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Article

A Transdisciplinary Unified Framework for Civilization Evolution: The Cognition-Substitution-Intensification Spiral Model

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Abstract

Human civilization has advanced through a sequence of profound transitions—from foraging bands to agricultural societies, industrial economies, information networks, and the emerging era of machine intelligence. Yet existing explanatory frameworks remain fragmented across disciplinary boundaries. This study proposes a transdisciplinary model that identifies cognitive breakthroughs as the primary driver of civilization evolution. These breakthroughs trigger two co-evolving mechanisms: paradigm substitution, which restructures technological and institutional orders, and efficiency intensification, which deepens the potential of the new paradigm. Together, they form an upward spiral—the Cognition-Substitution-Intensification (CSI) model—that governs long-run antihistorical dynamics. By integrating insights from complex systems theory, energy history, information theory, and innovation studies, the CSI model provides a unified explanation of past civilization transitions and offers a forward-looking framework for understanding the rise of intelligent civilization. The model further suggests that artificial intelligence, bio-computation, and quantum systems may constitute the next major cognitive breakthrough, reshaping the trajectory of human societies.

Keywords: civilization evolution; transmissibility; complex systems; cognitive breakthroughs; paradigm substitution; efficiency intensification; unified model

1. Introduction: From Transdisciplinary Inquiry to a Unified Model

The long arc of human civilization—from small bands of foragers to globally interconnected societies—has inspired extensive scholarly inquiry across history, sociology, economics, archaeology, and the philosophy of science. Yet these disciplines often illuminate only discrete fragments of the civilizational process [1]. Historians emphasize empirical contingencies [1]; sociologists focus on structural differentiation; economists model growth dynamics [2]; and historians of technology trace internal technological trajectories [3,4].

Such disciplinary perspectives operate like narrow spotlights—each illuminating a portion of civilization's structural landscape, but rarely revealing the underlying generative mechanisms. A transdisciplinary approach is therefore required, one capable of synthesizing insights across energy flows, information processing, technological paradigms, and institutional change [5–7].

Complex systems research conceptualizes civilization as an energy-processing and informatic processing system [8]. Information theory further demonstrates that increases in encoding and processing capacity strongly correlate with increased system complexity [9]. Historical evidence also points to long-wave structural transitions such as agrarian, industrial, and informational revolutions, each triggered by fundamental changes in epistemic capacity [10–12].

These observations motivate a deeper question: Is there a primary first-principles mechanism that governs civilization evolution?

We argue that the answer lies in cognitive breakthroughs—transformations in collective information-processing architectures that alter energy use, technological paradigms, and institutional ordering. These breakthroughs initiate two coupled mechanisms: (1) paradigm substitution, characterized by structural rupture and creative destruction [13], and (2) efficiency intensification, corresponding to long periods of optimization following paradigm stabilization [14–16].

These processes form a positive-feedback spiral: the Cognition-Substitution-Intensification (CSI) model.

2. The Core Framework: The Cognition-Substitution-Intensification Spiral

This section presents the complete theoretical foundation of the Cognition-Substitution-Intensification (CSI) model by integrating conceptual analysis with a formal mathematical structure. The CSI spiral proposes that civilization evolution is driven by recursive interactions among (1) cognitive breakthroughs, (2) paradigm substitution, and (3) efficiency intensification. The following subsections provide a unified conceptual-mathematical exposition.

2.1. Cognitive Breakthroughs as Primary Drivers

Cognitive breakthroughs refer to qualitative expansions in a civilization's collective information-processing capacity. These breakthroughs include the emergence of symbolic systems (language, writing), epistemic frameworks (scientific method), computational architectures (digital computing), and algorithmic cognition (machine learning). Each breakthrough re-structures the cognitive boundary conditions of civilization and increases its ability to manage complexity [12,17].

Formally, cognitive capacity C_t evolves as:

$$C_{t+1} = C_t + \alpha f(K_t, T_t, I_t)$$

where: K_t denotes accumulated knowledge stock, T_t denotes technological complexity, I_t denotes information-processing efficiency, $f(\cdot)$ is a knowledge-creation function, α is the cognitive acceleration coefficient.

This formulation aligns with information-centric theories of civilization development [8].

2.2. Paradigm Substitution: Mechanism of Revolutionary Change

Paradigm substitution describes discontinuous structural transformations, such as:

- energy regime shifts (biomass → fossil fuels → renewable),
- technological revolutions (mechanization, electrification, digitization),
- institutional transitions (sheikdoms → bureaucratic states).

These transitions are triggered when systemic complexity exceeds cognitive capacity, generating a cognitive bottleneck.

Formally:

$$S_t = \beta \cdot \max(0, L_t - \lambda C_t)$$

where: S_t is substitution intensity, L_t is cognitive load (systemic complexity), λC_t is the cognitive threshold, β is the substitution sensitivity coefficient.

When $L_t > \lambda C_t$, the system undergoes creative destruction [15,17].

2.3. Efficiency Intensification: Deepening the Paradigm

Once a new paradigm stabilizes, the system enters a long phase of optimization and refinement. Efficiency intensification includes:

- energy efficiency gains,
- spatial intensification (urban density, agricultural yield),
- temporal intensification (communication and transport speed),
- informational intensification (Moore's law [16]),
- organizational intensification (lean systems, bureaucratic rationalization).

Formally:

$$I_{t+1} = I_t + \gamma(S_t)^\delta$$

where γ measures intensification efficacy and $\delta > 0$ reflects the magnitude of substitution-induced potential.

2.4. Unified Spiral Dynamics of Civilizational Evolution

The overall civilization potential Ω_t emerges from interactions among cognition, intensification, and energy availability:

$$\Omega_t = \phi_1 C_t + \phi_2 I_t + \phi_3 E_t$$

where E_t denotes accessible energy resources.

The system evolves along a self-reinforcing spiral:

$$C_t \rightarrow S_t \rightarrow I_t \rightarrow \Omega_t \rightarrow C_{t+1}$$

This dynamic captures the empirical structure of civilization history: each cognitive breakthrough triggers new paradigms, which are subsequently intensified until new bottlenecks appear [14,18,19]. The result is a cyclical yet upward evolutionary trajectory.

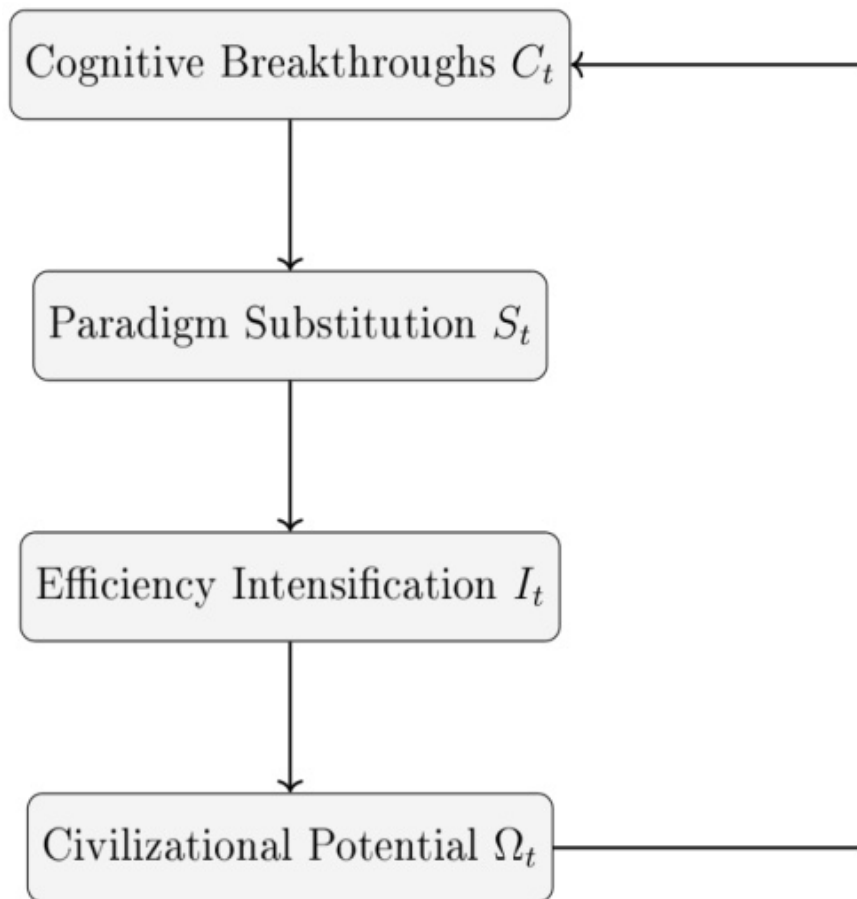


Figure 1. The Cognition-Substitution-Intensification Spiral.

This schematic illustrates the recursive and self-reinforcing structure underlying antihistorical civilization dynamics.

3. Case Studies: Historical Evidence for the CSI Model

To substantiate the CSI model, we examine four major civilization transitions: the emergence of agriculture, the rise of industrial civilization, the digital revolution, and the ongoing shift toward intelligent civilization. This approach aligns with Big History and long-cycle studies [1,20].

Each transition reflects a pattern: cognitive breakthroughs precede structural substitutions, followed by prolonged intensification phases. For example, the Industrial Revolution relied not simply on machinery but on the epistemic revolution of scientific reasoning [17].

The digital revolution exhibits similar patterns. The invention of the transistor and integrated circuits produced rapid substitution of analog systems, while decades of Moore's law represent intensification [16].

These processes support the model's claim that civilization evolves through alternating cycles of disruption and optimization [20].

Table 1. Historical Validation of the CSI Model.

Civilization Stage	Cognitive Breakthrough	Paradigm	Substitution	Efficiency	Intensification	Outcome
Hunter-Gatherer → Agricultural	language; domestication knowledge	nomadism agriculture	to settled agriculture	irrigation; fertilized tools	calendars; refined tools	rise in population and complexity
Agricultural → Industrial	scientific method; chemical reasoning	mechanization; fuels	fossil fuels	steam engine optimization; networks	engine engine	productivity explosion
Industrial → Informational	computation; information theory	analog → digital		Moore's law; global internet		global data-driven systems
Informational → Intelligent	AI; machine cognitive algorithmic making	algorithmic making	decision-making	smart grids; automated governance	auto-mated governance	systemic automation

4. Discussion: Theoretical Advantages of the CSI Model

This section places the cognition-substitution-intensification model within the existing theoretical framework of civilization evolution for comparison, demonstrating its theoretical advantages in terms of integration, dynamics, and predictability.

4.1. Integrative and Transdisciplinary Nature

Traditional explanatory paths of civilization often exhibit biases:

- The energetics school emphasizes that energy acquisition determines civilization evolution [7,21];
- Institutional economics stresses institutions as decisive variables [9];
- Technological determinism focuses on breakthroughs in key technologies [22];
- The information-theoretic school emphasizes information-processing capacity [11].

However, these perspectives often illuminate only parts of civilization" and lack a unified framework. The cognition" concept proposed in this study not only encompasses the above elements, but also reveals the internal logic among these variables—energy utilization, institutional forms, and technological systems are, in essence, outward manifestations of cognitive capacity; they are concrete implementations of a civilization's information-processing architecture.

This view is highly consistent with complex adaptive systems (CAS) theory: a system's structure and function are expressions of its "cognitive architecture" [23]. Therefore, this model possesses a natural advantage in disciplinary integration and can explain the convolution of technology, institutions, and culture in civilization evolution, rather than remaining at the level of single-variable explanations.

4.2. Dynamic Character and Explanatory Power

The Substitution-Intensification spiral provides a unified dynamic model for civilization evolution:

- The substitution phase corresponds to short-cycle paradigm revolutions, technological mutations, and institutional reconstruction;
- The intensification phase corresponds to long-cycle optimization, expansion, and deepening of efficiency;
- Together they constitute the burst-stability-rebuts rhythm of civilization growth [16,20,24].

This structure is highly consistent with Trumpeter's mechanism of creative destruction [15], and it aligns with the macro fluctuation patterns of Gurnets long waves and Operative cycles [14].

Therefore, the model can explain the following phenomena:

- Why civilization development is not continuous and smooth but exhibits leap-like transitions;
- Why technological revolutions are often accompanied by institutional turbulence and cultural reconfiguration;
- Why each new paradigm, once established, enters a prolonged period of efficiency improvement.

This endows the model not only with macro-historical explanatory power, but also with the ability to reveal micro-level mechanisms.

4.3. Predictive and Forward-Looking Power

Global civilization is currently in the early stage of transitionary from an information civilization to an intelligence civilization. Numerous studies indicate that human society is approaching the limits of traditional human cognitive capacity (decision-making complexity, data scale, system coupling degree) [25]. This "cognitive bottleneck" will trigger the next large-scale civilization leap, marked by:

- Artificial intelligence becoming a core factor of production [19];
- Compute power and algorithms becoming foundational infrastructure for social governance and economic operations [24];
- Bio-computing and quantum computing emerging as new cognitive tools [26].

According to this model, the early signals of an "intelligence civilization" are as follows:

- Cognitive breakthroughs — AI, foundation models, cognitive augmentation technologies;
- Paradigm substitution — human-centered decision-making → human-AI collaborative decision-making;
- Efficiency intensification — comprehensive improvement in algorithmic efficiency, energy dispatch efficiency, and organizational efficiency.

These trends are highly consistent with the predictions of the civilization cycle school regarding the age of knowledge civilization [22], and they accord with contemporary histories of science and technology that point to an intelligent paradigm shift.

Thus, the model possesses strong forward-looking predictive capacity: it not only explains the past, but also extrapolates the possible trajectories of future civilization.

5. Conclusions

The Cognition-Substitution-Intensification spiral model proposed in this paper provides a genuinely transdisciplinary unified framework for understanding the evolution of civilization. It views human civilization as a cognition-driven, complex self-organizing system: every civilization leap is the outcome of an upgrade in its cognitive architecture, while technological revolutions, institutional innovations, and changes in energy utilization are outward manifestations of this upgrade.

From the discussion and case analysis of the four major historical civilization transitions, we observe:

- Cognitive breakthroughs are the prime mover: they reshape the information-processing architecture of civilization and its capacity for energy regulation.

- Paradigm substitution is the transition mechanism: it triggers structural reorganization and creative destruction.
- Efficiency intensification is the process of paradigm deepening: it unlocks the potential of the new paradigm and ushers civilization into a steady phase of expansion.

The Cognition-Substitution-Intensification spiral not only depicts the past of civilization but also illuminates possible future trajectories. In the context of rapid advances in intelligent technologies and rising global system complexity, the model underscores the looming cognitive bottleneck and the potential for an “intelligence breakthrough, offering substantial theoretical significance and strategic insight.

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