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Social and Physical Technologies in Economic Development: A Co-Evolutionary Growth Model

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We develop a dynamic growth model where physical and social technologies co-evolve to jointly determine economic performance and well-being. Building on Richard R. Nelson's foundational insights, we conceptualize social technologies (encompassing institutions, norms, and governance) as direct inputs to both the production function and the representative agent's utility function. The model features an agent who maximizes intertemporal utility by allocating investment between these two forms of capital. The resulting system of differential equations is fundamentally nonlinear, driven by a critical threshold in institutional quality below which returns to social investment are negligible. Our central theoretical prediction, confirmed through numerical simulations, is the existence of multiple long-run equilibria: a robust, self-perpetuating poverty trap characterized by institutional failure, and a saddle-point prosperity equilibrium. Stability analysis reveals a profound asymmetry: the poverty trap is a stable node, while the prosperity equilibrium is a saddle point, meaning only trajectories on its one-dimensional stable manifold converge to sustained prosperity. The model's global dynamics, illustrated through basins of attraction, demonstrate strong path dependence and provide a unified explanation for the persistent divergence in development outcomes. Policy implications underscore the primacy of institutional investment and the necessity of coordinated interventions to shift economies out of development traps.

Key Words: Institutional economics; Social technology; Physical technology; Economic growth; Development traps; Richard Nelson; Co-evolution; Utility and institutions; Dynamic optimization; Endogenous institutions.

JEL Classification Numbers: B52, C61, D02, O11, O33, O43.

1. INTRODUCTION

Economic growth is the cumulative outcome of productive activity governed jointly by material capabilities and institutional arrangements. Richard R. Nelson's work, particularly his 2007 Veblen–Commons Award address

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and his 2005 collection Technology, Institutions, and Economic Growth, draws a crucial distinction between two co-evolving pillars of this process: physical technologies and social technologies. Physical technologies refer to the concrete tools, techniques, and scientific knowledge used to transform inputs into outputs: machines, engineering processes, chemical formulas, and production functions. In contrast, social technologies denote the structured patterns of human interaction that coordinate economic behavior: contracts, property rights, business practices, regulatory norms, bureaucracies, and broader institutional systems. These institutional patterns are not merely background conditions; they are technological artifacts in their own right, structuring the very feasibility and effectiveness of productive action.

Nelson emphasizes that while both types of technology evolve over time, their evolutionary trajectories are markedly different. Physical technologies often exhibit cumulative, modular, and scalable improvement, backed by organized R&D systems and competitive selection. By contrast, the evolution of social technologies (such as legal norms, corporate governance rules, or cultural expectations) tends to be slower, path-dependent, and more vulnerable to stagnation, conflict, and institutional failure. In this sense, social technologies constitute both enabling and constraining factors in the development process, and their relative fragility can result in persistent divergence across countries, even in the presence of physical capital and scientific knowledge.

Nelson's formulation builds upon a deep intellectual lineage in institutional economics. Thorstein Veblen's (1898) concept of "general habits of action and thought," John R. Commons's (1924) "working rules," and Douglass North's (1990) "rules of the game" all resonate with the notion that economic life is embedded in evolving social arrangements. Similarly, Andrew Schotter (1981) characterized institutions as "how the game is played," while Oliver Williamson (1985) viewed institutions as "governance structures" managing economic exchange. Geoffrey Hodgson's (1988, 1998, 2001, 2004) reconstructions of institutional economics emphasize these frameworks as forms of social technology: standardized, repeated, and socially legitimated modes of interaction that enable coordination under complexity and uncertainty.

The present paper also engages with a well-established formal literature on multiple equilibria and development traps. Azariadis and Drazen (1990) demonstrate that threshold externalities in human capital accumulation can sustain multiple locally stable steady states: economies whose investment remains below a critical threshold are trapped in low-income equilibria, while those that cross it converge to a high-growth path. Galor and Zeira (1993) establish, through a model with credit market imperfections and indivisibilities in human capital investment, that initial wealth distributions generate path-dependent, non-ergodic dynamics in which no market force automatically lifts poor dynasties to the high-income steady state. Matsuyama (1991) shows that increasing returns in manufacturing can produce indeterminate equilibria in which self-fulfilling expectations, rather than history alone, determine whether industrialization occurs. Benhabib and Farmer (1994) formalize a related class of indeterminacy driven by aggregate external economies, in which sunspot fluctuations sustain persistent macroeconomic volatility around an otherwise standard neoclassical steady state. The present paper departs from these antecedents in two respects. First, the source of the poverty trap is institutional rather than based on human capital or credit constraints: social technology $S(t)$ accumulates productively only above a critical threshold θ, reflecting the coordination and complementarity requirements of institutional development. Second, and more distinctively, social technology enters both the production function $F(P, S)$ and the household utility function $u(c, S)$, so that an institutional poverty trap imposes a welfare cost independent of its output effect, a dual role that, to our knowledge, has not been formalized in the existing multiple-equilibria literature.

The central contribution of this paper is to formalize Nelson's distinction between physical and social technologies into a unified dynamic model of economic development. We construct a general production function $F(P(t), S(t))$, where $P(t)$ represents the evolving stock of physical technology and $S(t)$ embodies the institutional or social technology stock. Both components accumulate endogenously through investments that are shaped by current income, behavioral norms, and interdependencies. Importantly, we allow social technology to evolve nonlinearly and discontinuously, subject to inertia, thresholds, and multiple equilibria, reflecting Nelson's view that institutional progress is far more fragile than technical innovation.

Moreover, this framework eschews the assumption of boundless growth found in endogenous growth theory (e.g., Romer, 1990; Lucas, 1988), instead modeling the economy as a bounded system subject to nonlinear dynamics and institutional constraints.

The remainder of this paper is organized as follows. Section 2 presents the formal model setup, defining the core utility and production functions that treat social technology as both a determinant of welfare and an input to production. Section 3 derives the optimal conditions and the complete dynamic system using optimal control theory. Section 4 provides an analytical characterization of the system's steady states. Section 5 then transitions to a comprehensive numerical analysis to validate and explore the model's theoretical predictions. Using a calibrated set of parameters, we first demonstrate the emergence of multiple equilibria, namely a low-level poverty trap and a high-level prosperity path. A detailed stability analysis then reveals a fundamental asymmetry between these outcomes: the poverty trap is a robust stable node, while the prosperity equilibrium is a fragile saddle point. We further visualize the system's global dynamics through phase portraits, including vector fields and basins of attraction, to illustrate the critical role of path dependence in determining long-run development fates. Section 6 concludes with policy implications derived directly from the model and a summary of the paper's contributions.

2. MODEL SETUP

We consider a continuous-time infinite-horizon economy populated by a representative agent who derives utility from consumption $c(t)$ and from the prevailing level of social technology $S(t)$, which embodies the quality of institutions, norms, governance, and social coordination mechanisms. The agent invests in two types of technology, physical technology $P(t)$ and social technology $S(t)$, subject to a resource constraint, and chooses optimal trajectories of consumption and investment to maximize lifetime utility.

The utility functional is:

$$\max_{c(t),i_P(t),i_S(t)} \int_0^\infty e^{-\rho t} u(c(t), S(t))dt, \tag{1}$$

where $\rho > 0$ is the subjective discount rate, and the utility function satisfies:

$$u_c > 0, \quad u_{cc} < 0, \quad u_S > 0, \quad u_{SS} \leq 0. \tag{2}$$

A tractable and expressive specification is:

$$u(c, S) = \frac{(c^\gamma S^{1-\gamma})^{1-\sigma}}{1-\sigma}, \quad \gamma \in (0, 1), \sigma > 0, \sigma \neq 1. \tag{3}$$

Here, $S(t)$ directly enters utility, capturing the idea that a rule-bound society with stable institutions, credible enforcement, and shared norms yields higher welfare even if material consumption is unchanged. For instance, the same income in a society with functioning courts, civic trust, and freedom of speech is worth more in utility than in one ruled by arbitrary coercion or corruption.

The aggregate production function is:

$$F(P(t), S(t)) = \left[\alpha P(t)^\psi + (1-\alpha)S(t)^\psi\right]^{1/\psi}, \quad \alpha \in (0, 1), \psi < 1. \tag{4}$$

This function is strictly increasing and concave in both arguments, with substitutability governed by ψ. The idea is that physical and social technologies are co-essential inputs to output: production systems require not just machinery and knowledge but also legal frameworks, regulatory institutions, and organizational culture.

The agent allocates total output $Y(t) = F(P(t), S(t))$ among consumption and investment:

$$c(t) + i_P(t) + i_S(t) = F(P(t), S(t)). \tag{5}$$

Dynamics of physical technology follow:

$$\dot{P}(t) = \chi_P i_P(t) - \delta_P P(t), \quad \chi_P > 0, \delta_P > 0. \tag{6}$$

Dynamics of social technology follow a more fragile and nonlinear path, consistent with Nelson's insight:

$$\dot{S}(t) = \chi_S i_S(t) \cdot \phi(S(t)) - \delta_S S(t), \tag{7}$$

where $\phi(S) \in [0, 1]$ captures the institutional threshold effect. A concrete specification is:

$$\phi(S) = \begin{cases} 0 & \text{if } S < \theta \\ \mu(S - \theta) & \text{if } S \geq \theta \end{cases}, \quad \theta > 0, \mu > 0. \tag{8}$$

This formulation captures institutional traps and fragility: institutional investments yield no return unless a society is already sufficiently coordinated and legitimate. Unlike physical capital, which often yields marginal returns even from zero, social technologies require a minimum scale and coherence to function at all.

The initial conditions $P(0) > 0$ and $S(0) > 0$ are given. The agent solves an intertemporal optimization problem subject to:

- Two capital accumulation equations (for $P(t)$ and $S(t)$);
- A budget constraint;
- A nonseparable utility function in c and S.

This setup allows us to explore the co-evolution of physical and social technologies, the emergence of multiple development paths, and the existence of welfare traps where low $S(t)$ impairs not only production but also utility, regardless of material consumption. Nelson's distinction is thus fully embedded: social technology enters both the production side and the utility side of the economy, thereby reinforcing its centrality in development.

3. OPTIMAL CONDITIONS AND DYNAMIC SYSTEM

In this section, we derive the optimal intertemporal behavior of a representative agent who seeks to maximize lifetime utility under endogenous technological evolution. The agent derives utility from both consumption $c(t)$ and the level of social technology $S(t)$, reflecting the notion that well-functioning institutions and cooperative norms directly contribute to welfare, beyond their indirect contribution through production. Let the lifetime utility function be given by:

$$\max_{\{c(t),\beta(t)\}} \int_0^\infty e^{-\rho t} \cdot u(c(t), S(t))dt, \tag{9}$$

where the utility function takes a Cobb-Douglas form in (c, S) with CRRA scaling

$$u(c, S) = \frac{(c^\gamma S^{1-\gamma})^{1-\sigma}}{1-\sigma}, \tag{10}$$

with $\gamma \in (0, 1)$ and $\sigma > 0$, $\sigma \neq 1$, where γ governs the consumption expenditure share relative to institutional quality, and σ is the coefficient of relative risk aversion. The production side is characterized by a generalized production function $F(P, S)$, where $P(t)$ denotes the stock of physical technology, encompassing tangible capital, machines, and scientific know-how, while $S(t)$ represents social technology, encompassing norms, legal systems, trust, and institutional arrangements. The agent faces a resource constraint that requires current output to be divided between consumption and investment in the two forms of capital: $c(t) + i_P(t) + i_S(t) = F(P(t), S(t))$, where $i_P(t)$ and $i_S(t)$ are the respective investments in physical and social technologies.

To capture the endogenous allocation decision between physical and social technology, we let $\beta(t) \in (0, 1)$ denote the share of the surplus $F(P, S) - c$ allocated to physical technology investment, such that:

$$i_P(t) = \beta(t)(F(P, S) - c(t)), \tag{11}$$

$$i_S(t) = (1 - \beta(t))(F(P, S) - c(t)). \tag{12}$$

The laws of motion for the two technologies reflect accumulation dynamics with constant depreciation rates and efficiency of investment transformation. For physical technology, the accumulation equation is

$$\dot{P}(t) = \chi_P i_P(t) - \delta_P P(t), \tag{13}$$

while for social technology, it is

$$\dot{S}(t) = \chi_S i_S(t) \cdot \phi(S(t)) - \delta_S S(t), \tag{14}$$

where $\phi(S)$ is a threshold function capturing fragility or institutional inertia, with $\phi(S)$ increasing slowly at low levels of S to reflect the difficulty of institution-building from a low base.

The agent's problem is thus to choose consumption $c(t)$ and investment share $\beta(t)$ to maximize utility subject to the accumulation dynamics of $P(t)$ and $S(t)$. We apply the Pontryagin Maximum Principle. Let $\lambda_P(t)$ and $\lambda_S(t)$ denote the current-value costate variables associated with physical and social technology, representing the shadow value of marginal increases in each capital stock. The current-value Hamiltonian becomes:

$$\mathcal{H} = u(c,S) + \lambda_P \left[\chi_P \beta(F-c) - \delta_P P\right] + \lambda_S \left[\chi_S(1-\beta)(F-c)\phi(S) - \delta_S S\right]. \tag{15}$$

The first-order condition with respect to $c(t)$ equates the marginal utility of consumption to the marginal value of foregone investment in both technologies. Differentiating the Hamiltonian with respect to c, we obtain:

$$\frac{\partial \mathcal{H}}{\partial c} = u_c(c,S) - \lambda_P \chi_P \beta - \lambda_S \chi_S (1-\beta)\phi(S) = 0. \tag{16}$$

This gives the key Euler-type condition for optimal consumption, balancing the marginal utility of consumption against the shadow values of the two investment opportunities:

$$u_c(c,S) = \lambda_P \chi_P \beta + \lambda_S \chi_S (1-\beta)\phi(S). \tag{17}$$

Next, differentiating with respect to $\beta(t)$ gives the optimal allocation of investment between physical and social technology:

$$\frac{\partial \mathcal{H}}{\partial \beta} = \lambda_P \chi_P (F-c) - \lambda_S \chi_S (F-c)\phi(S) = 0, \tag{18}$$

which, provided $F - c > 0$, implies the condition:

$$\lambda_P \chi_P = \lambda_S \chi_S \phi(S). \tag{19}$$

This equilibrium condition states that optimal investment allocation equates the marginal value of an extra unit of physical capital to that of an extra unit of social capital, adjusted for their respective productivity and institutional quality.

The co-state dynamics follow from the derivative of the Hamiltonian with respect to the states. The shadow price of physical technology evolves according to:

$$\begin{aligned}
\dot{\lambda}_P &= \rho\lambda_P - \frac{\partial \mathcal{H}}{\partial P} \\
&= \rho\lambda_P - \left[\lambda_P\left(\chi_P \beta F_P - \delta_P\right) + \lambda_S \chi_S (1-\beta) F_P \phi(S)\right] \\
&= \rho\lambda_P - \left[\lambda_P\left(\chi_P \beta F_P - \delta_P\right) + \lambda_P \chi_P (1-\beta) F_P\right] \\
&= \lambda_P\left(\rho + \delta_P - \chi_P F_P\right),
\end{aligned} \tag{20}$$

[1]while the shadow price of social technology evolves as:

$$
\begin{aligned}
\dot{\lambda}_S &= \rho\lambda_S - \frac{\partial \mathcal{H}}{\partial S} \\
&= \rho\lambda_S - [u_S(c,S) + \lambda_P\chi_P\beta F_S + \lambda_S(\chi_S(1-\beta)F_S\phi(S) + \chi_S(1-\beta)(F-c)\phi'(S) - \delta_S)] \\
&= \rho\lambda_S - u_S(c,S) - \lambda_P\chi_P\beta F_S - \lambda_S\chi_S(1-\beta)\left[F_S\phi(S) + (F-c)\phi'(S)\right] + \lambda_S\delta_S.
\end{aligned} \tag{21}
$$

These co-state equations capture how the value of marginal increases in P and S change over time, responding to returns in production, marginal utilities, and the institutional fragility encoded in $\phi(S)$. The dynamics of $P(t)$ and $S(t)$ follow directly from the accumulation laws, now rewritten using optimal $c(t)$ and $\beta(t)$:

$$\dot{P} = \chi_P\beta(F(P,S) - c) - \delta_P P, \tag{22}$$

$$\dot{S} = \chi_S(1-\beta)(F(P,S) - c)\phi(S) - \delta_S S. \tag{23}$$

Together, this system of six differential equations in $(c, \beta, P, S, \lambda_P, \lambda_S)$ forms a complete dynamic description of the representative agent economy with endogenous investment allocation and institutional effects. These equations allow us to characterize the possible steady states, development traps, and nonlinear trajectories that may emerge depending on initial conditions and parameter values. In the next section, we derive the steady-state structure of the system and examine the conditions under which multiple equilibria and bifurcations may arise.

4. STEADY STATE ANALYSIS

To analyze the long-run behavior of the economy, we now characterize the steady states implied by the dynamic system derived in Section 3. In steady state, the physical technology stock $P(t)$, the social technology stock $S(t)$, the costate variables $\lambda_P(t)$ and $\lambda_S(t)$, the consumption level $c(t)$, and the investment allocation share $\beta(t)$ are all constant. Thus, we set $\dot{P} = \dot{S} = \dot{\lambda}_P = \dot{\lambda}_S = 0$ and derive the corresponding algebraic conditions.

[1]The third equality uses the interior optimality condition $\lambda_P\chi_P = \lambda_S\chi_S\phi(S)$, which holds along the optimal trajectory by construction; off the optimal path the co-state equation retains its general form. Invoking interior optimality conditions within co-state derivations is standard in Hamiltonian optimal-control analysis (see, e.g., Chiang 1992, Elements of Dynamic Optimization).

We begin with the accumulation equations for physical and social technologies. Setting $\dot{P} = 0$ and $\dot{S} = 0$, we obtain:

$$\chi_P \beta (F(P^*, S^*) - c) = \delta_P P^*, \tag{24}$$
$$\chi_S (1-\beta)(F(P^*, S^*) - c)\phi(S^*) = \delta_S S^*. \tag{25}$$

These two equations express that, in steady state, gross investment in each form of capital equals depreciation. They determine how consumption c, given production $F(P, S)$, must be allocated between the two capital stocks to sustain them at constant levels. Taking their ratio, we eliminate $F - c$ and obtain a key identity linking capital stocks and investment allocation:

$$\frac{\delta_P P^*}{\chi_P \beta} = \frac{\delta_S S^*}{\chi_S (1-\beta)\phi(S^*)}. \tag{26}$$

This expression implies that the agent must distribute investment between physical and social technologies such that the marginal investment effort required to offset depreciation is equalized, after adjusting for institutional fragility. If $\phi(S)$ is small, i.e., institutions are weak, then more resources must be devoted to social investment to maintain the same stock of S, potentially crowding out physical capital accumulation and consumption.

From the first-order condition with respect to β, derived in Section 3, we have that:

$$\lambda_P \chi_P = \lambda_S \chi_S \phi(S), \tag{27}$$

which we can now use to link the marginal utility of investment across technologies. Substituting this expression into the first-order condition with respect to consumption, we recall:

$$u_c(c^*, S^*) = \lambda_P \chi_P \beta + \lambda_S \chi_S (1-\beta)\phi(S^*). \tag{28}$$

Substituting the equality $\lambda_P \chi_P = \lambda_S \chi_S \phi(S)$, we simplify this expression to:

$$u_c(c^*, S^*) = \lambda_S \chi_S \phi(S^*)[\beta + (1-\beta)] = \lambda_S \chi_S \phi(S^*). \tag{29}$$

Thus, the marginal utility of consumption must equal the effective return on investment in either technology, scaled by the institutional quality parameter $\phi(S)$. When $\phi(S) \to 0$, as in fragile states or failed institutions, the marginal utility of consumption must also converge to zero, which is only possible if $c \to \infty$, violating feasibility. Therefore, economies with very low S and low $\phi(S)$ are unsustainable unless extraordinary levels of physical capital support output.

To proceed analytically, we assume a CES production function of the form:

$$F(P,S) = \left[\alpha P^{\psi} + (1-\alpha)S^{\psi}\right]^{1/\psi}, \quad \psi < 1, \tag{30}$$

with Inada conditions to ensure interior solutions. Combining this with the utility function:

$$u(c,S) = \frac{(c^{\gamma}S^{1-\gamma})^{1-\sigma}}{1-\sigma}, \tag{31}$$

we can now write the marginal utility of consumption as:

$$u_c(c,S) = \gamma c^{\gamma(1-\sigma)-1} S^{(1-\gamma)(1-\sigma)}. \tag{32}$$

Setting this equal to $\lambda_S \chi_S \phi(S)$, we can solve for the costate variable λ_S in terms of observable quantities:

$$\lambda_S = \frac{\gamma c^{\gamma(1-\sigma)-1} S^{(1-\gamma)(1-\sigma)}}{\chi_S \phi(S)}. \tag{33}$$

To determine steady-state consumption, we now analyze the costate dynamics. From the co-state evolution for λ_S, the condition $\dot{\lambda}_S = 0$ yields:

$$\rho\lambda_S = u_S(c,S) + \lambda_P \chi_P \beta F_S + \lambda_S \chi_S (1-\beta)\left[F_S \phi(S) + (F-c)\phi'(S)\right] - \delta_S \lambda_S. \tag{34}$$

The first term on the right-hand side is:

$$u_S(c,S) = (1-\gamma) c^{\gamma(1-\sigma)} S^{(1-\gamma)(1-\sigma)-1}. \tag{35}$$

Combining these expressions, and substituting λ_P and λ_S from earlier equations, we obtain a non-linear algebraic equation in terms of c, P, S, β that characterizes the steady state. In general, closed-form solutions may not be available, but numerical analysis can reveal whether the system admits a unique equilibrium or multiple steady states.

The existence of multiple steady states is particularly likely when $\phi(S)$ exhibits threshold effects. If $\phi(S)$ is very low below a critical level of S, the marginal product of institutional investment is negligible. The system may therefore admit one low-level equilibrium with poor institutions, low production, and low welfare, and another high-level equilibrium with strong institutions, higher productivity, and sustained growth. This mechanism captures Nelson's central insight that social technologies evolve more slowly and less reliably than physical technologies, often requiring coordinated action or historical shocks to escape low-level traps.

In summary, the steady state of this system is defined by the intersection of three algebraic conditions: (1) balanced accumulation of physical and social technology, (2) equalized marginal returns to investment across sectors, and (3) consistency between marginal utility and shadow prices. These relationships reveal rich comparative dynamics. For instance, a society investing heavily in P but neglecting S may initially experience growth, but will eventually stall as social frictions erode productivity and utility. Conversely, even modest investments in S may trigger self-reinforcing gains in coordination, trust, and cooperation, unlocking higher productivity from existing physical capital. This sets the stage for Section 5, where we numerically explore equilibrium multiplicity, instability, development traps, and possible cyclical or chaotic patterns.

5. DYNAMICS, MULTIPLE EQUILIBRIA, AND DEVELOPMENT TRAPS

The theoretical framework developed in the preceding sections yields a rich set of predictions about the co-evolution of physical and social technologies, but the inherent nonlinearity of the system precludes closed-form analytical solutions for most parameter configurations. In this section, we turn to numerical methods to validate our theoretical predictions and to illuminate the complex dynamics that emerge when physical technology $P(t)$ and social technology $S(t)$ evolve under mutual interdependence. Our primary objective is to demonstrate concretely how the threshold effects in institutional accumulation generate multiple equilibria, development traps, and path-dependent trajectories, phenomena that are central to understanding persistent global inequality and the fragility of economic prosperity.

As discussed in Section 1, our model belongs to the history-determined poverty trap tradition of Azariadis and Drazen (1990) and Galor and Zeira (1993): initial conditions, rather than self-fulfilling expectations, govern long-run outcomes, distinguishing our framework from the indeterminate equilibria of Matsuyama (1991) and Benhabib and Farmer (1994).

Our model confirms the history-determined character of the poverty trap through stability analysis: the low-level steady state $(P^*, S^*) = (0.020, 0.001)$ is a stable node (both eigenvalues negative), while the prosperity equilibrium $(P^*, S^*) = (1.307, 2.456)$ is a saddle point (eigenvalues of opposite sign), so that only trajectories originating on its one-dimensional stable manifold converge to prosperity. The coexistence of a globally attracting poverty trap with a knife-edge prosperity equilibrium in the same model, separated by a continuous separatrix in(P, S) space, is structurally richer than the single-threshold models of Azariadis and Drazen (1990) and Galor and Zeira (1993), and derives from the interaction of two co-evolving stocks rather than from a single capital variable. The distinguishing feature of our framework remains the dual role of social technology: whereas existing models embed thresholds in the accumulation of a single capital good, our threshold operates on the complementarity between physical and social technologies, and the direct welfare cost of low institutional quality (captured by $S(t)$ entering $u(c,S)$) has no counterpart in the canonical poverty-trap literature.

Before proceeding to the numerical results, it is instructive to explicitly state the complete system of equations that governs the economy's optimal co-evolutionary path. As derived in Section 3, the dynamics are described by a four-dimensional nonlinear autonomous system, comprising two differential equations for the state variables, $P(t)$ and $S(t)$, and two for their respective costate variables (shadow prices), $\lambda_P(t)$ and $\lambda_S(t)$. Utilizing the derived form of the costate variable dynamics, the system is given by:

$$\begin{cases} \dot{P}(t) = \chi_P \beta(t) \left[F(P(t), S(t)) - c(t)\right] - \delta_P P(t), \\ \dot{S}(t) = \chi_S (1-\beta(t)) \left[F(P(t), S(t)) - c(t)\right] \phi(S(t)) - \delta_S S(t), \\ \dot{\lambda}_P(t) = \lambda_P \left(\rho + \delta_P - \chi_P F_P(P(t), S(t))\right), \\ \dot{\lambda}_S(t) = \rho \lambda_S(t) - u_S(c(t), S(t)) - \lambda_P(t) \chi_P \beta(t) F_S(P(t), S(t)) \\ \qquad -\lambda_S(t) \chi_S (1-\beta(t)) \left[F_S(P(t), S(t)) \phi(S(t)) \right. \\ \qquad \left. + \left(F(P(t), S(t)) - c(t)\right) \phi'(S(t))\right] + \delta_S \lambda_S(t), \end{cases} \tag{36}$$

This system of differential equations is supplemented at every point in time by two algebraic first-order conditions, which determine the optimal allocation of resources to consumption, $c(t)$, and the optimal investment share, $\beta(t)$:

$$u_c(c(t), S(t)) = \lambda_P(t) \chi_P \beta(t) + \lambda_S(t) \chi_S (1-\beta(t)) \phi(S(t)), \tag{37}$$

$$\lambda_P(t) \chi_P = \lambda_S(t) \chi_S \phi(S(t)). \tag{38}$$

It is this complete, highly nonlinear dynamic system that we solve numerically. The interaction between these equations, particularly the feedback loops involving the institutional threshold function $\phi(S)$, generates the rich dynamic behavior that we explore in the following sections.

5.1. Model Calibration

The numerical implementation of our theoretical framework requires careful calibration of model parameters. Our approach to parameter selection follows a deliberate methodology: rather than attempting to match the specific characteristics of any particular economy or historical episode, we choose parameter values that lie within economically plausible ranges while ensuring that the model's core mechanisms (threshold effects, multiple equilibria, and path dependence) emerge clearly and robustly. This strategy allows us to demonstrate the universal qualitative properties of the co-evolutionary dynamics between physical and social technologies, properties that we argue are fundamental to understanding development processes across diverse contexts and time periods.

TABLE 1.

Calibrated Parameter Values for Baseline Simulation

Symbol	Parameter Name	Value
α	Physical Capital Share	0.5
ψ	Substitution Parameter	0.3
γ	Consumption Weight	0.5
σ	Coeff. of Relative Risk Aversion	2.0
ρ	Subjective Discount Rate	0.02
χ_P	Physical Investment Efficiency	0.2
χ_S	Social Investment Efficiency	0.3
δ_P	Physical Capital Depreciation	0.05
δ_S	Social Capital Depreciation	0.04
θ	Institutional Threshold	2.0
μ	Transition Steepness	3.0
$\phi_{\min}$	Minimum Institutional Return	0.1

Table 1 presents the complete set of parameter values employed in our baseline simulations. The production function parameters are set at $\alpha = 0.5$ and $\psi = 0.3$, yielding a CES elasticity of substitution of approximately 1.43 between physical and social technologies, a value that classifies them as substitutes. For the utility function, we adopt $\gamma = 0.5$ and $\sigma = 2$, reflecting balanced weights between consumption and institutional quality in welfare, with a coefficient of relative risk aversion consistent with empirical estimates. The depreciation rates $\delta_P = 0.05, \delta_S = 0.04$ correspond to annual depreciation of 5% and 4% respectively. The subjective discount rate $\rho = 0.02$ is a standard value in the macroeconomic literature, reflecting a patient representative agent. In an interesting departure from some empirical observations, our calibration sets the social investment efficiency ($\chi_S = 0.3$) higher than the physical investment efficiency ($\chi_P = 0.2$). This setup allows us to explore a scenario where institutional improvements, once past the threshold, can be accumulated more efficiently than physical capital, highlighting the potent role of institutional learning.

The most critical parameter for our analysis is the institutional threshold $\theta = 2$, which defines the minimum level of social technology required for institutional investments to become productive. This value is chosen to represent a moderate but significant barrier to institutional development: neither so low that it becomes trivial to overcome through minimal investment, nor so high that escape from the poverty trap becomes practically impossible. The threshold value of 2 implies that social technology must reach approximately twice its normalized baseline level before institutional investments begin to yield positive returns, capturing the notion that functioning institutions require a critical mass of coordination, trust, and organizational capacity before they can become self-sustaining. To implement this threshold effect numerically while maintaining mathematical tractability, we employ a smooth approximation

$$\phi(S) = \phi_{\min} + \frac{1 - \phi_{\min}}{1 + \exp(-\mu(S - \theta))} \tag{39}$$

with a transition parameter $\phi_{\min} = 0.1$. This logistic function closely approximates a step function centered at θ while avoiding the numerical instabilities and corner solutions associated with true discontinuities. Moreover, this smooth transition arguably provides a more realistic representation of institutional development, where the effectiveness of institutional investments increases gradually as social capacity approaches and surpasses the critical threshold, rather than switching instantaneously from zero to full productivity.

Empirical interpretation of S and θ. While the calibration above is designed to illustrate theoretical mechanisms rather than to match specific country moments, the social technology variable S admits a natural empirical counterpart. The World Bank Worldwide Governance Indicators (WGI) Rule of Law index is cross-nationally standardized to a range of approximately $[-2.5,\ 2.5]$. The affine transformation

$$S = \frac{4}{5}\left(\text{RoL} + 2.5\right), \quad \text{equivalently} \quad \text{RoL} = \frac{5}{4}S - 2.5,$$

maps the weakest observed institutional quality (RoL $= -2.5$) to $S = 0$ and the strongest (RoL $= +2.5$) to $S = 4$, placing the model's range in correspondence with the full cross-country governance distribution. Under this normalization the institutional threshold $\theta = 2$ corresponds exactly to RoL $= 0$, the global median of institutional quality. Economies whose governance score falls below the world median (a category encompassing most low-income and lower-middle-income countries) face diminishing marginal returns to institutional investment, consistent with the empirical finding that governance reforms have limited traction in fragile-state environments (Worldwide Governance Indicators, 2025). This mapping is illustrative; a formal calibration to country-level governance moments is left for future work.

5.2. The Emergence of Multiple Equilibria

The numerical solution of our calibrated model powerfully confirms the central theoretical prediction: the co-evolutionary system of physical and social technologies admits multiple long-run equilibria, each representing a fundamentally different development regime. As shown in the stability analysis panel and phase portraits, our simulations identify precisely two steady-state equilibria that satisfy the first-order optimality conditions and the capital accumulation constraints. These equilibria are not merely mathematical artifacts but represent economically meaningful and empirically relevant development outcomes: one corresponding to a poverty trap characterized by institutional failure, the other to a prosperous path sustained by functional institutions.

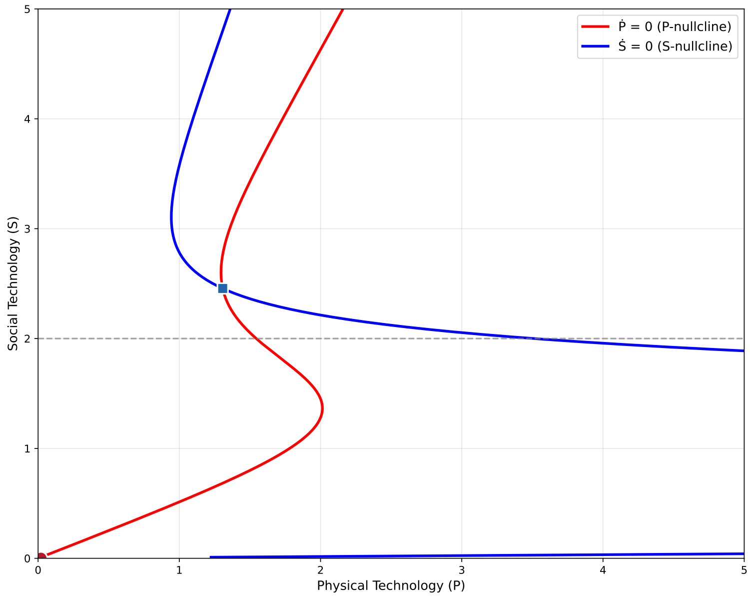
The first equilibrium, marked by a red circle in Figure 1, represents a low-level development trap located at $P^* = 0.020, S^* = 0.001$. At this equilibrium, the social technology level S^* falls drastically below the institutional threshold $\theta = 2$, rendering all institutional investments completely unproductive. The economy becomes locked in a vicious cycle: low social technology undermines production efficiency and investment returns, which in turn limits the resources available for institutional development, even as the threshold effect ensures that any modest attempts at institutional investment yield zero returns. The resulting steady state features minimal physical capital accumulation, subsistence-level consumption ($c^* = 0.009$), and an investment share heavily skewed toward physical technology ($\beta^* = 0.867$) despite its limited productivity in the absence of complementary institutions. This equilibrium precisely captures the empirical reality of development traps observed across many low-income countries, where weak institutions perpetuate economic stagnation despite occasional injections of physical capital or foreign aid.

In stark contrast, the second equilibrium, indicated by a green square in Figure 1, represents a high-level prosperity path at $P^* = 1.307, S^* = 2.456$. Here, the social technology level successfully surpasses the institutional threshold, activating a virtuous cycle of mutually reinforcing accumulation. With $S^* > \theta$, institutional investments become productive, generating returns that justify continued allocation of resources to social technology development. The steady state features substantially higher output ($F^* = 1.819$), consumption ($c^* = 1.091$), and a more balanced investment allocation ($\beta^* = 0.449$) that maintains both forms of capital at elevated levels. The institutional quality parameter $\phi^* = 0.817$ at this equilibrium confirms that the economy operates in a regime where social technologies function effectively, supporting both production efficiency and direct welfare contributions through improved governance, trust, and coordination mechanisms.

The mathematical verification of these multiple equilibria emerges elegantly from the nullcline analysis presented in Figure 1. The P-nullcline ($\dot{P} = 0$, shown in red) and the S-nullcline ($\dot{S} = 0$, shown in blue) intersect at exactly two points in the economically relevant region of the state space.

The shape of these nullclines reveals the fundamental nonlinearity driving the multiplicity: the S-nullcline exhibits a sharp backward bend around the threshold level $S = 2$, reflecting the dramatic change in institutional investment productivity as the economy crosses this critical boundary. This intersection pattern confirms that the multiple equilibria are not accidents of particular parameter choices but arise from the deep structural features of the model, specifically, the interaction between threshold effects in institutional accumulation and the complementarity between physical and social technologies in production. The existence of exactly two equilibria, rather than a continuum or a unique solution, underscores that development outcomes are fundamentally discrete: economies converge either to persistent poverty or to sustained prosperity, with no stable intermediate possibilities under our baseline parameters.

FIG. 1. Nullclines and Steady-State Equilibria



5.3. Stability Analysis: The Robustness of Poverty and the Fragility of Prosperity

The local stability properties of the two equilibria, derived through eigenvalue analysis of the system's Jacobian matrix at each point, reveal a profound asymmetry that fundamentally shapes the nature of economic development. The stability analysis presented in Table 2 provides precise mathematical characterization of each equilibrium's dynamic properties, exposing a stark contrast between the robust self-perpetuation of poverty and the inherent fragility of prosperity. This asymmetry is not merely a technical curiosity but offers deep insights into why escaping poverty proves so difficult for many nations while maintaining prosperity requires constant vigilance and favorable conditions.

The low-level equilibrium exhibits the characteristics of a stable node. As detailed in Table 2, both of its eigenvalues have negative real parts ($\lambda_1 = -0.0224, \lambda_2 = -0.0400$). This configuration implies that the poverty trap possesses powerful self-reinforcing mechanisms that actively resist perturbations. Like a ball resting at the bottom of a deep basin, any economy that finds itself in the neighborhood of this equilibrium experiences forces that inexorably pull it toward the center. Small positive shocks, whether from temporary commodity price booms, foreign aid, or sporadic reform attempts, are systematically reversed as the underlying dynamics reassert themselves. The negative eigenvalues indicate that deviations in both physical technology and social technology are simultaneously corrected, creating a two-dimensional convergence that makes escape nearly impossible through gradual, marginal improvements. The institutional quality measure $\phi^* = 0.102$ at this equilibrium confirms that the economy operates far below the threshold where institutional investments become productive, effectively shutting down one of the two engines of growth.

In stark contrast, the high-level equilibrium presents an entirely different structure: it is a saddle point, characterized by eigenvalues with opposite real parts ($\lambda_1 = -0.0254, \lambda_2 = 0.0561$). This configuration represents perhaps the most profound insight from our numerical analysis. The positive eigenvalue indicates that the prosperity equilibrium is fundamentally unstable in exactly one direction of the state space, meaning that most trajectories starting near this equilibrium will eventually diverge away from it. The only paths that lead to sustained prosperity are those that approach along the stable manifold, a one-dimensional curve in the two-dimensional state space that represents the unique "saddle path" to development. This mathematical structure provides a rigorous foundation for understanding prosperity as a knife-edge phenomenon: achieving sustained development requires not just reaching high levels of capital stocks but doing so along a precise trajectory that maintains the delicate balance between physical and social technology accumulation.

The implications of this saddle-point instability extend far beyond technical mathematics. This instability explains why seemingly successful developing economies can suddenly collapse back into stagnation when they deviate even slightly from the optimal development path. A country that invests too heavily in physical infrastructure while neglecting institutions, or conversely one that attempts institutional reforms without adequate material foundations, will find itself sliding away from the high equilibrium despite having temporarily achieved respectable levels of both P and S.

Therefore, not only must countries find the narrow path to prosperity, but they must also maintain sufficient foresight and institutional memory to stay on that path across multiple political cycles and generations.

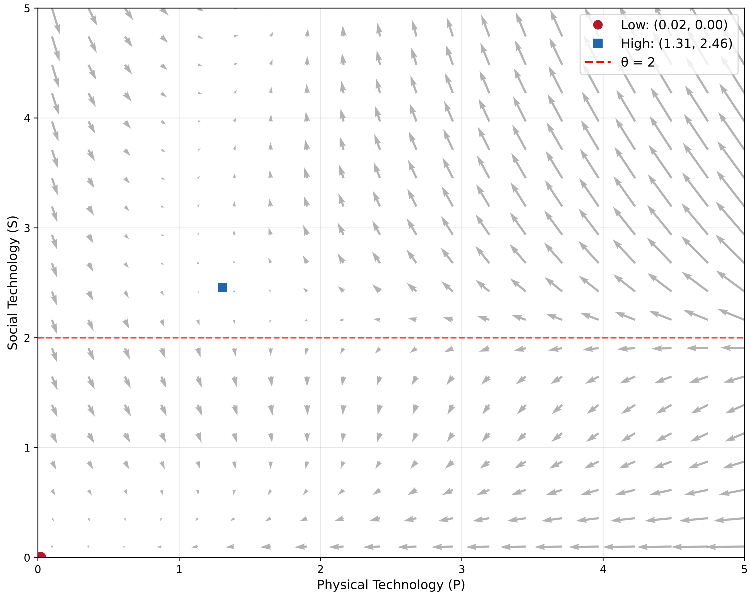
TABLE 2.

Stability Properties of Steady-State Equilibria

Equilibrium Type	**Stability Class**	λ_1	λ_2
Low (Poverty Trap)	Stable Node	-0.0224	-0.0400
High (Prosperity)	Saddle Point	-0.0254	$+0.0561$

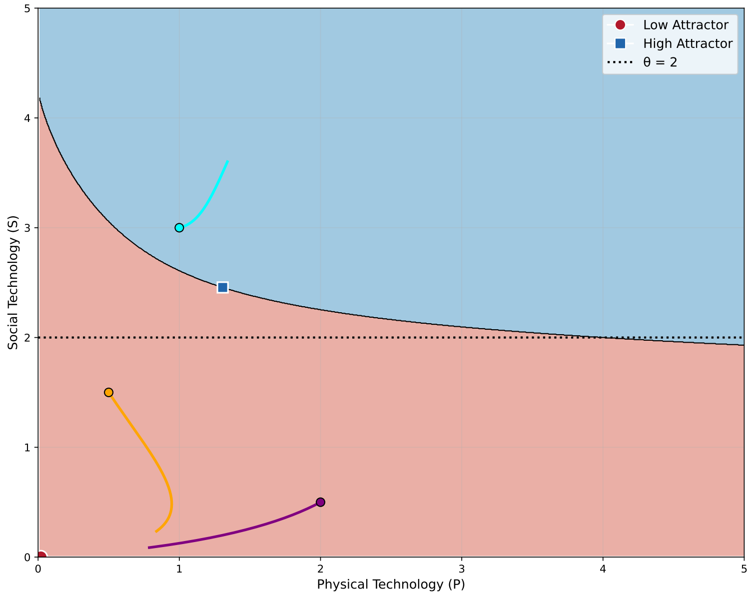
5.4. Global Dynamics: Basins of Attraction and Path Dependence

FIG. 2. Vector Field of Economic Dynamics



While the stability analysis reveals the local properties of each equilibrium, understanding the global dynamics requires examining how trajectories evolve throughout the entire state space. Figure 2 depicts the vector field, providing a comprehensive visualization of the instantaneous forces acting on any economy at any point in the (P, S) plane. The gray arrows indicate the direction and magnitude of change at each location, revealing a dramatic shift in the system's behavior around the institutional threshold $\theta = 2$. Below this critical level, the arrows predominantly point downward and leftward, indicating that both physical technology and social technology tend to decay when institutions are dysfunctional. Above the threshold, the vector field becomes more complex, with regions of accumulation and depletion creating swirling patterns that guide economies along specific development trajectories. The discontinuous change in vector orientation near $S = 2$ graphically illustrates how the threshold effect fundamentally alters the economy's evolutionary dynamics, creating what amounts to two distinct "gravitational fields" operating in different regions of the state space.

FIG. 3. Basins of Attraction for Economic Development



The basin of attraction analysis presented in Figure 3 represents the culmination of our global dynamic investigation, revealing which initial conditions lead to which long-run outcomes. The state space divides into two distinct regions: the red area constitutes the basin of attraction for the poverty trap, while the blue area represents the basin for the high-prosperity equilibrium. Every point in the red region, regardless of its specific location, will eventually converge to the low-level equilibrium, while points in the blue region are destined for prosperity. The boundary between these basins, the separatrix, emerges as a critical curve that determines the fate of entire economies. Notably, this boundary is neither vertical nor horizontal but follows a complex, sloping trajectory that reflects the intricate interplay between physical and social capital in determining development outcomes. The color-coded trajectories overlaid on the diagram vividly demonstrate this sorting process: economies starting in different regions follow dramatically divergent paths, with those in the red zone spiraling downward toward poverty while those in the blue zone ascending toward prosperity.

The shape and location of the separatrix yield profound insights that challenge simple intuitions about development. Contrary to what one might expect, crossing the institutional threshold $\theta = 2$ is neither necessary nor sufficient for escaping the poverty trap. The boundary's complex, sloped trajectory reveals a crucial interplay between the two forms of capital. For instance, consider an economy with substantial material wealth but weak institutions, located at $P = 4, S = 1.5$. Despite its high level of physical technology, this point lies deep within the red basin of attraction, condemning the economy to eventual decline. This provides a clear illustration of the "resource curse," where material abundance fails to translate into prosperity without a sufficiently strong institutional foundation. Conversely, the separatrix also reveals that economies with modest physical technology but strong institutions (for example, a point in the upper-left portion of the blue region, such as $P = 1, S = 3$) can successfully achieve prosperity. This highlights the primacy of institutional quality in development. This asymmetric relationship between P and S in determining basin membership provides a rigorous theoretical foundation for understanding such empirical puzzles.

The existence of distinct basins of attraction constitutes the most compelling evidence for path dependence in economic development. Two economies that differ only marginally in their initial conditions, one located just to the left of the separatrix, and the other just to the right, will experience entirely different developmental trajectories despite their initial similarity. This sensitive dependence on initial conditions means that historical accidents, colonial legacies, or early policy choices can have permanent consequences, locking economies into development paths that become increasingly difficult to alter over time. The path dependence is particularly severe because the basins are not merely attracting regions but are separated by a saddle point that actively repels trajectories, making transitions between basins extremely difficult without large, coordinated interventions. Small, incremental reforms or marginal improvements in capital stocks are insufficient to cross from one basin to another; what is required is either a massive coordinated push that moves the economy across the separatrix in a single leap, or a carefully orchestrated development strategy that navigates along specific trajectories that can breach the boundary. This global perspective thus provides a rigorous mathematical framework for understanding why development assistance often fails, why some economies remain trapped in poverty despite decades of investment, and why successful development experiences are relatively rare and often appear miraculous when they do occur.

5.5. Summary of Numerical Results

The numerical simulations presented in this section provide compelling computational validation of our theoretical framework while revealing additional layers of complexity that emerge from the nonlinear interaction between physical and social technologies. Through systematic parameter calibration and comprehensive dynamic analysis, we have demonstrated three fundamental features of the co-evolutionary development process that could not be fully appreciated through analytical methods alone. First, the system exhibits robust multiple equilibria, with a poverty trap at $P^* = 0.020, S^* = 0.001$ and a prosperity equilibrium at $P^* = 1.307, S^* = 2.456$, confirming that development outcomes are fundamentally bifurcated rather than continuously distributed. Second, these equilibria possess starkly different stability properties—the poverty trap operates as a stable node that actively resists escape attempts, while the prosperity equilibrium manifests as a saddle point whose inherent instability makes sustained development a precarious achievement requiring precise navigation along a one-dimensional stable manifold. Third, the global dynamics reveal extensive path dependence through clearly delineated basins of attraction, where minute differences in initial conditions can determine whether an economy converges to perpetual poverty or achieves lasting prosperity.

The phase portraits and stability analyses presented here transcend mere mathematical exercises; they provide a rigorous theoretical foundation for understanding some of the most persistent puzzles in development economics. The stable node property of the poverty trap explains why incremental reforms and marginal improvements so often fail to generate sustained development; small perturbations are systematically reversed by the equilibrium's attractive forces, rendering most development interventions ineffective unless they achieve sufficient scale to push the economy entirely out of the poverty basin. The saddle point nature of prosperity explains why economic success appears so fragile, why middle-income countries often stagnate or regress, and why maintaining development requires not just achieving high levels of capital stocks but doing so along precise trajectories that balance physical and institutional accumulation. The complex, sloped separatrix between the basins of attraction demonstrates that simple thresholds or linear development strategies are insufficient; what matters is the precise combination of physical technology and social technology relative to the basin boundary, explaining why resource-rich nations with weak institutions fail while resource-poor nations with strong institutions can succeed.

These numerical findings establish a solid quantitative and theoretical foundation for examining the policy implications of our co-evolutionary framework. The existence of multiple equilibria and path dependence suggests that development policy must be fundamentally reconceptualized: away from marginal improvements and toward coordinated transformations capable of shifting economies between basins of attraction. The fragility of the prosperity equilibrium implies that successful development requires not just reaching high levels of development but establishing institutional mechanisms that can maintain the delicate balance between physical and social technology accumulation across time. The primacy of institutional quality revealed by the basin analysis challenges conventional approaches that prioritize physical technology accumulation, suggesting instead that sustainable development must begin with and continuously reinforce institutional foundations.

6. CONCLUSION

This paper has developed a rigorous theoretical framework in which economic growth and welfare are jointly determined by the co-evolution of physical technologies $P(t)$ and social technologies $S(t)$, the latter encompassing institutions, norms, and organizational forms. Building upon the foundational insights of Richard R. Nelson, we model these two technological domains not only as jointly productive in the aggregate production function but also as arguments in the representative agent's utility function, thereby directly linking institutional quality to human well-being.

The formal analysis reveals that the dynamics of such an economy are governed by a system of nonlinear differential equations, subject to threshold effects and diminishing returns in both technological domains. While physical technologies can be accumulated relatively smoothly through investment, social technologies exhibit discontinuities and fragility due to their reliance on trust, coordination, and legitimacy. This asymmetry gives rise to the possibility of multiple equilibria, development traps, and even chaotic trajectories depending on initial institutional conditions, investment shares, and functional forms. Our numerical simulations, using realistic parameter values, demonstrate that economies with low initial $S(0)$ remain trapped in stagnation despite high savings or initial capital, while those above the institutional threshold converge to a high-level steady state of prosperity.

Three policy implications follow directly from the model. First, when $S(t) < \theta$, the threshold condition $\phi(S) = 0$ implies zero marginal return to institutional investment, so the economy cannot escape stagnation through increased physical capital accumulation alone; lifting S above θ is a necessary precondition for any development strategy. Second, in economies with

$S(0) > \theta$, convergence to the high steady state requires approaching along the one-dimensional stable manifold of the prosperity saddle point, implying that the investment allocation β must be calibrated to maintain the co-evolutionary balance between P and S. Third, because $S(t)$ enters the utility function directly, welfare-improving development requires improvements in institutional quality as an intrinsic goal; purely consumption- or output-based metrics systematically understate the welfare cost of institutional poverty traps.

Historically, the model provides a unifying explanation for the divergent growth paths of societies and the rise and fall of civilizations. Nelson's insight that social technologies evolve more slowly, and are more vulnerable to disruption, than physical technologies is mathematically validated by the fragility of high-equilibrium trajectories and the ease with which institutional decay can precipitate economic collapse. In this light, institutions are not mere "rules of the game" but active co-determinants of prosperity and welfare, social technologies that must be cultivated, protected, and repaired.

Ultimately, this paper contributes to the ongoing project of institutional economics by offering a dynamic, intertemporal, and formal model in which physical and social technologies are inseparable components of development. Future research can extend the framework to heterogeneous agents, common shocks, ideological polarization, and global interactions. But at its core, the message remains: no sustainable prosperity is possible without enduring and evolving institutions. Physical capital builds factories; social technologies build civilizations.

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