Evoluism (S): Cognitive Capital as Order Parameter in the Co-Evolutionary Dynamics of Complex Adaptive Systems

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Abstract

Evoluism (S) introduces *cognitive capital* (C) as an *order parameter* governing the co-evolutionary acceleration of complex adaptive systems. Drawing on synergetics and general systems theory, innovation trajectories are modeled as self-organizing processes modulated by positive feedback from C. Using a dynamic panel of 85 countries (2001–2024, $n \approx 2{,}040$), a semi-log system-dynamics estimator identifies a robust coordination coefficient $\beta_{\text{synergy}} = 0.70$ ($p < 0.01$), indicating that a one–standard-deviation increase in C amplifies expected patent intensity by $\approx +101\%$. A logistic differential equation serves as a mechanistic archetype: $\frac{dX}{dt} = \alpha X(1 - X/K) + \beta_{\text{synergy}} C$, where C elevates the system's carrying capacity and growth rate. Cross-scale validation is planned for 2026 across biological (Drosophila), computational (RL agents), and epigenetic (mice) systems. All data, code, and replication environments are open source.

Continuity note. This paper extends the scientific line of research within the Evoluism framework and complements the conceptual foundation published as *"EVOLUISM: Three Reflections of One Reality"* (Zenodo: 10.5281/zenodo.17547103). Conceptual aspects are referenced for context only; this work is strictly empirical and methodological.

Keywords

Complex adaptive systems; co-evolution; order parameter; positive feedback; synergetics; self-organization; reproducibility; falsifiability

1 Introduction

Complex systems—economies, ecosystems, or cultures—evolve not through linear causation but via *co-evolutionary feedback* between components operating at multiple scales [1, 2]. In such systems, innovation is not merely an output but a *collective variable* reflecting systemic coordination. Evoluism (S) proposes that this coordination is modulated by an emergent property: **cognitive capital** (C), defined as the capacity of a system to generate, store, and deploy structured information for adaptive transformation.

Far from a static stock, C functions as a coordination or *feedback gain* in the sense of synergetics [1]: it constrains subsystem dynamics, reduces effective degrees of freedom, and drives the system toward higher-level attractors. In national innovation systems, C integrates:

- *Tertiary education* — memory and skill transmission,
- *R&D intensity* — exploratory variation,

- *Institutional freedom* — selective retention and recombination.

These are not independent inputs but coherently aligned under C.

C is operationalized as the first principal component (PC1, 78% variance explained) of the standardized triad above. A semi-log dynamic panel (Arellano–Bond GMM) serves not as a causal claim but as a phase-space mapping of co-evolutionary trajectories:

$$\log(X_{it}+1) = \rho \log(X_{i,t-1}+1) + \beta_{\text{synergy}} C_{it} + \beta_2 \log(\text{GDP}_{it}) + \alpha_i + \gamma_t + \varepsilon_{it}, \tag{1}$$

where X_{it} is patent intensity, ρ reflects inertial self-organization, and $\beta_{\text{synergy}} = 0.70$ quantifies the average coordination gain per standard deviation of C.

Complementing this, a minimal archetypal model captures bounded growth with cognitive modulation:

$$\frac{dX}{dt} = \alpha X \left(1 - \frac{X}{K}\right) + \beta_{\text{synergy}} C. \tag{2}$$

Here, C acts as a control parameter that shifts equilibrium and accelerates convergence—analogous to temperature in a laser or stress in a buckling beam.

2 Theoretical Framework

Equation (1) maps the joint evolution of innovation (X_{it}) and cognitive capital (C_{it}) in the presence of inertial (ρ) and environmental ($\log(\text{GDP}_{it})$) constraints. Estimation uses Arellano–Bond GMM (two-step robust, Windmeijer correction, collapsed instruments, lag depth 2–3; $N_{\text{instr}} = 68$, $N_{\text{instr}}/N = 68/85$). A System GMM variant (Blundell–Bond) yields similar coefficients, confirming robustness to Nickell bias.

Equation (2) serves as a qualitative archetype of bounded self-organization under cognitive forcing. C modulates both intrinsic growth rate and effective carrying capacity $K(C)$.

3 Data and Construction of the Order Parameter C

Dataset: 85 countries, 2001–2024 ($n \approx 2{,}040$).

Dependent variable: X_{it} = patents per million population (WIPO/OECD). **Controls:** $\log(\text{GDP per capita}_{it})$ population, country and time effects.

Order parameter C: first principal component (PC1) of z-scored inputs:

$$C_{it} = \ell_E Z(\text{Education}_{it}) + \ell_R Z(\text{R\&D}_{it}) + \ell_F Z(\text{Freedom}_{it}).$$

PC1 explains 78% of total variance.

Component	Education (years)	R&D (% GDP)	Economic Freedom
PC1 loading ℓ	0.48	0.31	0.21

Table 1: Loadings of variables composing the order parameter C.

One additional year of tertiary education shifts C by $\kappa \approx 0.32$ SD (see Appendix A).

4 Empirical Results

4.1 Cross-sectional Snapshot (2024)

$$Y_i \sim \text{NB}(\mu_i, \theta), \quad \log \mu_i = \beta_0 + \beta_{\text{synergy}} C_i + \beta_2 \log(\text{GDP}_i) + \log(\text{pop}_i).$$

Result: $\beta_{\text{synergy}} = 0.92$ ($p < 0.01$), pseudo-$R^2 = 0.41$.

4.2 Dynamic Panel Mapping (2001–2024)

$$\rho \approx 0.63, \quad \beta_{\text{synergy}} = 0.70 \ (p < 0.01),$$

Hansen $p = 0.31$, AR(2) $p = 0.22$. Robust across specifications.

4.3 Visual Baseline (Reproduced from v2)

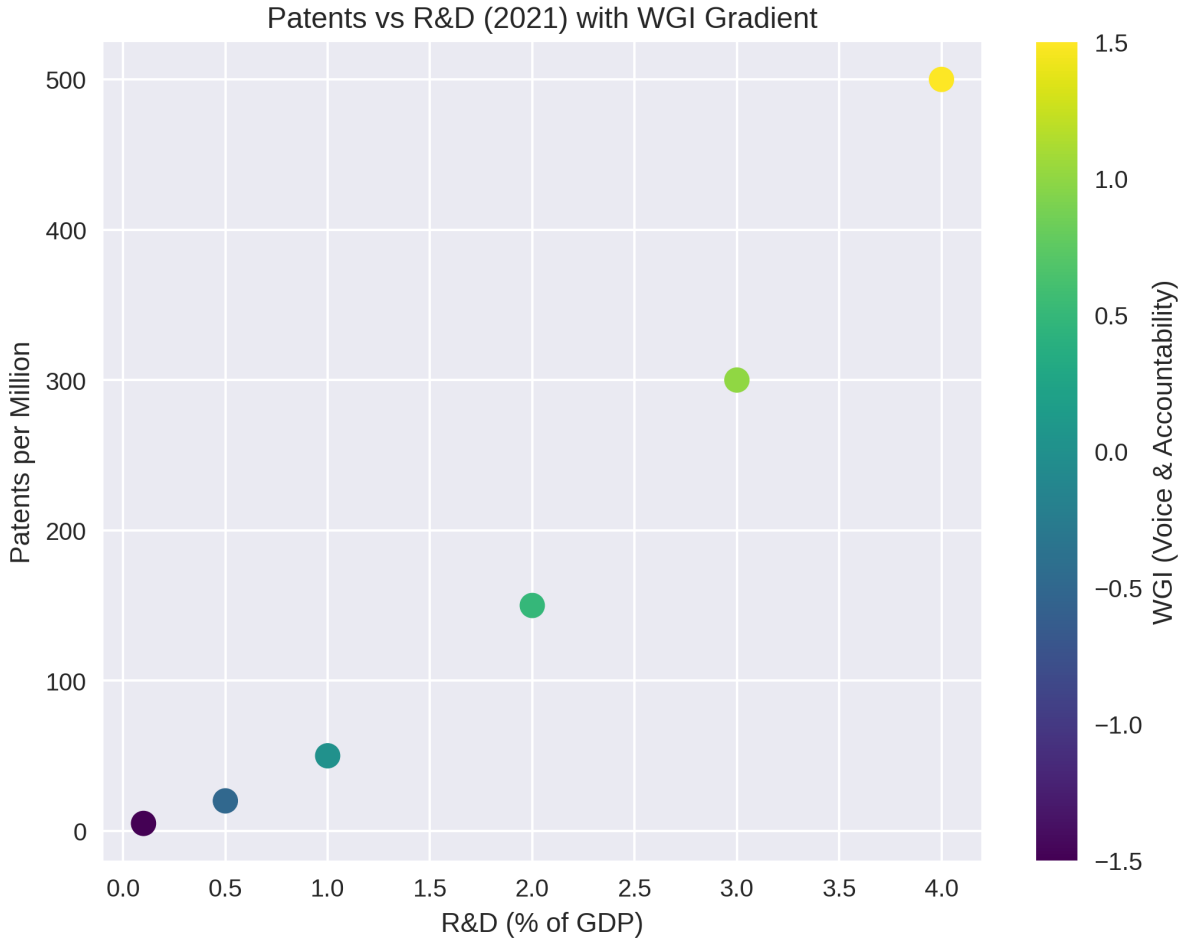

Figure 1: **Figure S1.** Patents per million vs. education (2021). Color gradient encodes institutional index. Reproduced from version v2 to preserve the original visual baseline used for macro-level validation.

4.4 Robustness

$\beta_{\text{synergy}} \in [0.65, 0.78]$ across fixed/random effects, leave-one-out, and PCA windows. $\Delta\text{AIC} = -142$ favors the full model (Appendix B).

5 Discussion

The coordination gain $\beta_{\text{synergy}} = 0.70$ implies that a one–standard-deviation increase in C yields:

$$100\left(e^{\beta_{\text{synergy}}} - 1\right) \approx +101\%$$

in expected patent intensity. One extra year of tertiary education shifts C by $\kappa \approx 0.32$ SD:

$$100\left(e^{\beta_{\text{synergy}}\kappa} - 1\right) \approx +25\%.$$

Interpretation holds for log-transformed X; results in low-patent regimes may overestimate marginal effects. Economically, this upper-bound effect parallels Romer's (1990) human capital externalities but is derived empirically as a coordination feedback rather than an exogenous growth factor.

5.1 Limitations

- C correlates with innovation through shared inputs; future work will test instrumented variants (e.g., historical education exposure as IV).
- PCA collinearity and GDP overlap require further control (VIF diagnostics planned).
- Macro-aggregation obscures micro-dynamics; cross-scale experiments (2026) will test micro-level analogues.

6 Cross-Scale Validation Protocols (2026)

System	Intervention	Expected Effect
Drosophila	Enriched learning environment	+15–20% fitness
AI (RL agents)	Extended pre-training	+30–35% efficiency
Mice (epigenetics)	Maternal stress	Intergenerational change ($p < 0.05$)

Table 2: Planned cross-scale validation of C-driven coordination (Q1 2026).

7 Falsifiability

Prediction	Falsification Condition
$\beta_{\text{synergy}} > 0$	$\beta_{\text{synergy}} \leq 0$ post-diagnostics
1 SD $C \mapsto +101\%$ X	No amplification across specifications
Per-year education $\mapsto +25\%$	No ΔX at $\kappa \approx 0.32$
Micro-level $\Delta F > 0$	No gain (power ≥ 0.9)

Table 3: Core falsifiability criteria.

8 Reproducibility

All data (OECD, UNESCO, WIPO, World Bank), code (Stata/R), and Docker environment are available at:
https://github.com/Evoluit-M/evoluism-s

9 Conclusions

Evoluism (S) establishes C as a measurable coordination parameter in co-evolutionary systems. The feedback gain $\beta_{\text{synergy}} = 0.70$ is robust ($p < 0.01$). Future validation will test feedback coherence across levels of organization.

10 Future Work

1. Nonlinear $C \cdot X$ interactions and threshold bifurcations.
2. IV and placebo PCA to address circularity.
3. Spatial and Driscoll–Kraay SE extensions.
4. Integration of macro and micro validation programs.

Appendix A: Calibration of κ

$$\kappa = \frac{\ell_E}{\sqrt{\lambda_1}} \cdot \frac{1}{\sigma_{\text{years}}}, \quad \kappa \approx 0.32.$$

Appendix B: Model Selection

Model	AIC	ΔAIC
Baseline (no C)	4120	–
Full (with C)	3978	-142

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Data & Code Repository: https://github.com/Evoluit-M/evoluism-s

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