Evolutionary Systems Thinking: From Equilibrium Models to Open-Ended Adaptive Dynamics

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Presented at the 44th **International System Dynamics Conference** (ISDC) , July 23, 2026

Abstract

Complex change is often described as "evolutionary" in economics, policy, technology, and organizations, yet many system dynamics models represent behavior within a fixed set of stocks, flows, relationships, and transition rules. Such models can generate nonlinear, oscillatory, path-dependent, or chaotic behavior, but structural novelty must ordinarily be specified in advance. This paper argues that evolutionary dynamics should be treated as a core systems-thinking problem rather than as a biological metaphor.

We introduce Stability-Driven Assembly (SDA), a minimal non-equilibrium framework in which stochastic interactions and differential persistence generate endogenous selection without genes, template-based replication, or an externally specified fitness function. Longer-lived configurations accumulate in the population and therefore become more likely to participate in subsequent interactions. This creates feedback among persistence, population composition, and future pattern formation. The resulting abundance-weighted sampling is equivalent to fitness-proportional selection, allowing SDA to be interpreted as a natural genetic algorithm driven by persistence-weighted population dynamics.

SDA provides a conceptual basis for distinguishing fixed-state-space dynamics from evolving possibility spaces, in which persistent structures can reshape future flows, interactions, and available configurations. It also suggests that equilibrium should be treated as provisional: a quasi-stable regime may be reorganized when a more persistent configuration emerges. We conclude by outlining two ways to extend system dynamics practice: constructing an SDA-style population model alongside a stock–flow model, and using SDA perturbation analysis to examine the vulnerability of an existing regime to structural innovation.

Keywords: evolutionary system dynamics, system dynamics, non-equilibrium systems, stability-driven assembly, agent-based modeling

1 Introduction

The term *evolution* is widely used in economic, policy, technological, and organizational studies to describe long-term change. System dynamics provides a mature framework for representing feedback, accumulation, delays, and nonlinear behavior (Meadows, 2008; Sterman, 2000). Yet in

many system dynamics models, the relevant stocks, flows, relationships, and transition rules are specified before the simulation begins. Such models can exhibit nonlinear behavior, oscillation, path dependence, multiple attractors, and collapse, but they ordinarily describe change within a predefined structure. New strategies, institutions, technologies, or categories can appear only if the modeler has already represented them as possible states or transitions. This gap has long motivated evolutionary approaches in economics (Nelson & Winter, 1982), but it remains difficult to represent the endogenous construction of new categories and interaction structures.

The central distinction is between a system that moves through a fixed possibility space and one that changes the space through which it can subsequently move. In a conventional dynamical model, the state variables may change, while the identities of those variables and the rules governing their interaction remain fixed. In an evolutionary system, by contrast, persistent structures generated during the process can become part of the causal environment for future dynamics. A strategy can create a market niche, an organizational routine can enable new capabilities, and a policy can create agencies, constituencies, and constraints that shape later policy choices. System dynamics makes behavior endogenous to feedback structure; evolutionary system dynamics must additionally allow aspects of that structure to become endogenous to accumulated history.

This distinction reflects a broader issue in scientific explanation. Idealized models (Cartwright, 1983) often succeed by suppressing history, population heterogeneity, and contextual variation in order to isolate tractable causal relationships. As philosophers of science have emphasized, idealization is not a flaw but a necessary methodological tool (Potochnik, 2017). However, when the phenomenon of interest is inherently historical, cumulative, and population-dependent, fixing the relevant entities and transition structure in advance can remove the mechanism that requires explanation. In such cases, simulation-based approaches may offer explanatory value not simply because they contain more detail, but because they preserve feedback among system state, population composition, and the formation of future structure.

This distinction is developed more fully in (Adler, 2026a) as a contrast between *episodic* and *constructive* epistemic regimes. Episodic models treat successive interactions as applications of invariant rules within a fixed state space, whereas constructive systems allow the products of earlier interactions to persist, accumulate, and become causal conditions for later ones. The present paper translates that philosophical distinction into a system dynamics context by asking how population-level memory can make aspects of feedback structure endogenous to the history of the system.

Darwinian evolution is conventionally modeled through heritable variation, with heredity usually implemented by molecular or template-based replication (Fisher, 1930). Before such machinery existed, however, physical and chemical configurations already differed greatly in how long they persisted under prevailing conditions. Across physics, chemistry, and materials science, differences in persistence arise from energetic minima, kinetic barriers, symmetry, spatial organization, and hierarchical assembly, spanning timescales from transient states to structures that endure for geological durations. This raises a more general question: can differential persistence create population-level selection before high-fidelity replication exists?

In an open system with continued stochastic formation and turnover, persistence can bias population composition. At comparable formation rates, configurations that last longer accumulate more instances and remain available for more interactions. Their increased abundance then raises the probability that they will participate in subsequent formation events. This closes a feedback loop: persistence shapes population composition, population composition biases future interactions, and those interactions generate configurations whose persistence further reshapes the population. Selection therefore need not be imposed as an external criterion; it can emerge from the coupling of differential persistence, recurrent formation, and abundance-weighted interaction.

In this paper, we use *Stability-Driven Assembly* (SDA) (Adler, 2025) as a minimal framework to make this feedback explicit. SDA combines stochastic interaction, finite lifetimes, continuous replenishment, and removal of expired configurations in an open, non-equilibrium population. Longer-lived configurations become overrepresented and are consequently sampled more often in later interactions. This produces abundance-proportional sampling equivalent to fitness-proportional selection when persistence acts as an implicit fitness measure. With recombination and mutation, the same mechanism can be interpreted as a natural genetic algorithm, SDA/GA (Adler, 2026b), without an externally specified objective function or template-based replication.

The purpose of the paper is not to argue that conventional system dynamics models must converge to equilibrium, nor that agent-based simulation is intrinsically evolutionary. Rather, it is to identify the additional mechanism required when persistent structures alter future flows, interactions, or available configurations. We first distinguish fixed-state-space dynamics from evolving possibility spaces and present the minimal SDA mechanism and illustrative simulation results. We then show how differential persistence can produce quasi-stable regimes that are punctuated when a more persistent configuration emerges and reorganizes population flows. Finally, we discuss the relationship of SDA to stock–flow and agent-based modeling and propose two practical extensions to system dynamics: constructing an SDA-style population model alongside an existing stock–flow model, and using SDA perturbation analysis to examine the vulnerability of an established regime to structural innovation.

2 Fixed-state-space Dynamics and Evolving Possibility Spaces

The central distinction developed in this paper is not between systems that reach equilibrium and systems that remain in motion. A conventional system dynamics model may exhibit oscillation, overshoot, path dependence, multiple attractors, chaos, or collapse while remaining structurally fixed. The relevant distinction is, instead, between dynamics within a predefined possibility space and dynamics that can modify the effective space of future possibilities.

A conventional dynamical system may be represented schematically as

$$\frac{dx}{dt} = F(x;\theta), \tag{1}$$

where the state variables x, the parameters θ, and the functional form of the interactions are

specified before the simulation begins. The values of the variables change over time, but the identities of the variables and the repertoire of possible transitions remain fixed. Therefore, any new strategy, institution, technology, or organizational form must be represented in advance, even if its eventual occurrence is uncertain.

An evolutionary system requires an additional form of endogeneity. Let $P(t)$ denote the population of persistent configurations generated by the system's history. The effective dynamics may then be represented schematically as

$$\frac{dx}{dt} = F(x; P(t)), \tag{2}$$

where the accumulated population structure modifies future flows, interaction probabilities, or accessible transitions. The notation is schematic rather than a complete formalism: its purpose is to express that the effective dynamics depend on structures produced during the process itself.

This distinction can be summarized as follows. A fixed-state-space dynamical system moves through a possibility space specified by the modeler. An evolutionary system can construct persistent configurations that become part of the causal environment and thereby alter what can occur next. System dynamics makes behavior endogenous to feedback structure; evolutionary system dynamics additionally asks how aspects of that structure can become endogenous to accumulated history.

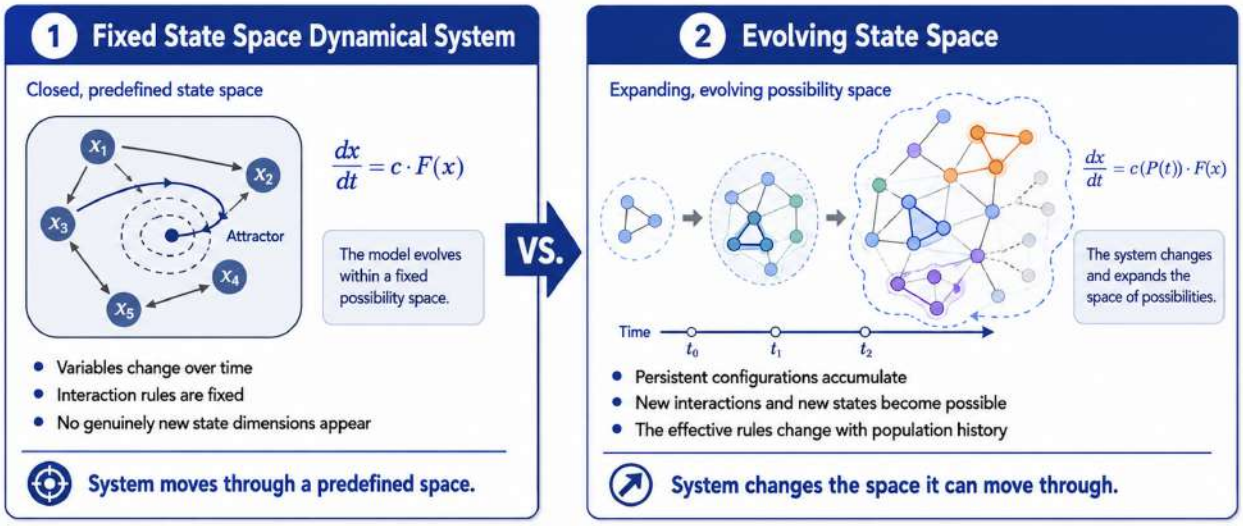

Figure 1: Fixed-state-space models move through a predefined possibility space, whereas evolutionary systems can reshape the effective space of future possibilities as persistent structures accumulate.

In economic, technological, organizational, and policy systems, such persistent configurations can include strategies, institutions, standards, infrastructures, routines, metrics, or regulatory arrangements. A persistent strategy may create niches for complementary strategies; an organizational routine may enable new capabilities; and a policy may create agencies, constituencies, and

constraints that shape future policy choices. These structures do not merely change the current state of the system. They modify the conditions under which subsequent states are generated.

Evolutionary language is therefore mechanistically meaningful only when the model identifies how variants arise, why some persist longer than others, and how the resulting population changes subsequent dynamics. Competition, learning, imitation, and adaptation may contribute to this process, but they do not by themselves guarantee an evolving possibility space. The decisive condition is that the structures produced by earlier interactions persist and feed back into the generation of later ones.

This criterion also clarifies the relationship between evolutionary dynamics and evolutionary game theory. Standard evolutionary game models describe changes in the frequencies of strategies within a specified set of strategies and payoff structure (Nowak, 2006). Such models are evolutionary in the population-dynamical sense, but they do not necessarily represent the endogenous construction of new strategies, payoff relations, or categories. The present paper addresses this additional constructive dimension: how population history can reshape the effective structure of the system itself.

3 Stability-Driven Assembly as an Evolutionary Mechanism

Stability-Driven Assembly (SDA) is a minimal non-equilibrium framework in which differential persistence biases the accumulation of structure over time (Adler, 2025). A companion study extends the framework through recombination and mutation and applies it to chemical symbol space, where it produces scaffold-level dominance, entropy reduction, and sustained novelty (Adler, 2026b). The term "assembly" here refers to pattern formation through interaction and is distinct from Assembly Theory (Sharma et al., 2023), which measures constructional complexity rather than modeling population-level selection.

The core SDA mechanism is intentionally simple. Patterns are generated through stochastic interactions in an open population, assigned finite lifetimes, and removed when those lifetimes expire. Base elements are continually replenished to maintain turnover and continued exploration. Relative to unconstrained random assembly, the decisive addition is differential persistence.

Figure 2 provides a conceptual comparison with purely accumulative random assembly. The simulation in Section 3.1 uses a stricter uniform-persistence control: both conditions include expiration and differ only in whether lifetimes vary among patterns.

Patterns that persist longer remain available for more interactions and, when recurrently generated, accumulate more instances. Their greater abundance raises their probability of participating in subsequent interactions. This closes the central SDA feedback loop shown in Figure 3.

This mechanism produces selection without an externally imposed selection operator. Stochastic interaction supplies variation, while differential persistence alters the population from which subsequent interactions are sampled. When the interaction operator includes recombination and mutation, abundance-proportional sampling plays the role of fitness-proportional or roulette-wheel

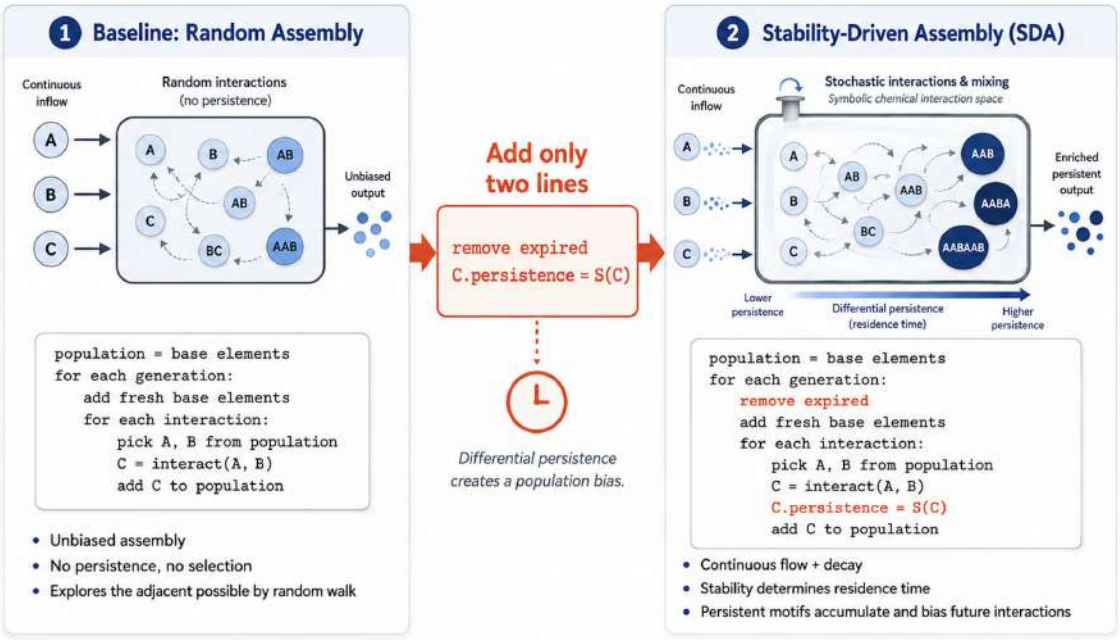

Figure 2: From random assembly to Stability-Driven Assembly. In the baseline case, stochastic interaction alone performs an unbiased search over nearby possibilities. Adding only two operations—removal of expired patterns and assignment of persistence according to a stability function S—creates a population bias. Persistent motifs remain in the population longer, accumulate, and participate more often in subsequent interactions.

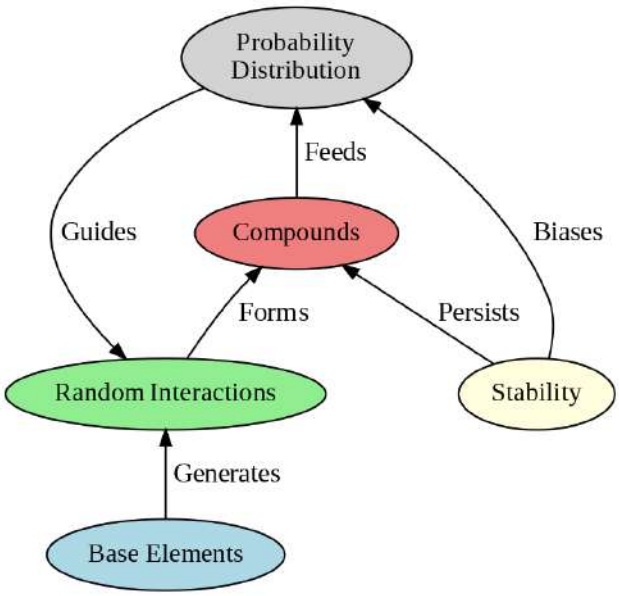

Figure 3: Core feedback structure underlying SDA. Stochastic interactions generate patterns; differential persistence reshapes population composition; and the evolving population distribution biases future interactions. Selection emerges endogenously from this feedback loop.

selection (Goldberg, 1989; Holland, 1975). SDA can therefore be interpreted as a natural genetic algorithm, SDA/GA (Adler, 2026b), in which persistence acts as an implicit fitness measure.

The analogy does not require biological lineage or template copying. Multiple instances of a motif may arise through independent interaction events and share structural identity without descending from a common replicating individual. More generally, persistence should be understood as a context-dependent residence time. In physical systems, it may depend on bonding, activation barriers, or spatial organization; in socio-technical systems, it may depend on switching costs, legitimacy, network effects, complementary capabilities, or institutional support. In each case, the population-level consequence is the same: configurations that remain active longer have more opportunities to participate in and influence subsequent dynamics.

3.1 Illustrative Symbolic Result

To illustrate the population-level effect of differential persistence, we compare a minimal symbolic SDA simulation with a uniform-persistence control. In both cases, patterns are generated stochastically through interaction, expired instances are removed, and base elements are continuously replenished. In the SDA condition, lifetimes vary according to the stability function $S(p)$; in the control condition, all patterns receive the same lifetime. No explicit fitness function or selection operator is applied (Adler, 2025, 2026b).

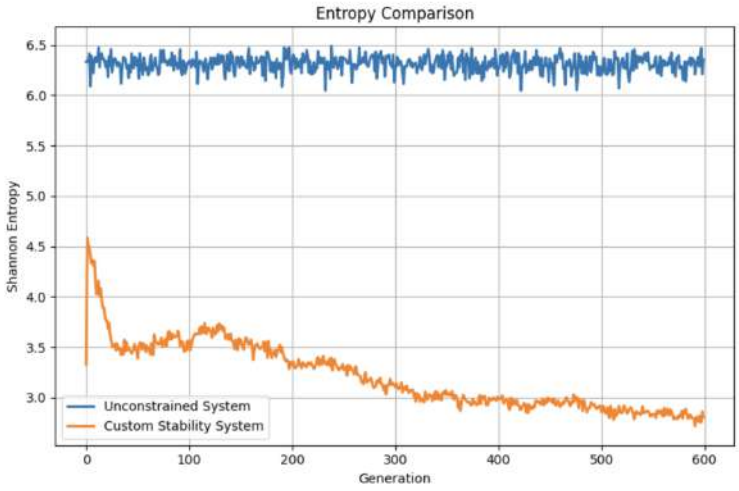

Figure 4: Shannon entropy of the population distribution under SDA and a uniform-persistence control. Entropy remains comparatively high when all patterns receive the same lifetime. Under differential persistence, probability mass becomes concentrated on a smaller set of long-lived motifs, producing lower population entropy.

Figure 4 shows the Shannon entropy of the population distribution over time. In the uniform-persistence control, continued stochastic formation maintains a relatively dispersed distribution. Under SDA dynamics, entropy declines as longer-lived motifs accumulate and become more frequently represented in subsequent interactions. The resulting concentration of probability mass

demonstrates that differential persistence, coupled to recurrent formation and abundance-proportional sampling, is sufficient to generate endogenous selection pressure without an explicit fitness function or template-based replication. This establishes the minimal selection mechanism used in the remainder of the paper. It does not, by itself, demonstrate open-ended evolution or indefinite state-space expansion; rather, it shows how persistence-weighted population feedback can transform stochastic assembly into directed, path-dependent search. Extended simulations, intervention experiments, and chemical-symbol applications are reported elsewhere (Adler, 2025, 2026b).

4 Population Memory and Structural Change

The symbolic result above establishes a minimal population-level mechanism: differential persistence changes abundance, and abundance biases the interactions from which later configurations are generated. The population therefore retains information about earlier formation events. History is represented not only by the current values of aggregate variables, but also by the configurations that remain active and continue to participate in the system.

Important precursors to this perspective emphasized the historical and non-equilibrium character of evolutionary processes. Brooks and Wiley's *Evolution as Entropy* (Brooks & Wiley, 1986) rejected teleological and optimization-based accounts in favor of irreversibility, constraint, and information accumulation. Related work in econophysics challenged equilibrium and representative-agent assumptions by modeling economies as heterogeneous populations of interacting entities (Farmer & Foley, 2009; Farmer et al., 2005). SDA contributes a specific mechanism through which such history becomes causally active: persistent configurations remain available for reuse and thereby alter the population from which subsequent interactions are sampled.

However, persistence-driven selection and structural evolution are not the same. Differential persistence alone can concentrate a population on a subset of configurations, as shown in Section 3.1. A stronger evolutionary effect occurs when those accumulated configurations also modify later formation rates, interaction opportunities, persistence conditions, or aggregate flows. Population memory then changes not only which configurations are common, but also the effective conditions under which future configurations are generated and retained.

It is also useful to distinguish SDA from standard birth–death and predator–prey models. Such models already represent turnover and population feedback: births and deaths change population abundance, and the abundance of one population may affect the growth or decline of another (Kendall, 1948). In their standard formulations, however, the relevant population types and interaction channels are specified in advance. SDA does not differ merely because it includes decay or population-dependent interaction. It adds a constructive layer in which interactions generate configurations, differential persistence determines which remain available, and the resulting population biases the formation of subsequent configurations. The distinction is therefore between feedback among predefined populations and feedback through which the active population repertoire can itself be constructed and reshaped. Models with evolving traits, adaptive interactions, or endogenous

network structure may cross this boundary and are best understood as neighboring approaches to evolutionary system dynamics.

The present symbolic model demonstrates persistence-driven selection and provides a basis for investigating this stronger structural effect. It does not by itself establish unlimited novelty or literal expansion of state-space dimensionality. Its more specific contribution is to identify persistence-weighted population feedback as a bridge from stochastic formation to path-dependent structural change. The following sections consider how this mechanism can be represented using agent-based and stock–flow models.

5 Agent-Based Modeling and Evolutionary System Dynamics

5.1 ABM as an Implementation Substrate

Agent-based models (ABMs) (Hamill & Gilbert, 2016; Railsback & Grimm, 2012; Resnick, 1994) provide a natural computational substrate for evolutionary system dynamics because they can represent heterogeneous entities, stochastic interaction, entry and exit, local adaptation, and endogenous network formation. Related approaches in evolutionary economics likewise model economic change through populations of firms, routines, technologies, and institutions rather than through representative agents or static equilibrium alone (Dopfer & Potts, 2008; Hodgson & Knudsen, 2010).

Agent-based representation, however, does not by itself make a model evolutionary in the constructive sense developed here. An ABM may contain heterogeneous and adaptive agents while retaining a predefined set of agent types, strategies, interaction rules, and possible transitions. Such a model can produce complex emergent behavior within its specified architecture without allowing structures generated during the simulation to modify the effective space of subsequent possibilities.

Conversely, ABMs are not intrinsically limited to fixed structures. They can be designed so that strategies, networks, organizations, or interaction rules emerge and subsequently alter agent behavior. The relevant question is therefore not whether a model is agent-based, but whether its generated population structure becomes causally active in future dynamics.

SDA supplies one minimal mechanism for creating this coupling. Differential persistence changes the abundance of configurations in the population, and abundance changes the probability that those configurations participate in subsequent interactions. The population distribution is therefore not merely a summary statistic. It is part of the mechanism determining which interactions occur and which new configurations become accessible.

This distinction may be expressed as a design criterion for evolutionary ABMs. Such a model should represent the generation of structural variation; differential persistence, removal, or turnover; interaction probabilities that depend on the resulting population composition; and feedback through which persistent structures modify later flows, interactions, or available configurations. An ABM satisfying these conditions could implement SDA directly or realize a related evolutionary mechanism. SDA should therefore be understood not as an alternative to agent-based modeling, but as a population-feedback principle that agent-based simulation is especially well suited to represent.

5.2 Stochastic Interaction and Differential Persistence

In many physical, social, and organizational systems, novelty originates through contingent interaction. Molecules encounter one another, individuals form collaborations, firms establish partnerships, and institutions combine existing procedures into new organizational forms. Most such encounters leave no durable trace, while a smaller number produce configurations that remain available for further interaction.

Persistence acts as a population-level filter on this variation. A durable collaboration may attract additional participants; a successful routine may become embedded in organizational practice; and a technical standard may acquire complementary products and infrastructure. These structures need not copy themselves directly. Because they remain present, they receive more opportunities to participate in subsequent events and to contribute components to later configurations.

This is the mechanism formalized by SDA. Stochastic interaction supplies exploration, while differential persistence changes the population from which later interactions are sampled. Selection arises through unequal continued participation rather than through centralized choice or an externally specified optimization criterion. Persistent structures need not be globally optimal; they need only remain sufficiently viable under prevailing conditions to accumulate and influence subsequent dynamics.

Stochasticity is useful because it continually exposes the system to new combinations, but randomness alone is not sufficient for evolutionary change. Without persistence, accumulation, and population feedback, novel configurations disappear without affecting what happens next. Likewise, persistence without continued variation may produce concentration without sustained innovation. Evolutionary dynamics arise from the coupling of exploration with differential retention and reuse.

6 Adding Evolutionary Dynamics to Stock–Flow Models

One of the enduring strengths of system dynamics is the unifying power of the stock–flow formalism (Martín García, 2019; Meadows, 2008; Sterman, 2000). Inventories, bank balances, populations, chemical concentrations, and other accumulated quantities can be represented using a common language of stocks, inflows, outflows, delays, and feedback. This abstraction allows behavior to emerge endogenously from a model's feedback structure.

Evolutionary systems require an additional form of endogeneity. The issue is not merely that stock values change, but that persistent structures generated during the process may alter the flows, relationships, and possibilities available afterward. A new strategy can create opportunities for complementary strategies; an organizational routine can enable previously unavailable capabilities; and a policy can create agencies, constituencies, metrics, and constraints that influence later interventions. The products of the dynamics become part of the causal environment for subsequent dynamics.

In an SDA representation, stocks correspond to populations of configurations rather than only to quantities of predefined substances. Formation events create new configurations, while expira-

tion and removal provide their outflows. Differential persistence changes the residence time of each configuration, and the resulting abundance distribution biases later interaction flows. New configurations may therefore enter the active population, become causally important, and eventually decline or disappear.

This does not require abandoning stock–flow modeling. Rather, it requires coupling a conventional aggregate model to a population-level constructive process. The stock–flow model represents the current macroscopic regime, while the SDA component represents the generation, persistence, and selection of structures capable of modifying that regime.

6.1 Quasi-Stable Regimes and Punctuated Reorganization

Differential persistence can produce periods in which a small number of configurations dominate the population and the associated flows become approximately stable. Such a regime may resemble equilibrium from the perspective of an aggregate stock–flow model, even though it is maintained by continuing formation, expiration, and replacement at the population level. We refer to this as a *quasi-stable regime*.

Quasi-stability is provisional. Suppose that configurations A and B have accumulated substantial population mass and jointly support the current pattern of interactions. If a new configuration C is generated or introduced and persists longer under the prevailing conditions, it may accumulate, participate increasingly in subsequent interactions, and redirect population flows away from the previously dominant structures. The system may then reorganize around a new dominant configuration.

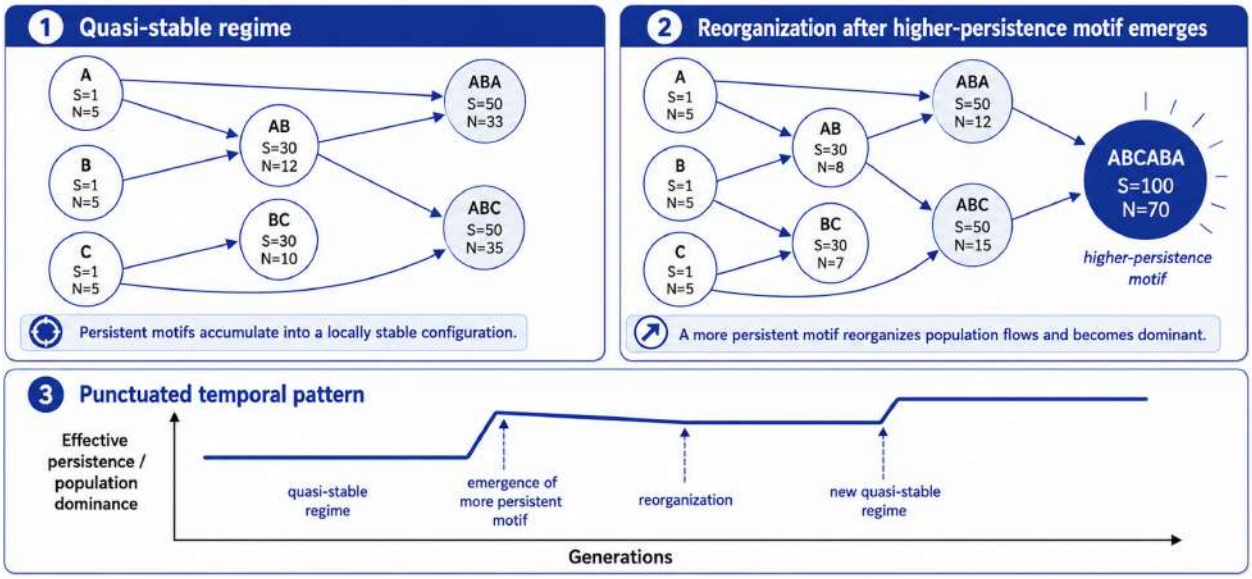

Figure 5: Punctuated reorganization in an SDA population. A quasi-stable regime dominated by persistent configurations can be disrupted when a higher-persistence configuration emerges or is introduced. As the new configuration accumulates, it redirects interaction flows and establishes a new quasi-stable regime.

Figure 5 illustrates the resulting temporal pattern: extended periods of apparent stability interrupted by comparatively rapid reorganization. Similar patterns are described as punctuated equilibrium in evolutionary biology, creative destruction in economics, regime change in policy studies, and technological disruption in innovation research. SDA does not claim that these phenomena share identical domain-specific mechanisms. It identifies a common population-level structure: persistent configurations concentrate interaction opportunities until the emergence of a sufficiently persistent alternative reorganizes those opportunities.

This distinction also clarifies what an evolutionary extension may add to an existing system dynamics model. If collapse, instability, or regime transition is already represented as an attractor within the model's specified structure, SDA need not improve its prediction. SDA becomes relevant when the transition depends on a new strategy, technology, institution, organizational form, or interaction structure that is not represented in the original state space.

An equilibrium identified by a stock–flow model may therefore be locally valid while remaining vulnerable to structural innovations outside the model's specified repertoire. The equilibrium is not necessarily wrong; it may be incomplete as a long-term description.

6.2 Illustrative Domain Mappings

In system dynamics applications, persistent configurations are generally not molecules or symbolic strings. They are domain-specific structures such as strategies, routines, standards, technologies, institutions, and policy arrangements. Although the mechanisms responsible for their persistence differ across domains, they can play the same dynamical role: once established, they remain available for further interaction and become part of the environment shaping what can occur next.

Markets. Local trades, signals, and imitation can cause particular strategies to become widespread. Once a strategy such as trend-following becomes a persistent feature of the market, it changes the environment faced by other participants. It may create opportunities for liquidity provision, mean-reversion strategies, execution services, risk-management products, or regulatory responses. The persistent strategy therefore does more than increase its own frequency: it helps alter the effective strategy space available to others.

Organizations. Teams continually develop routines, metrics, workflows, and internal tools in response to local problems and incentives. Some disappear when the immediate problem passes, while others become embedded in organizational practice. Once persistent, these structures can support new roles, capabilities, reporting relationships, and operating models. Organizational history is therefore retained not only in aggregate performance measures, but in the operational structures that determine what the organization can subsequently do.

Policy systems. Policy interventions frequently create structures that outlast the initial decision: programs, administrative agencies, reporting requirements, metrics, funding streams, legal

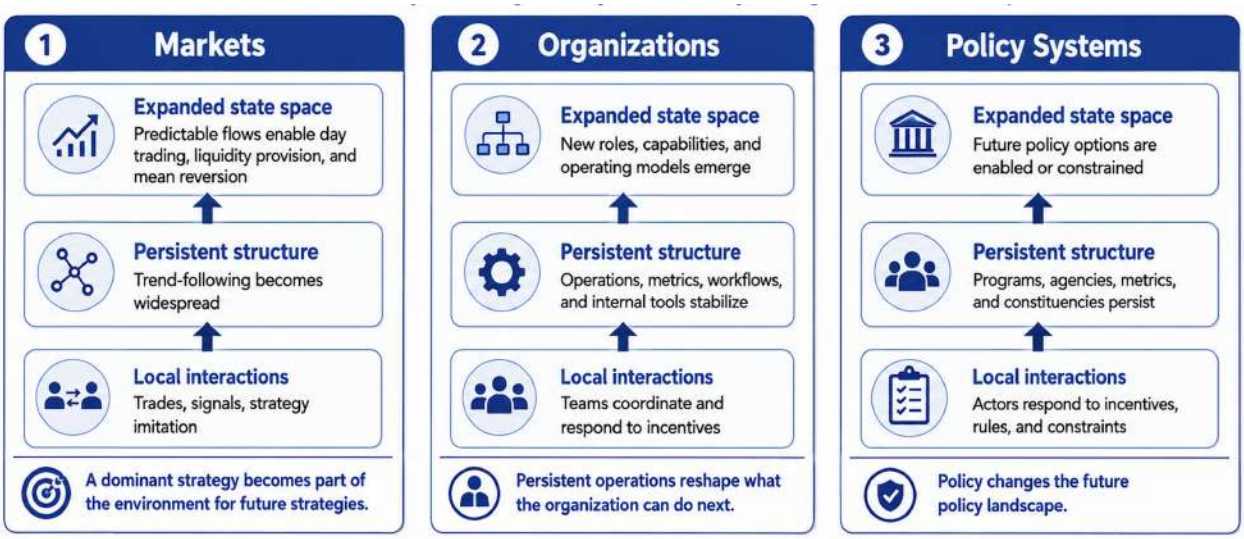

Figure 6: Illustrative pathways through which persistent structures can reshape future possibilities in three system dynamics domains. In markets, a widely adopted strategy can create niches for complementary strategies and services. In organizations, persistent operations, metrics, workflows, and tools can enable new roles and capabilities. In policy systems, programs, agencies, metrics, and constituencies created by one intervention can enable or constrain subsequent policy choices. These examples are conceptual mappings rather than calibrated models.

precedents, and organized constituencies. These persistent products of earlier policy become constraints and affordances for later interventions. Policy therefore changes not only the current state of the system, but also the policy landscape within which future decisions are made.

Across all three domains, the common mechanism is a progression from local interaction to persistent structure to altered future possibilities. The relevant persistence function is context-dependent: a strategy, routine, or institution remains active because of factors such as profitability, switching costs, legitimacy, complementary resources, legal authority, network effects, or organizational memory. SDA abstracts these different mechanisms into their shared population-level consequence: longer-lived structures have more opportunities to participate in and influence subsequent dynamics.

These examples do not establish that every persistent structure produces an evolving possibility space. The additional condition is that the structure must affect later formation, interaction, or persistence. Persistence that merely preserves an object is retention; persistence that changes what can form or remain viable next becomes evolutionary feedback.

6.3 Two Approaches to Evolutionary Extension

The SDA perspective suggests two complementary ways to extend system dynamics practice. The first introduces evolutionary dynamics directly by coupling a population-level constructive model to a stock–flow model. The second retains an existing system dynamics model and uses SDA-style perturbations to examine whether a reference regime is vulnerable to structural innovations not

represented in the original model.

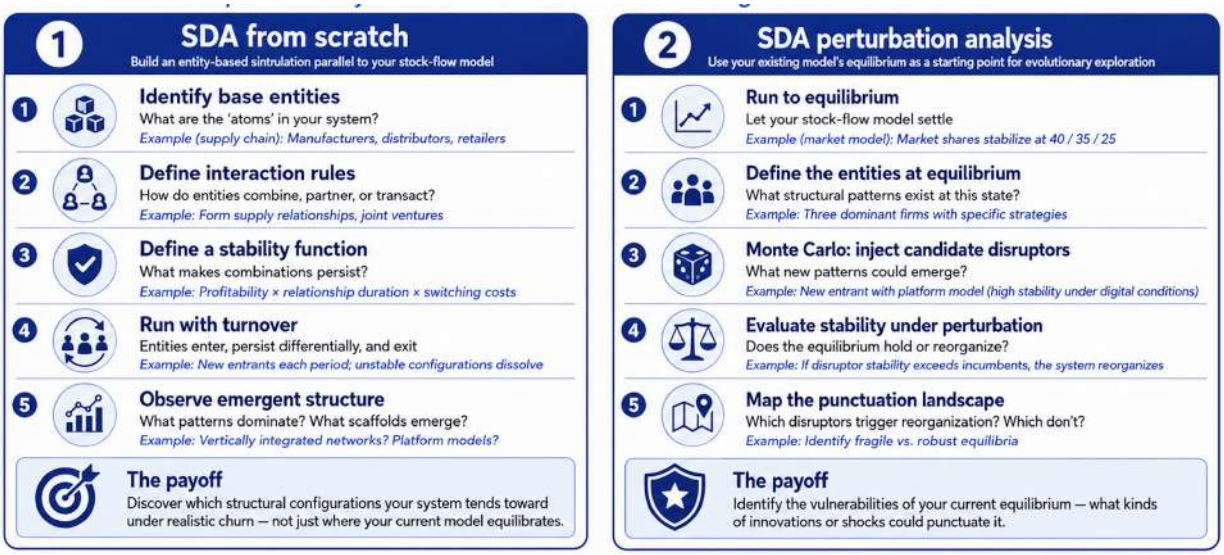

Figure 7: Two proposed approaches to introducing evolutionary dynamics into system dynamics models. **Left:** A coupled SDA population model represents the formation, context-dependent persistence, turnover, and accumulation of entities such as strategies, technologies, institutions, or organizational configurations. **Right:** SDA perturbation analysis begins from a reference regime generated by an existing stock–flow model and introduces candidate structural disruptors to test whether they disappear, coexist with existing structures, or reorganize the regime.

The two strategies answer different questions. A coupled SDA population model asks which structures emerge and become dominant under continuing variation and turnover. SDA perturbation analysis asks a conditional question: if a configuration with specified persistence and coupling properties appeared, would the existing regime absorb it or reorganize?

7 Toward Evolutionary System Dynamics

The preceding analysis suggests three progressively stronger forms of endogeneity. In conventional system dynamics, behavior is endogenous to a feedback structure specified by the modeler. In population-based evolutionary models, the relative abundance of competing configurations also changes endogenously through formation, interaction, persistence, and turnover. In a constructive evolutionary model, persistent configurations additionally modify the effective interactions, persistence conditions, or structural possibilities that shape later dynamics.

Evolutionary system dynamics is concerned primarily with this third form. It seeks to couple population-level construction and selection to aggregate stock–flow behavior so that structures generated during the process can become part of the causal environment for subsequent change. The aim is not to abandon conventional system dynamics, but to extend it from the endogenous evolution of system behavior toward the endogenous evolution of aspects of the effective feedback structure itself.

SDA provides a minimal mechanism for connecting the second and third levels. Differential persistence changes population composition, and population composition changes which configurations are most likely to participate in later interactions. When persistent configurations also modify aggregate flows or enable new combinations, population history begins to reshape the effective possibility space of the system. The result is not simply movement toward another predefined attractor, but the endogenous construction of conditions that influence which attractors or regimes can subsequently arise.

The present symbolic results demonstrate endogenous selection pressure and population concentration; they do not by themselves establish open-ended evolution in its strongest sense. A stronger demonstration would require sustained generation of structural novelty, continued turnover without convergence to a terminal repertoire, and feedback by which generated structures modify the mechanisms of later variation, interaction, or persistence. Novel configurations need not be listed individually at initialization, although the model must still specify a generative representation and a set of composition rules.

Agent-based modeling offers a useful implementation architecture for such systems because it can represent heterogeneous configurations, local interaction, entry and exit, endogenous networks, and population-dependent behavior. SDA is not an alternative to agent-based modeling, but a mechanism that can be implemented within it. The coupled approach proposed in Section 6.3 would use an agent- or entity-based population model to generate and select structures, while a stock–flow model represents the aggregate environment that determines their persistence and is, in turn, modified by their accumulation.

Artificial intelligence may expand the repertoire of generative operators available within this architecture. For example, learning agents or generative models could propose new strategies, representations, or combinations that were not individually enumerated by the modeler. AI does not, however, supply evolutionary dynamics by itself. Unless generated variants undergo differential persistence and feed back into the future generation process, learning merely searches within an externally defined objective and representation. Its possible role here is therefore as a source of structured variation, not as a substitute for population-level selection.

The immediate research agenda is to test these ideas in established system dynamics domains. This includes coupling SDA populations to canonical stock–flow models, defining empirically meaningful persistence functions, comparing SDA extensions with evolutionary agent-based models, and evaluating whether perturbation analysis reveals structural vulnerabilities that conventional parameter sensitivity analysis does not. These studies would clarify when evolutionary extensions add explanatory value and when a fixed-structure system dynamics model remains sufficient.

8 Conclusion

This paper has argued that the central distinction between conventional and evolutionary system dynamics is not whether a model reaches equilibrium. System dynamics models can generate oscil-

lation, collapse, path dependence, multiple attractors, and other complex behavior while remaining within a structure specified in advance. The relevant distinction is between behavior that unfolds within a predefined possibility space and dynamics in which persistent structures generated during the process become part of the causal environment for what can occur next.

Stability-Driven Assembly provides a minimal illustration of the population feedback required for this additional form of endogeneity. Stochastic interaction generates variation, differential persistence changes population composition, and abundance-proportional sampling biases subsequent interactions. Selection pressure therefore emerges without an explicit selection operator, externally specified objective function, or template-based replication. The symbolic results show that this mechanism concentrates probability mass on persistent motifs and transforms undirected assembly into path-dependent evolutionary search.

The present results do not by themselves establish open-ended evolution in its strongest sense. They identify a more specific mechanism through which population history can become causally active. When persistent configurations also modify aggregate flows, interaction opportunities, or the viability of later configurations, the system's effective possibility space can change over time. Temporarily dominant structures may then support quasi-stable regimes that are punctuated when a more persistent configuration emerges or is introduced and reorganizes population flows.

For system dynamics practice, this perspective suggests two complementary strategies. A coupled SDA population model can represent the continuing formation, persistence, turnover, and selection of strategies, technologies, institutions, or organizational forms alongside an aggregate stock–flow model. Alternatively, SDA perturbation analysis can begin from a regime generated by an existing model and test its conditional vulnerability to candidate structural innovations. The first models evolutionary construction directly; the second stress-tests a specified regime for evolutionary fragility.

These approaches extend rather than replace conventional system dynamics. Stock–flow models remain powerful tools for explaining accumulation, delay, feedback, and behavior within a defined structure. Evolutionary system dynamics adds the question of how structures themselves arise, persist, alter later feedback, and are eventually displaced. Agent-based modeling offers a useful implementation architecture for this purpose, but the defining requirement is not the presence of agents or complexity alone. It is feedback through which generated population structure influences future formation and persistence.

Evolution, on this account, is not merely a biological metaphor for long-term change. It is a class of population-dependent dynamics in which persistent products of history reshape the conditions of subsequent change. Establishing when this extension adds explanatory value will require applications to canonical system dynamics models, empirically meaningful persistence functions, and comparisons with conventional sensitivity and stress-testing methods. These provide a practical research agenda for developing evolutionary system dynamics as a complement to established systems modeling.

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