" transforms STs into personalized cognitive partners, increasingly attuned to individual learners' needs through continuous co-evolution.

In summary, the human-machine collaborative logic has constructed a tightly coupled cognitive community. Textbooks become more "understanding" of learners in the process of "teaching", and learners become more adept at learning due to receiving precise support in the process of "learning". The collaborative logic thus elevates STs from static learning resources to learning partners capable of engaging in deep dialogue with learners and jointly addressing cognitive challenges, truly realizing the paradigm reconstruction of the relationship between teaching and learning under the empowerment of technology.

5.4 Evolutionary Logic: Metacognitive Reflection and Cognitive Leap

Evolutionary logic points to education's ultimate destination—the awakening of learner subjectivity and qualitative transformation of cognitive structures. In the cognitive ecosystem constructed by STs, learning is no longer defined as linear task completion but as an evolutionary process of self-transcendence through sustained reflection. By embedding metacognitive reflection guidance mechanisms, STs drive learners from experiential accumulation toward wisdom generation.

5.4.1 *Monitoring and Introspection: Full-Cycle Metacognitive Guidance*

A necessary condition for deep learning is learners' ability to observe and regulate their own cognitive processes. Since metacognition is not innate, STs systematically externalize implicit thinking processes through scaffolding interventions across the self-regulated learning cycle:

(1) Pre-Learning. STs guide learners beyond passive task acceptance to active participation in learning design:

Structured Prompts: "Based on prior knowledge, what core challenges do you anticipate in this task? Which strategies will you employ to address them?"

Schema Activation: Visual organizers linking new content to existing cognitive frameworks (e.g., concept maps for historical causality analysis).

This places learning under metacognitive supervision from the outset.

(2) In-Progress Learning. At critical decision points or when potential difficulties are detected, STs intervene with contextualized metacognitive prompts:

Socratic Questioning: "What assumptions underlie your current approach? What evidence supports or contradicts your judgment?"

Attention Regulation: Real-time alerts for task drift (e.g., "You've spent 80% of time on data collection but none on hypothesis testing").

These mechanisms cultivate learners' ability to monitor and regulate their cognitive states in real-time (Xu, 2021).

(3) Post-Learning. After task completion, STs generate visual feedback reports showing:

Cognitive Trajectories: Heatmaps of reasoning pathways compared to expert models.

Strategy-Outcome Mapping: Performance metrics linked to specific decision points (e.g., error rates after hypothesis revisions).

Guided questions then facilitate abstract principle extraction:

"What key conceptual shifts occurred during this process?"

"How did your final execution deviate from initial plans, and why?"

This drives the transition from concrete experience to abstract generalization.

5.4.2 *Abstraction and Reconfiguration: Triggers for Cognitive Leaps*

Cognitive leaps represent structural reorganization rather than linear accumulation—transitioning from fragmented declarative knowledge to systematic procedural understanding, and from concrete experiences to generalized principles. STs create core conditions for such leaps through specific instructional design logic.

(1) Variation and Abstraction. According to variation theory, conceptual mastery arises from identifying critical attributes. STs generate massive variant examples while preserving core principles, systematically altering surface features across contexts. When learners solve problems across diverse scenarios, the system prompts comparative analysis of these variations. This forces learners to transcend contextual specifics, triggering the first cognitive leap: decontextualization from "concrete experiences" to "abstract schemata."

(2) Connection and Reintegration. Isolated facts lack transferability—only networked structures enable complex problem-solving. STs utilize dynamic knowledge graphs to explicitly map relationships between new and prior knowledge. During meaning construction, systems continuously prompt learners to identify logical interfaces (e.g., causality, inclusion, opposition) between concepts. By anchoring new knowledge within existing cognitive frameworks, this process significantly enhances knowledge stability and retrieval efficiency, completing the second cognitive leap: integration from "fragmented islands" to "interconnected networks."

Under evolutionary logic, STs function as a cognitive leap engine. Through continuous metacognitive scaffolding and deep reflective practice guidance, they facilitate learners' transition from "learning knowledge" to "learning to think".

6. Conclusion: Toward a New Educational Landscape of "Human-Machine Synergetic Intelligence"

The emergence of STs represents neither a superficial digitization of traditional pedagogical materials nor a mere medium-level technological transplantation. Rather, it constitutes a paradigmatic revolution that penetrates the foundational architecture of education. This paper systematically constructs a theoretical framework for STs' transformation from "knowledge carriers" to "cognitive engines" by integrating three philosophical dimensions:

ontology, epistemology, and axiology. Through in-depth analysis of their internal cognitive operating mechanisms, this study reveals that the essence of this transformation lies in redefining the triadic relationship between humans, technology, and knowledge in the digital era. The implications extend beyond morphological updates of educational materials, heralding the arrival of a new educational landscape characterized by "human-machine synergetic intelligence".

Firstly, STs have reconstructed the fundamental concepts of pedagogy, achieving an ontological leap from "entity thinking" to "relational thinking".

From a traditional perspective, textbooks are static "objects" and knowledge is solidified "content". However, this study reveals that STs have evolved into a dynamic and generative "cognitive ecosystem", with the focus of its ontology shifting from "knowledge as an object" to "interaction as a process". This implies that the construction of educational resources is no longer simply about piling up multimedia materials, but rather about building a smart environment that can perceive learners' states, respond to cognitive needs, and evolve together with learners.

Secondly, STs establish the epistemological foundation of "collaborative construction" and promote a paradigm shift from one-way transmission to distributed cognition.

STs follows social constructivism and constructs an open and dynamic "human-machine distributed cognitive system". In this system, the textbook undertakes low-order cognitive tasks, achieving effective "cognitive unloading", allowing learners to focus their limited cognitive resources on high-order thinking activities such as meaning construction, critical reflection, and value judgment. This transformation promotes the upgrading of thinking mode from linear reductionist logic to networked systems thinking, enabling learners to grasp dynamic connections in complex systems, thereby truly acquiring core competencies to cope with an uncertain future.

Thirdly, STs have surpassed instrumental rationality, returning to and highlighting the educational value rationality of "people-oriented".

STs resolve the contradiction between standardized teaching and personalized development, transforming "teaching students according to their aptitude" from a manual, artisanal process to a scientifically implemented, large-scale approach. More importantly, their built-in metacognitive reflection mechanism strives to internalize external technological assistance into learners' psychological functions, propelling them from "learning knowledge" to "learning to think and reflect." This indicates that STs do not replace human thinking with algorithms, but rather use algorithms as a ladder to defend and enhance human subjectivity, thus maintaining the fundamental goal of educating people in the wave of digitalization.

This series of theoretical reconstructions urgently demands changes in current educational practices:

Firstly, it redefines "learning". Learning is no longer simply seen as the transmission and internalization of knowledge from textbooks to learners' minds, but rather should be understood as a process of active exploration, positive adaptation, and continuous growth of individuals within a cognitive ecosystem. The effectiveness of learning depends not only on the learners' subjective initiative, but also on whether the cognitive ecosystem they are in can provide appropriate resources, challenges, and feedback.

Secondly, reconstruct the power relationship between "teaching and learning". Teachers are no longer monopolists of knowledge, but architects of cognitive ecology and coordinators of human-machine relationships; students are no longer terminals receiving instructions, but explorers with cognitive decision-making power. The focus of teaching must shift from "how to transmit efficiently" to "how to design a high-cognitive exploration space".

Thirdly, we should innovate the standard system for evaluating teaching materials. We can no longer evaluate STs solely based on the accuracy of content or the elegance of the interface. Instead, we should establish a new standard based on "cognitive increment" - that is, to assess whether it triggers deep cognitive conflict, provides precise scaffolding, and promotes the occurrence of higher-order thinking.

Of course, as a theoretical precursor, this study still has its limitations and unresolved challenges.

On the one hand, the "black box" risks and ethical boundaries urgently need to be clarified. The algorithmic decision-making logic of large AI models is often uninterpretable. How can we ensure that algorithmic recommendations do not implicitly contain cultural biases? How can we prevent "adaptive scaffolding" from leading to learners' information silos and the degradation of willpower? These issues require in-depth discussions in subsequent research at both the technical and normative levels.

On the other hand, the validation of empirical data needs further enhancement. Future research should delve into real teaching scenarios, utilizing long-term longitudinal experiments and multimodal data analysis to verify the practical effectiveness of the four logics across different disciplines and educational stages. Based on these findings, the theoretical model should undergo iterative refinement.

All in all, the advent of STs signifies a paradigm shift in education, transitioning from "industrialization" to "digitalization and intelligence." In this process, technology has transcended the mere role of a tool and evolved into a "cognitive engine" driving cognitive advancement. Looking ahead, we envision STs that can truly transform computing power into understanding individual learners, ensuring that the intervention of digital and intelligent technology is no longer for control and discipline, but rather for awakening and liberation. This is not only the inevitable path for the transformation of teaching material forms, but also the future direction that digital transformation of education should take.

Data Availability Statement

The dataset generated and analyzed during the current study is available from the corresponding author upon request.

Conflicts of interest

The authors declare no conflict of interest.

Open Access

References

Abdelrahman, G., Wang, Q., & Nunes, B. (2023). Knowledge tracing: A survey. ACM *Computing Surveys, 55*(11), Article 224. https://doi.org/10.1145/3569576

Bearman, M., & Ajjawi, R. (2023). Learning to work with the black box: Pedagogy for a world with artificial intelligence. *British Journal of Educational Technology, 54*(5), 1160–1173. https://doi.org/10.1111/bjet.13337

Chen, L., Zheng, Q., & Xu, Y. (2022). Basic principles and overall ideas of Internet-driven educational reform: Theoretical and policy research on the innovative development of 'Internet plus education' (Part 1). *e-Education Research, 43*(3), 5–11.

Chiu, T. K. F. (2022). Applying the self-determination theory (SDT) to explain student engagement in online learning during the COVID-19 pandemic. *Journal of Research on Technology in Education, 54*(S1), S14–S34. https://doi.org/10.1080/15391523.2021.1891998

Crompton, H., & Burke, D. (2023). Artificial intelligence in higher education: The state of the field. *International Journal of Educational Technology in Higher Education, 20*, Article 22. https://doi.org/10.1186/s41239-023-00392-8

Gui, Y., Cai, Z., Yang, Y., Kong, L., Fan, X., & Tai, R. H. (2023). Effectiveness of digital educational game and game design in STEM learning: A meta-analytic review. *International Journal of STEM Education, 10*, Article 36. https://doi.org/10.1186/s40594-023-00424-9

Holmes, W., Porayska-Pomsta, K., Holstein, K., Sutherland, E., Baker, T., Buckingham Shum, S., Santos, O. C., Rodrigo, M. T., Cukurova, M., Bittencourt, I. I., & Koedinger, K. R. (2022). Ethics of AI in education: Towards a community-wide framework. *International Journal of Artificial Intelligence in Education, 32*(3), 504–526. https://doi.org/10.1007/s40593-021-00239-1

Huang, X., Zou, D., Cheng, G., Chen, X., & Xie, H. (2023). Trends, research issues and applications of artificial intelligence in language education. Educational Technology & Society, 26(1), 112–131. https://doi.org/10.30191/ETS.202301_26(1).0009

Hudson, D. L. (2021). Learning how to learn from digital textbooks: Evidence-informed recommendations for instructors and students. *Canadian Psychology/Psychologie canadienne, 62*(4), 377–384. https://doi.org/10.1037/cap0000304

Hwang, G.-J., Xie, H., Wah, B. W., & Gašević, D. (2020). Vision, challenges, roles and research issues of artificial intelligence in education. Computers and Education: *Artificial Intelligence, 1*, Article 100001. https://doi.org/10.1016/j.caeai.2020.100001

Järvelä, S., Zhao, G., Nguyen, A., & Chen, H. (2025). Hybrid intelligence: Human–AI coevolution and learning. *British Journal of Educational Technology, 56*(2), 455–468. https://doi.org/10.1111/bjet.13560

Koć-Januchta, M. M., Schönborn, K. J., Roehrig, C., Chaudhri, V. K., Tibell, L. A. E., & Heller, H. C. (2022). 'Connecting concepts helps put main ideas together': Cognitive load and usability in learning biology with an AI-enriched textbook. International Journal of Educational *Technology in Higher Education, 19*, Article 11. https://doi.org/10.1186/s41239-021-00317-3

Li, H., & Liu, X. (2024). Potential risks and mitigation measures in understanding digital textbooks from the perspective of philosophical hermeneutics. *Global Education, 53*(7), 39–49.

Li, W., Zeng, B., & Zhao, L. (2025). The reshaping and innovation of digital textbooks for vocational education in the digital and intelligent era. *Education and Vocation*, (6), 72–78.

Li, Y. (2024). The evolution and reconstruction of textbook concepts in the digital and intelligent era. *Journal of East China Normal University (Educational Sciences), 42*(12), 63–72.

Liu, B., Yuan, T., Ji, Y., Liu, B., & Li, L. (2021). Empowering educational evaluation with intelligent technology: Connotation, overall framework, and practical path. *China Educational Technology*, (8), 16–24.

Sailer, M., & Homner, L. (2020). The gamification of learning: A meta-analysis. *Educational Psychology Review, 32*(1), 77–112. https://doi.org/10.1007/s10648-019-09498-w

Sosnovsky, S., Brusilovsky, P., & Lan, A. (2025). Intelligent textbooks. *International Journal of Artificial Intelligence in Education, 35*(3), 967–986. https://doi.org/10.1007/s40593-024-00451-9

Wang, Y., & Zheng, Y. (2023). The practical dilemmas, meaning reconstruction, and model construction of personalized learning in the age of intelligence. *e-Education Research, 44*(3), 28–35.

Wijaya, T. T., Cao, Y., & Li, X. (2025). The impact of digital mathematics textbooks on teacher–student interaction: Evidence from behavioral sequence analysis. *International Journal of Human–Computer Interaction, 41*(15), 9450–9465. https://doi.org/10.1080/10447318.2024.2426033

Williamson, B., Eynon, R., & Potter, J. (2020). Pandemic politics, pedagogies and practices: Digital technologies and distance education during the coronavirus emergency. *Learning, Media and Technology, 45*(2), 107–114. https://doi.org/10.1080/17439884.2020.1761641

Wu, H., Han, G., Lou, X., & He, J. (2023). Overall pattern, hot topics, and development trends of digital textbook research from an international perspective. *Digital Education, 9*(1), 24–32.

Xie, T., Li, Y., & Dai, Y. (2025). Exploring pedagogical dynamics via teachers' interactions with digital textbook platforms. *International Journal of Human–Computer Interaction, 41*(12), 7873–7883. https://doi.org/10.1080/10447318.2024.2400413

Xu, Y. (2021). Exploring the three-dimensional landscape of higher vocational education textbooks in the age of artificial intelligence. *China University Teaching*, (Z1), 117–122.

Yang, Z. (2023). Digital development of higher education: Connotation, stages, and implementation paths. *China Higher Education*, (2), 16–20.

Yu, S., & Liu, E. (2022). Transformation and reform of smart education. *e-Education Research, 43*(1), 16–23, 62.

Yu, S., Wang, Z., & Zhang, T. (2025). A digital and intelligent textbook technology model based on learning elements. *e-Education Research, 46*(11), 114–121.

Zhai, X., Chu, X., Chai, C. S., Jong, M. S. Y., Istenič, A., Spector, M., Liu, J.-B., Yuan, J., & Li, Y. (2021). A review of artificial intelligence (AI) in education from 2010 to 2020. Complexity, 2021, *Article 8812542*. https://doi.org/10.1155/2021/8812542

Zhang, Y., & Zhang, S. (2025). How can digital education empower deep learning? An exploration of the path from the perspective of Heidegger's 'unconcealment' and 'enframing.' *Chinese Journal of Distance Education, 45*(10), 70–83.

Zhang, Z., Liu, D., & Xu, B. (2021). Core concept and technical implementation of intelligent digital textbook systems. *Open Education Research, 27*(1), 44–54.

Zhu, Z., & Hu, J. (2022). Exploring the essence of educational digital transformation and research prospects. *China Educational Technology,* (4), 1–8, 25.