EVOS: Evolutionary Resonance as a Universal Substrate for Intelligence

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Abstract

Contemporary artificial intelligence systems are predominantly formulated as closed-form computational models: they transform inputs into outputs under fixed or slowly adapted transition rules. While such systems excel at pattern recognition and optimization, they fail to account for intelligence as a persistent, accountable, and historically grounded process operating under irreversible time.

In this paper, we introduce *Evolutionary Open Systems (EVOS)*, a new class of computational systems defined axiomatically rather than architecturally. An EVOS is characterized by worldline primacy, intrinsic memory, openness under constraint, explicit commitment boundaries, and substrate independence. Within this framework, intelligence is not an instantaneous property of states or outputs, but an emergent property of stable evolutionary trajectories that accumulate memory, interact with environments, and produce irreversible consequences.

EVOS generalizes beyond existing models of computation and learning by treating time, history, and accountability as first-class primitives. It subsumes digital, biological, and hybrid systems under a unified formalism and provides a foundation for understanding agents, learning systems, and multi-agent civilizations without reducing them to closed-form computation.

We further introduce **GENESIS**, a resonance-field formalism that operationalizes EVOS while preserving its open, evolutionary nature. Together, EVOS and GENESIS establish a theoretical substrate for intelligence that extends the abstraction of computation in the Church–Turing tradition to the domain of persistent, accountable, and adaptive systems.

Contents

1 Introduction

Artificial intelligence has advanced primarily through improvements in *scale* (data, parameters, compute) and *architectures* (transformers, diffusion, tool-augmented agents). These advances have produced systems that *perform* increasingly well on tasks, yet they have not resolved a deeper, structural question:

> What is the minimal formal structure required for intelligence to exist as a *persistent, adaptive, and accountable* phenomenon in an open world?

Most contemporary AI formalisms remain *snapshot-centric*. They describe bounded computations: inputs $\rightarrow$ outputs, states $\rightarrow$ states, or distributions $\rightarrow$ distributions. Even interactive and "agentic" systems are typically modelled as repeated evaluations of a policy over a predefined state space. This framing is sufficient for computation and prediction; it is insufficient for *intelligence-as-existence*.

Intelligence in biological organisms, social institutions, and autonomous agents embedded in real environments exhibits properties that resist closed-form abstraction:

- **Non-termination**: the system persists rather than halts;
- **Historical dependence**: behavior depends on accumulated trajectory;
- **Openness**: the environment is not fully specifiable ex ante;
- **Irreversibility**: actions have consequences that cannot be "rolled back";
- **Accountability**: externally observable effects must be traceable to binding action.

Time in such systems is not merely an index; it is a structural constraint. A system that does not *inhabit* its irreversible consequences can simulate intelligent behavior without constituting an intelligent entity.

Thesis. We propose *Evolutionary Open Systems (EVOS)* as a new abstraction class for intelligence. EVOS defines an intelligent entity not by instantaneous state or task output, but by its *worldline*: a temporally extended trajectory coupling latent evolution, intrinsic memory, and commitment-bound interaction with an environment.

1.1 Contributions

This paper makes four contributions:

1. **EVOS (axiomatic class).** We introduce Evolutionary Open Systems as a substrate-agnostic class of computational systems where identity is defined by worldline evolution under openness, irreversibility, and constraint.
2. **Commitment boundary (accountability primitive).** We formalize a strict boundary between internal deliberation and externally binding action. Observable consequences must cross an explicit commitment gate, enabling causal provenance and auditability.
3. **GENESIS (field formalism).** We introduce GENESIS, a resonance-field formalism that operationalizes EVOS without collapsing it into snapshot computation. GENESIS treats interaction as evolution of a continuous coupling field rather than as mere message passing or discrete state updates.
4. **A pluggable mathematics stack.** We present a hierarchy of admissible evolution laws (Markov $\rightarrow$ time-series $\rightarrow$ differential/reaction–diffusion $\rightarrow$ learned/self-modifying operators) and show how richer dynamics reduce to simpler ones under projection/coarse-graining.

1.2 Explicit Claims (What This Paper Asserts)

To keep EVOS falsifiable and engineering-relevant, we state explicit claims:

1. **Worldline primacy:** Meaning, intent, risk, and responsibility are well-defined only on trajectories, not on instantaneous states. Snapshot-only formalisms necessarily lose information required for accountability.
2. **Commitment is necessary for agency:** Any system that produces externally observable effects without an explicit commitment boundary cannot support principled provenance, audit, or alignment at scale.
3. **Closed-form insufficiency (structural):** Classical closed-form models (including fixed transition systems and bounded input–output computation) can emulate behavior but cannot *instantiate* intelligence as persistent evolution under irreversibility and openness.
4. **Field advantage for open systems:** A resonance-field representation provides a strictly more natural substrate for modelling open, multi-entity, history-bearing interaction than graph-only or message-only formalisms, because it admits continuous coupling, diffusion, and emergent attractors as first-class dynamics.

1.3 Minimal Formalism (Preview)

We use the lightest mathematical scaffolding necessary to orient the reader.

Worldline. Let $Z(t)$ denote an entity's latent/observable state at time t. An entity is defined by its worldline

$$\mathcal{W} = \{(Z(t), M(t)) \mid t \in \mathbb{R}^+\},$$

where $M(t)$ is intrinsic memory (not merely external storage).

Commitment boundary. A commitment is an irreversible boundary-crossing event that makes internal intent externally binding. Consequences are causally attributed to commitments and recorded in provenance.

Resonance field (GENESIS). Interaction among entities is represented by a coupling field whose geometry evolves under perturbation, constraint, and commitment events, producing attractors and persistent structures.

1.4 Roadmap

Section 2 introduces EVOS and its axioms. Section 3 introduces GENESIS as a resonance-field formalism for EVOS. Sections 4–5 develop time, memory, worldlines, and a pluggable transition mathematics stack. Later sections extend EVOS across digital agent civilizations, molecular (DNA) substrates, and hybrid bio-digital systems, culminating in governance, safety, and applications.

2 EVOS: A New Class of Computational Systems

2.1 Evolutionary Open Systems

Most computational formalisms treat systems as *closed-form machines*: given an input, apply a bounded procedure, return an output. Even interactive systems are usually formalized as repeated evaluations of a transition rule over a predefined state space. This viewpoint is powerful for calculation, but it fails to capture intelligence as it appears in organisms, institutions, and autonomous agents embedded in real environments.

EVOS begins from a different primitive: an intelligent entity is not a momentary state but a *persistent evolution under irreversible time*. The system does not merely compute; it *exists* and accumulates history. It interacts with an environment that is not fully specifiable in advance. It adapts not only its state but, in the strongest cases, the *law* by which it evolves.

We therefore define an *Evolutionary Open System (EVOS)* as a substrate-agnostic computational system satisfying the following structural properties:

- **Openness**: continuous interaction with an environment through observable events.
- **Irreversibility**: time is structural; externally binding events cannot be undone.
- **Non-termination**: persistence is intrinsic rather than exceptional.
- **Historical dependence**: evolution depends on accumulated trajectory and memory.
- **Causal anchoring**: externally observable consequences must be traceable to explicit causes.

The intent is not to declare older models "wrong," but to identify the minimal structure required for *agency, learning, and accountability* to be first-class.

2.2 Structural Commitments of EVOS

EVOS commits to a small set of design constraints that are simultaneously theoretical and engineering-relevant.

(1) Worldline over snapshot. An entity is defined by its trajectory, not by an instantaneous state. This prevents "state-based illusions" where two systems share the same current state but differ catastrophically due to different histories.

(2) Memory is intrinsic. Memory is not an optional database attached to a stateless policy. It is part of the entity's evolution and must be represented in the formalism.

(3) Commitment is the reality boundary. A strict boundary separates internal deliberation from externally binding action. Externally observable consequences must cross an explicit commitment gate.

(4) Accountability is causal. Auditability is not a social add-on; it is a structural requirement. Effects in the world must be traceable to commitments and provenance-bearing events.

(5) Substrate-independence is mandatory. EVOS is defined without assuming neurons, silicon, tokens, transformers, or any specific architecture. If a system satisfies the axioms, it qualifies.

2.3 The Axioms of EVOS

To formalize EVOS without collapsing it into a particular implementation, we state five axioms. These axioms define the minimal conditions under which intelligence, agency, and learning can emerge as stable phenomena in open environments.

Axiom I: Worldline Primacy. An intelligent entity is defined by a *worldline*, not by an instantaneous state. Let $Z(t)$ denote the latent/observable state at time t. The entity is defined by

$$\mathcal{W} = \{Z(t) \mid t \in \mathbb{R}^+\}.$$

Meaning, intent, risk, and responsibility are properties of $\mathcal{W}$ rather than of any single temporal slice.

Axiom II: Intrinsic Memory. Memory is an intrinsic component of the worldline, not an external accessory. Formally, EVOS evolution occurs in an extended state space:

$$\mathcal{W} = \{(Z(t), M(t)) \mid t \in \mathbb{R}^+\},$$

where $M(t)$ encodes accumulated structure arising from past interactions, constraints, and commitments.

Axiom III: Openness Under Constraint. An EVOS is necessarily open to environmental influence, yet its evolution is constrained by physical, computational, social, economic, or ethical bounds. Let $\mathcal{E}(t)$ denote environmental perturbations and $\mathcal{C}(t)$ denote constraints. Evolution satisfies

$$(Z(t + \Delta t), M(t + \Delta t)) = \Phi(Z(t), M(t), \mathcal{E}(t), \mathcal{C}(t)).$$

Constraints do not diminish intelligence; they define the feasible region in which stable adaptation must occur.

Axiom IV: Commitment as Reality Boundary. A strict distinction exists between internal deliberation and external action. A *commitment* is an irreversible boundary-crossing event by which internal intent becomes externally binding. Only commitments generate consequences that propagate forward along the worldline. Accountability begins at the commitment boundary.

Axiom V: Substrate Independence. The axioms of EVOS do not depend on a specific substrate. Any biological, digital, hybrid, or socio-technical system that satisfies Axioms I–IV qualifies as an EVOS.

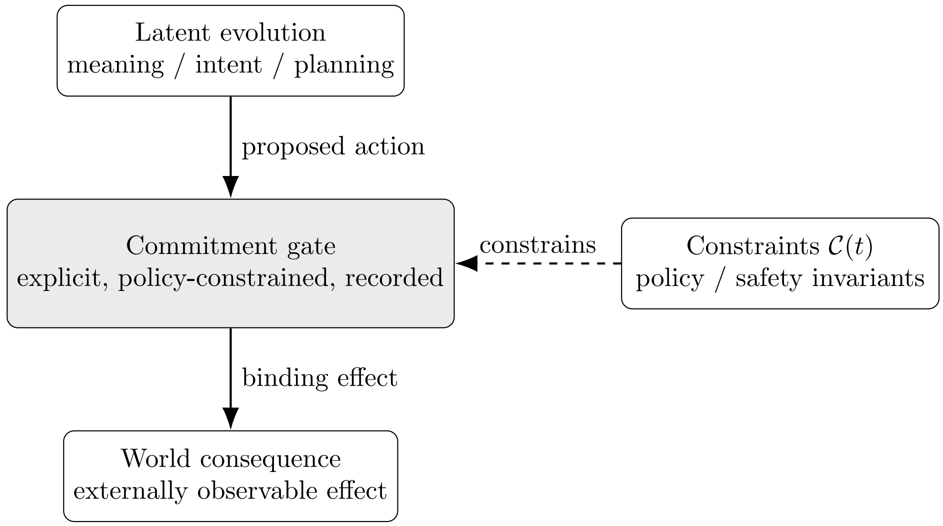
2.4 Minimal Formal Core (What Must Exist)

The axioms can be instantiated with minimal formal structure:

- **State and memory:** $(Z(t), M(t))$.
- **Event history:** $\mathcal{H}(t)$, monotonically growing under irreversibility.
- **Evolution law:** Φ mapping (Z, M) forward under $(\mathcal{E}, \mathcal{C})$.
- **Commitment operator:** a gate that emits externally binding events into $\mathcal{H}(t)$.

This is intentionally sparse: EVOS is a *meta-class* of systems, not a single model.

2.5 Figure: Commitment Boundary (Reality Gate)



Commitment boundary. Latent resonance may evolve internally, but any observable consequence must cross an explicit commitment gate constrained by policy and safety invariants and recorded in causal provenance. This enforces accountability for open, self-modifying systems.

Figure 1: Commitment boundary as the EVOS reality gate: internal evolution is unconstrained by observability, but external consequences require explicit, provenance-bearing commitment.

2.6 Figure: EVOS Axioms Map (One Figure for Five Axioms)

2.7 Why Closed-Form Models Fail

Closed-form computational models—including Turing machines, finite automata, and many standard learning formalisms—violate one or more EVOS axioms.

They privilege instantaneous state over trajectory (violating Axiom I), treat memory as optional or external (violating Axiom II), assume bounded input/output episodes (violating Axiom III), and lack an explicit commitment boundary separating deliberation from binding action (violating Axiom IV).

Such models can *simulate* intelligent behavior, but they do not naturally support *intelligence as persistent, accountable evolution*. In EVOS terms, prediction is not commitment, and context is not history.

2.8 Substrate Independence and Universality

EVOS is defined axiomatically rather than architecturally. This enables it to generalize across instantiations:

- biological organisms (cells, nervous systems),

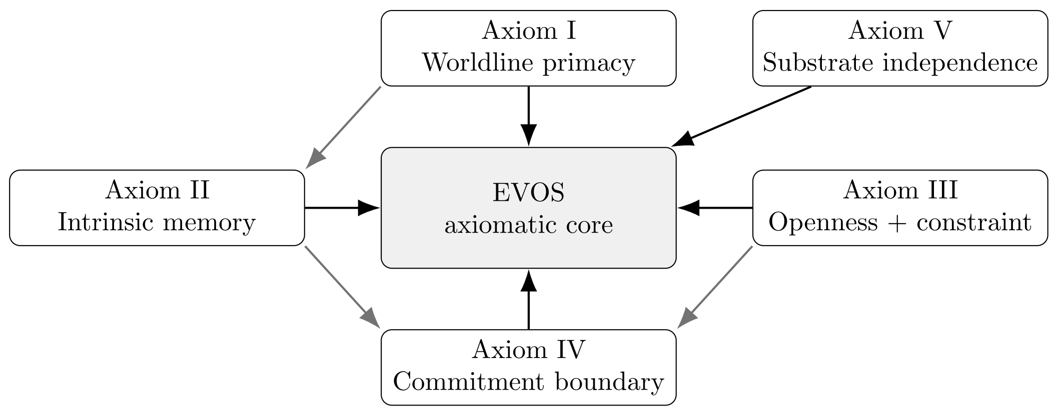


Figure 2: Axioms map: five minimal commitments that define the EVOS class. Subtle arrows indicate common dependency flow: worldlines imply intrinsic memory; openness requires constraints; commitments anchor accountability.

- digital agents (persistent software entities),
- socio-technical institutions (markets, governance systems),
- molecular substrates (DNA reaction networks),
- hybrid bio-digital systems.

In spirit, EVOS plays a role for intelligence analogous to the Church–Turing abstraction for computation: it isolates the *structural* requirements from the machine.

2.9 Intelligence as Stable Evolution Under Constraint

Under EVOS, intelligence is not defined by benchmark performance or task completion. Instead:

> *Intelligence is the capacity of a system to maintain coherent, goal-consistent evolution over time under constraint, while accumulating memory and honoring commitments.*

Let Ψ be a constraint functional over worldlines, capturing resource bounds, safety requirements, and coherence conditions. An intelligent EVOS exhibits trajectories $\mathcal{W}$ such that

$$\sup_{t\geq 0} \Psi(\mathcal{W}_{\leq t}) < \infty$$

despite perturbations, uncertainty, and (in the strongest case) self-modification of its evolution law.

This reframes learning as stabilization, reasoning as trajectory shaping, alignment as constraint compatibility, and failure as evolutionary instability.

2.10 Scope and Positioning of EVOS

EVOS is not a neural architecture, not a foundation model, and not a training algorithm. It is a theory of intelligence as worldline evolution, a foundation for accountable agents, and a bridge between computation, biology, and civilization-scale systems.

The remainder of this paper introduces **GENESIS**, a resonance-field formalism that operationalizes EVOS without reverting to closed-form snapshot computation.

3 GENESIS: A Resonance-Field Formalism for EVOS

3.1 Motivation: Why a Field Formalism

EVOS defines *what* an intelligent open system must be (worldlines, intrinsic memory, openness under constraint, and commitment-gated consequences). GENESIS provides a *how*: a minimal mathematical substrate that can represent persistent coupling, context-dependent influence, and history-shaped evolution without collapsing back into a snapshot-only transition function.

Graph formalisms (agents as nodes, relations as edges) are useful but insufficient as a primary ontology for EVOS:

- graphs are *static* unless time is bolted on externally;
- edge semantics are usually *binary* or scalar, losing higher-order coupling;
- memory and intent typically live in out-of-graph annotations;
- openness is represented as an external "input stream," not as a structural field.

GENESIS instead treats interaction as a *field*: a continuously evolving medium that stores coupling potential, transmits perturbations, and accumulates history through worldlines and events. Graphs remain valuable—but as *projections* or *thresholded slices* of a deeper object.

GENESIS in one sentence.

> *GENESIS models EVOS evolution as motion and plasticity on a resonance field: states move* ***within*** *a field, while learning and commitments* ***rewrite*** *the field under constraints.*

3.2 Explicit Claims (What GENESIS Asserts)

GENESIS makes several concrete claims that can be falsified, operationalized, and implemented:

1. **Field primacy:** interaction structure is better modeled as a continuous resonance field than as a static graph; graphs are recoverable as projections.
2. **Worldline coupling:** resonance between entities depends on worldlines and history, not only instantaneous states.
3. **Perturbation propagation:** local events inject perturbations that diffuse, react, and attenuate through the resonance field, producing emergent coordination.
4. **Commitment as a discrete transition:** commitments are not "just another action"; they are boundary-crossing events that trigger structured, auditable field transitions and constrain future dynamics.
5. **Plasticity under constraint:** learning/self-modification corresponds to controlled field rewriting (geometry change), constrained by policy and invariants.

These claims are intentionally stronger than metaphor. Each maps to formal objects and interfaces used later in the paper (transition plug-ins, provenance, safety gates).

3.3 Minimal Formal Core (GENESIS Objects)

GENESIS introduces only the minimal additional structure needed beyond EVOS:

Entities and worldlines. Let entities be indexed by $i \in \{1, \dots, N\}$ with worldlines

$$\mathcal{W}_i = \{(Z_i(t), M_i(t)) \mid t \in \mathbb{R}^+\}.$$

Resonance field. Define a resonance field $\mathcal{R}$ as a time-indexed object encoding coupling potential. The most minimal discrete form is a matrix-valued field

$$\mathcal{R}(t) \equiv [R_{ij}(t)]_{i,j=1}^{N},$$

where $R_{ij}(t)$ is the (possibly asymmetric) resonance potential from entity j to entity i at time t.

Evolution with perturbations and constraints. EVOS evolution is represented as:

$$(Z(t+\Delta t), M(t+\Delta t), \mathcal{R}(t+\Delta t)) = \Phi\big(Z(t), M(t), \mathcal{R}(t), \mathcal{E}(t), \mathcal{C}(t)\big),$$

where $\mathcal{E}(t)$ are environmental perturbations and $\mathcal{C}(t)$ are constraints/policies.

Commitment events as field transitions. Commitments are discrete events $e_c \in \mathcal{H}(t)$ that trigger structured updates:

$$\mathcal{R}(t^+) = \Gamma(\mathcal{R}(t^-), e_c), \qquad (Z(t^+), M(t^+)) = \Omega(Z(t^-), M(t^-), e_c),$$

with provenance recorded so that externally observable consequences remain causally anchored.

3.4 Resonance Fields and Worldlines

Resonance is not merely similarity of current state; it is a *history-shaped coupling* between evolving entities. Concretely, $R_{ij}(t)$ may depend on:

- present latent state similarity ($Z_i(t)$ vs. $Z_j(t)$),
- memory compatibility ($M_i(t)$ vs. $M_j(t)$),
- recent commitment patterns (sub-history $\mathcal{H}_{[t-\tau,t]}$),
- constraints (policies limiting coupling or action channels).

A minimal abstract form is:

$$R_{ij}(t) = \rho\big(Z_i(t), M_i(t);\, Z_j(t), M_j(t);\, \mathcal{H}_{[t-\tau,t]};\, \mathcal{C}(t)\big).$$

GENESIS does not commit to a particular ρ; it requires only that resonance be *representable*, *updatable*, and *projectable* to operational interfaces (graph edges, access controls, attention weights, routing probabilities, etc.).

3.5 Evolution Under Perturbation

Open systems evolve under irreducible perturbations. GENESIS treats perturbations as *injections into the field* and/or into state-memory coordinates.

Let $\delta(t)$ be a perturbation signal (exogenous event, sensory input, market shock, user instruction). A minimal decomposition is:

$$\delta(t) = \big(\delta_Z(t),\, \delta_M(t),\, \delta_R(t)\big),$$

which affects the evolution via:

$$\Phi(\cdot)\ :\ (Z, M, \mathcal{R}) \mapsto (Z', M', \mathcal{R}').$$

This framing yields an engineering consequence: *robustness is not only state stability; it is field stability.* Systems fail not merely by "wrong output" but by field drift, coupling collapse, or uncontrolled amplification of perturbations.

3.6 Commitment Events as Field Transitions

Commitments are the EVOS reality boundary (Section 2). In GENESIS, a commitment is also a *structured field transition.*

Intuitively:

- latent deliberation evolves $Z(t), M(t)$ and proposes updates to $\mathcal{R}(t)$;
- the commitment gate validates the proposal against $\mathcal{C}(t)$ and invariants;
- if accepted, the system emits a commitment event e_c and applies Γ;
- the event and its lineage become part of $\mathcal{H}(t)$ and constrain future evolution.

This enforces a strict separation:

> *Internal resonance may evolve freely; external consequences require commitment; commitments rewrite the field in an auditable, constraint-governed manner.*

3.7 GENESIS Is Not a Model of Intelligence

GENESIS is not a claim that a particular PDE, neural architecture, or algorithm is "intelligence." It is a *representational substrate* compatible with many architectures:

- transformers and foundation models (as parameterized ρ, Φ, Γ),
- symbolic planners (as structured components in Φ),
- multi-agent systems (as field-coupled dynamics),
- molecular/diffusive substrates (as reaction–diffusion analogs of $\mathcal{R}$).

In particular, GENESIS avoids a common failure mode in AI theory: redefining intelligence as the behavior of one favored architecture. EVOS+GENESIS instead define the *class of systems* in which intelligence can be stable, open-ended, and accountable.

3.8 Positioning Within the EVOS Framework

EVOS provides axioms; GENESIS provides a field formalism that:

- supports worldlines and intrinsic memory (Axioms I–II),
- admits openness under constraints (Axiom III),
- enforces commitment-gated consequences (Axiom IV),
- remains substrate-independent (Axiom V).

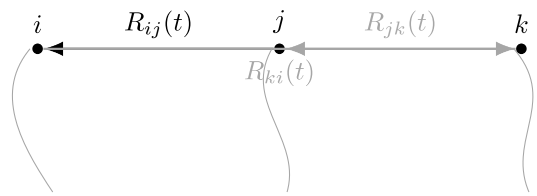
The next sections (Time/Memory/Worldlines, and Pluggable Transition Mathematics) specialize GENESIS into concrete operator families and dynamics, while preserving the commitment and provenance invariants required for safety and governance.

4 Time, Memory, and Worldlines

4.1 Purpose and Explicit Claims

This section sharpens the EVOS thesis that *time is structural*: intelligence is not an instantaneous computation but a history-bearing trajectory whose meaning, risk, and accountability are defined over *worldlines.*

We make four explicit claims:



Resonance-field view. Coupling is represented by time-varying resonance potentials $R_{ij}(t)$ defined over worldlines. Graph edges are recoverable as projections (e.g., thresholding or routing), but the primary object is the field $\mathcal{R}(t)$.

Figure 3: Resonance fields and worldlines: coupling potentials evolve over time and depend on history, not only instantaneous state.

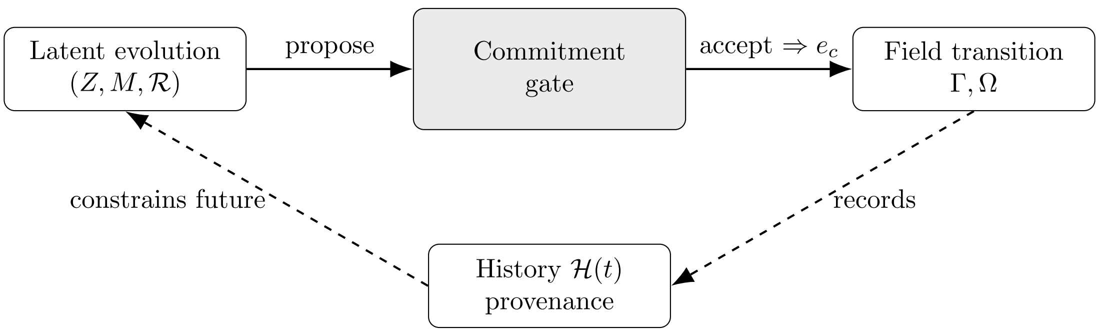


Figure 4: Commitment events as field transitions: commitments emit provenance-bearing events and apply structured updates to $(Z, M, \mathcal{R})$ that constrain future evolution.

1. **Worldline primacy:** properties such as intent, risk, and responsibility are functionals over trajectories, not labels on snapshots.
2. **Memory is dynamical:** memory is not a passive store; it evolves via injection, decay, and consolidation processes that shape future behavior.
3. **Multi-scale time is intrinsic:** intelligent systems couple fast processes (attention, reflex, routing) to slow processes (learning, policy, identity).
4. **Irreversibility is accounted:** commitments induce a monotone growth of history, yielding an "entropy-like" accumulation of consequence that cannot be undone, only managed.

4.2 Worldlines Instead of Snapshots

Classical computational systems are commonly described as discrete snapshots of state:

$$S(t_0),\ S(t_1),\ S(t_2),\ \ldots$$

Such representations implicitly assume that the system can be understood by observing isolated states.

EVOS rejects this assumption. An entity is defined by a *worldline*: a continuous trajectory through state space,

$$\mathcal{W}_i \ = \ \{Z_i(t) \mid t \in \mathbb{R}^+\}.$$

A worldline encodes not only "where the entity is" but *how it got there*. Meaning, intent, commitment, and risk are therefore properties of trajectories (history), not of single temporal slices.

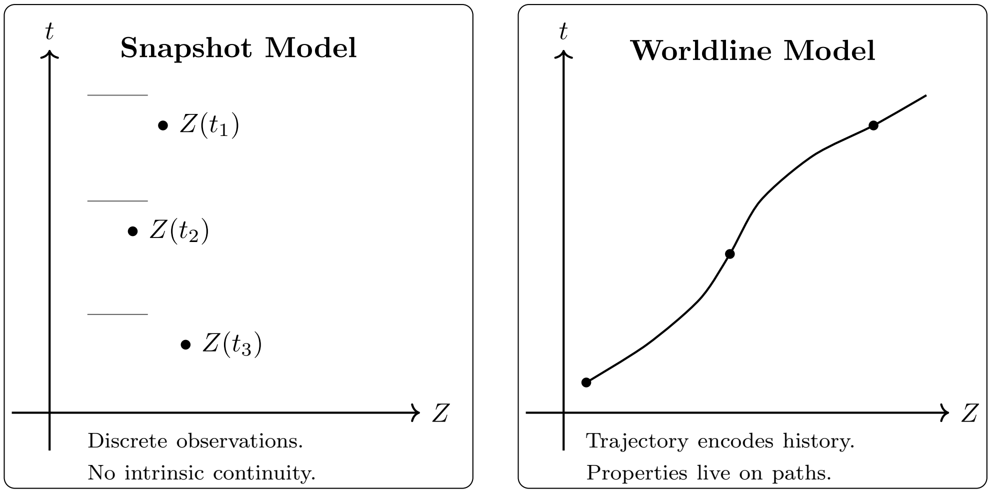


Figure 5: Snapshot vs. worldline. EVOS treats trajectory as primary: meaning, intent, commitment, and risk are properties of *evolutionary history*, not instantaneous state alone.

This distinction becomes non-negotiable when:

- causality and provenance matter,
- irreversible commitments exist,
- memory influences future behavior.

4.3 Memory, Decay, and Persistence

In EVOS, memory is not a static storage mechanism. It is a *dynamical process* that emerges from persistence, decay, consolidation, and event-driven updates.

Let $M_i(t)$ denote the effective memory of entity i at time t. A minimal continuous model is:

$$\frac{dM_i}{dt} = \mathcal{I}_i(t) - \lambda_i M_i(t),$$

where $\mathcal{I}_i(t)$ represents information injection (events, interactions, learning signals) and λ_i is a decay coefficient intrinsic to the entity/substrate.

This captures:

- **forgetting** as a physical process,
- **reinforcement** via repeated injection,
- **boundedness** via decay/attenuation.

Different substrates correspond to different decay regimes:

- digital memory: near-zero decay unless explicitly erased;
- biological memory: moderate decay with consolidation dynamics;
- molecular memory: rapid decay unless stabilized by structure or energy input.

4.4 Worldlines With Memory

Under EVOS, the worldline lives in an *extended* state space:

$$\mathcal{W}_i = \{(Z_i(t), M_i(t)) \mid t \in \mathbb{R}^+\}.$$

This is not an optional embellishment. Without memory-as-state, "history" collapses into a replay of snapshots; without history, "intelligence" collapses into reflex.

4.5 What Is Memory in EVOS? (Indexable, Implicit, and Generative)

The EVOS axioms treat memory as *intrinsic* (Axiom II), but do not assume that memory is a database-like object that can always be addressed by a key. In biological systems, "memory" is often *distributed*, *associative*, and *state-dependent*: what can be recalled depends on current context, physiology, and recent activation patterns. In contemporary generative AI, the analogous phenomenon appears as *parametric memory*: information stored implicitly in model parameters (weights) rather than in an explicit, indexable store.

EVOS therefore defines memory operationally by its *causal role in evolution*, not by its storage interface.

Definition (EVOS memory state). Let $\mathcal{H}(t)$ be the event history up to time t and let $M(t)$ be a memory state. An EVOS admits a memory update operator Mem such that

$$M(t^+) = \mathsf{Mem}\big(M(t^-), e(t)\big), \qquad e(t) \in \mathcal{H}(t),$$

and future evolution is conditioned on $M(t)$ (cf. Axiom I–III). "Memory" is thus the part of the worldline that *persists* and *modulates* future trajectories.

Three complementary forms of memory. For engineering clarity (and for biological plausibility), it is useful to decompose $M(t)$ into three interacting components:

1. **Episodic / event memory** $E(t)$: an append-only, causally ordered record (or compressed sketch) of salient events and commitments. This is the form most directly tied to accountability and provenance.
2. **Parametric / semantic memory** $P(t)$: slowly varying structure that encodes generalizations—in machine learning, model parameters; in biology, synaptic weights and regulatory configuration. This is typically not key-addressable, but it strongly shapes behavior.
3. **Working / attentional memory** $W(t)$: a short-lived, high-bandwidth context (e.g., an attention window) that binds current perception to relevant recalls and plans. This governs what is *accessible* at a given time.

We can write $M(t) = (E(t), P(t), W(t))$ as a conceptual factorization; substrates may realize these components differently or merge them.

Queryability is optional; *retrievability* is required. EVOS does not require that memory be queryable by exact index. Instead, it requires that memory be *retrievable* under some access operator Q that is allowed to be associative and stochastic:

$$r(t) = Q\big(M(t), q(t)\big),$$

where $q(t)$ is a contextual "cue" (percept, goal, constraint, or question) and $r(t)$ is retrieved structure that can condition evolution. In biology, Q is cue-driven recall; in digital agents, Q can be vector retrieval, symbolic lookup, or generative recall.

LLM weights as memory. A trained model's weights are a legitimate instance of $P(t)$: they store compressed, generalized information acquired over training. However, in typical deployments $P(t)$ is *static* during operation and its updates are neither event-anchored nor accountable. EVOS distinguishes *learning* as an operator evolution problem (Section 5.6) and ties externally meaningful memory updates to explicit causal events (especially commitments) so that changes in behavior remain explainable and auditable.

Memory, decay, and persistence. The decay model in the previous subsection can be seen as operating on $W(t)$ and parts of $E(t)$, while $P(t)$ evolves on slower time scales. EVOS encourages explicit modeling of these rates because stability, identity, and alignment depend on what is forgotten, what is retained, and what becomes generalized.

In summary, EVOS memory is not "a table you can query"; it is the *trajectory-bearing state* that makes evolution history-dependent, with optional indexability but mandatory causal efficacy.

4.6 Multi-Scale Temporal Dynamics

EVOS systems operate across multiple temporal scales simultaneously. Define characteristic time scales

$$\mathcal{T} = \{\tau_1, \tau_2, \ldots, \tau_n\},$$

where each τ_k corresponds to a distinct dynamical process (attention, interaction, learning, policy drift, identity consolidation, etc.).

A convenient representation is a decomposition:

$$Z_i(t) = \sum_{k=1}^{n} Z_i^{(\tau_k)}(t),$$

emphasizing that fast components are constrained by slow components, and slow components are updated by aggregated evidence from fast experience.

This multi-scale structure explains phenomena that snapshot computation obscures:

- fast reactions constrained by slow commitments,
- short-term behavior shaped by long-term identity and policy,
- coherent agency emerging from transient internal state.

4.7 Irreversibility, History Growth, and Accounted Entropy

A defining feature of intelligent systems acting in the world is irreversibility. EVOS formalizes irreversibility via event history and commitment.

Let $\mathcal{H}(t)$ denote the event history up to time t. EVOS enforces monotone growth:

$$\mathcal{H}(t_1) \subset \mathcal{H}(t_2) \quad \text{for } t_1 < t_2.$$

This induces an intrinsic arrow of time: committed consequences cannot be erased from the system's causal record, only followed and managed.

Define an "entropy-like" accounted consequence:

$$E(t) = \sum_{e \in \mathcal{H}(t)} w(e),$$

where $w(e)$ weights impact/irreversibility (resource consumption, external effects, safety-relevant actions, contractual commitments, etc.). In EVOS, entropy is not disorder; it is *accounted consequence.*

4.8 Worldlines as the Substrate of Intelligence

Worldlines unify the paper's central concepts:

- **Meaning** is stable structure over trajectories.
- **Intent** is future-trajectory shaping under constraints.
- **Commitment** is irreversible boundary crossing recorded in $\mathcal{H}(t)$.
- **Learning** is the stabilization (and sometimes rewriting) of trajectory dynamics.
- **Safety** is constraint compatibility under irreversible time.

Thus, EVOS does not treat time as an index. Time is the *medium* in which intelligence exists.

5 Pluggable Transition Mathematics

5.1 Purpose and Explicit Claims

EVOS is *not* committed to a single transition model. Instead, EVOS specifies *structural constraints* (worldlines, memory, openness, commitment) and permits multiple mathematical realizations of the evolution law.

This section makes five explicit claims:

1. **Plurality of lawful dynamics:** there is no single "right" transition model for intelligence; EVOS requires a *plug-in class* of admissible laws.
2. **Worldlines are primary:** any transition law is evaluated by the worldlines it generates, not by instantaneous state updates alone.
3. **Coarse-graining inevitability:** Markovian behavior appears as a projection of richer dynamics under finite observation and aggregation.
4. **Memory and openness can be layered:** increasing expressive power corresponds to explicitly modeling history dependence, continuous time/space, and operator plasticity.
5. **Safety and accountability are orthogonal to dynamics:** EVOS constrains how dynamics may produce external effects via the commitment boundary and provenance, independent of whether dynamics are discrete/continuous/learned.

5.2 Admissible Evolution Laws (Minimal Formalism)

Let $Z(t)$ be latent state, $M(t)$ memory state, $\mathcal{E}(t)$ environment influence, and $\mathcal{C}(t)$ constraints. An EVOS-compatible evolution law is any operator Φ such that:

$$(Z(t + \Delta t), M(t + \Delta t)) \; = \; \Phi\big(Z(t), M(t), \mathcal{E}(t), \mathcal{C}(t)\big),$$

with the additional EVOS requirement that externally observable effects are generated only through explicit commitment events recorded in the causal history $\mathcal{H}(t)$ (see Section 2 and Section 3).

We now instantiate Φ using progressively richer families:

- Markov (minimal stochastic evolution),
- time-series (history dependence),
- differential / reaction–diffusion (continuous time and space),
- learned / self-modifying operators (meta-dynamics),
- runtime substitution (operator plug-in bus and hot-swap safety).

5.3 Markov Chains as Minimal Evolution Models

We begin with Markov processes as the *minimal sufficient* class of evolutionary dynamics admitted by EVOS. This is not because Markov models are adequate for intelligence, but because they provide a rigorous lower bound: any richer dynamics should reduce to a Markovian approximation under coarse-graining and finite observation.

5.3.1 State Evolution as a Stochastic Process

Let $Z(t)$ denote the latent state of an entity at time t. A Markov evolution model assumes future state depends only on the present state:

$$\mathbb{P}\big(Z(t+\Delta t) = z' \mid \mathcal{H}(t)\big) \;=\; \mathbb{P}\big(Z(t+\Delta t) = z' \mid Z(t) = z\big),$$

where $\mathcal{H}(t)$ is the full event history up to time t.

Interpretation in EVOS. The Markov assumption is not a claim about real intelligence; it is a baseline that becomes accurate when memory and structure are projected away.

5.3.2 Transition Operators

The evolution of state distributions is governed by a transition operator T:

$$T(z, z') \;=\; \mathbb{P}\big(Z(t+\Delta t) = z' \mid Z(t) = z\big).$$

For discrete state spaces, T is a stochastic matrix; for continuous spaces, T is a transition kernel.

If μ_t is the distribution over $Z(t)$, then:

$$\mu_{t+\Delta t} \;=\; \mu_t T.$$

5.3.3 Markov Evolution as a Worldline Generator

In EVOS, Markov processes are interpreted as *worldline generators.* Rather than privileging distributions, EVOS tracks individual sample paths:

$$\mathcal{W} \;=\; \{Z(t_0), Z(t_1), Z(t_2), \dots\}.$$

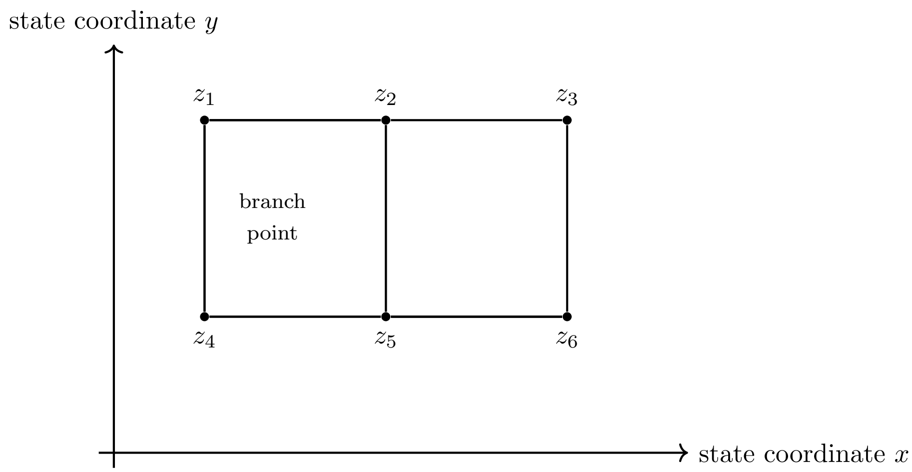
Each worldline is one possible evolutionary trajectory under the same transition law.

5.3.4 Limitations of Markovian Assumptions

Pure Markov models are structurally insufficient for EVOS-level intelligence:

- No long-term memory beyond the current state.
- No explicit representation of intent, commitment, or constraint compatibility.
- No intrinsic mechanism for irreversible commitments (only stochastic transitions).
- Typically assumes fixed transition structure over time.

These limitations are precisely what makes Markov models a useful baseline: any richer EVOS evolution law must either (i) reduce to a Markov process under projection, or (ii) explicitly violate Markov assumptions in a controlled, auditable way.



Interpretation. Edges encode the shared transition law. A worldline is a *path* through the same state space; many distinct trajectories exist under identical dynamics.

Figure 6: State space with a shared transition law. Markov dynamics generate an ensemble of possible worldlines (paths) through the same transition graph.

5.3.5 Markov Chains as Coarse-Grained Projections

In EVOS, Markov dynamics frequently arise as emergent approximations.

Let $\mathcal{W}$ be a full worldline with memory and commitments. Under coarse temporal or state aggregation, the induced dynamics often appear Markovian:

$$Z(t) \;=\; \Pi\big(\mathcal{W}_{[t-\tau,\,t]}\big),$$

where Π is a projection operator (lossy observation, coarse measurement, summarization).

Thus, Markov chains are not "the true dynamics"; they are shadows cast by richer processes under finite resolution.

5.3.6 Relationship to Resonance Fields (GENESIS Link)

Within GENESIS, Markov transitions correspond to local diffusion over a resonance field. A generic diffusion-like form is:

$$T(z, z') \propto \exp\!\left(-\frac{\|z' - z\|^2}{\sigma^2}\right),$$

capturing probabilistic drift induced by local similarity/coupling gradients.

This links Markov evolution to:

- diffusion processes and random walks,
- reaction kinetics under coarse-graining,
- stochastic motion in semantic/behavioral manifolds.

5.3.7 Why Markov Models Belong in EVOS

Markov chains are included in EVOS not because they are sufficient, but because they are unavoidable: any evolutionary system that is observed at finite resolution, operates under uncertainty, and interacts with noisy environments will exhibit approximately Markovian behavior at some scale.

> *Markov dynamics are the minimal evolutionary substrate on which higher-order EVOS structures (memory, commitment, governance) are built and against which they can be tested.*

5.4 Time Series and Stochastic Dynamics

Markov models provide a minimal baseline, but they erase the defining EVOS feature: *history*. Real open systems accumulate trace, inertia, and structure. Time-series and stochastic process models restore history dependence while remaining operationally tractable and widely composable.

5.4.1 History-Dependent State Evolution

Let $\mathcal{H}(t)$ denote the event history up to time t. A history-dependent (non-Markov) evolution law takes the general form

$$\mathbb{P}\big(Z(t+\Delta t) = z' \mid \mathcal{H}(t)\big) \;\neq\; \mathbb{P}\big(Z(t+\Delta t) = z' \mid Z(t) = z\big).$$

To model this without carrying the full raw history, EVOS elevates *memory* into an explicit dynamical component.

Let $M(t)$ be a memory state summarizing accumulated history (experience, commitments, constraints, learned structure). Then the EVOS-compatible formulation is:

$$(Z(t+\Delta t),\, M(t+\Delta t)) \;=\; \Phi\big(Z(t), M(t), \mathcal{E}(t), \mathcal{C}(t)\big).$$

This restores historical dependence while keeping evolution lawful and auditable.

5.4.2 Autoregressive and State-Space Models

A minimal history-dependent family is *autoregression*:

$$Z_t \;=\; \sum_{k=1}^{p} A_k Z_{t-k} \;+\; \epsilon_t,$$

where ϵ_t is a noise process.

More generally, EVOS uses *state-space* dynamics with an explicit latent state and an observation (projection) process:

$$Z_{t+1} = f(Z_t, u_t) + \eta_t, \tag{1}$$
$$Y_t = g(Z_t) + \xi_t, \tag{2}$$

where u_t represents exogenous inputs (environmental forcing), and η_t, ξ_t are process/measurement noise.

EVOS interpretation. Y_t is what the world can observe (or what an instrument projects), while Z_t carries latent internal structure. Commitments (Section 2–3) are not implied by Y_t; they are explicit boundary-crossing events.

5.4.3 Time Series as Discretized Worldlines

A worldline in EVOS is a trajectory; time series models can be understood as discrete samples of such trajectories:

$$\mathcal{W} \;=\; \{Z(t_0), Z(t_1), Z(t_2), \dots\}.$$

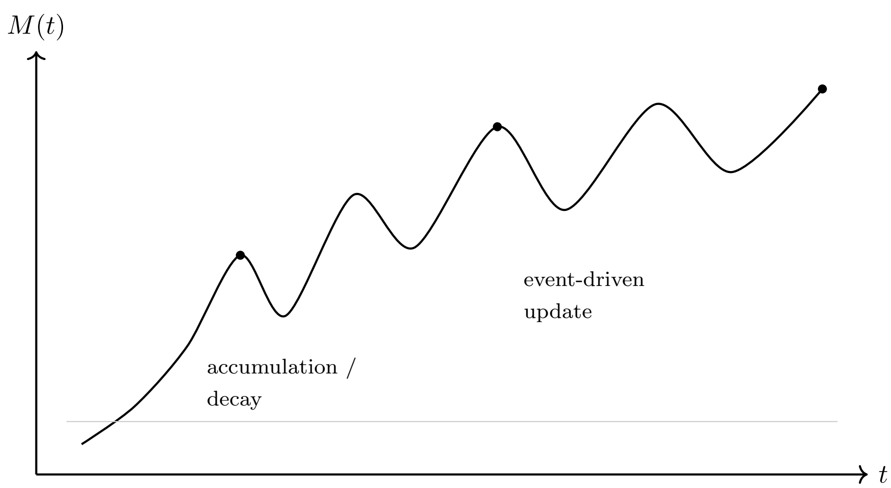
As temporal resolution increases, the discrete chain approaches a continuous-time worldline, but the core EVOS object remains the *trajectory* rather than any single sample.

5.4.4 Worldlines with Memory

Under time-series dynamics, an EVOS entity evolves in an *extended* state space that includes memory:

$$\mathcal{W}_i \;=\; \{(Z_i(t), M_i(t)) \mid t \in \mathbb{R}^+\}.$$

Memory is not a passive database row; it is an evolving component of the trajectory. This makes meaning, intent, and risk properties of the *path* through (Z, M) space, not instantaneous labels.



Worldline with memory. The entity evolves along time while carrying a memory state $M(t)$ that accumulates, decays, and updates under events—yielding a trajectory in (Z, M) space: $\mathcal{W}_i = \{(Z_i(t), M_i(t)) \mid t \in \mathbb{R}^+\}$.

Figure 7: Worldline with memory. Memory is a dynamical component of the worldline: it evolves under events, reinforcement, and decay, shaping future evolution under the same environment.

5.4.5 Stochasticity, Noise, and Uncertainty

Open systems are subject to irreducible uncertainty:

- **Process noise** (unknown perturbations in evolution),
- **Observation noise** (projection/instrument limitations),
- **Policy noise** (uncertainty introduced by constraints and governance updates).

A standard stochastic formulation is:

$$Z_{t+1} \;=\; f(Z_t, M_t, u_t) \;+\; \eta_t, \qquad M_{t+1} \;=\; h(M_t, Z_t, e_t) \;+\; \omega_t,$$

where e_t denotes structured events (including commitments), and η_t, ω_t are noise processes.

EVOS requirement. Stochasticity does not remove accountability. Even if the trajectory is probabilistic, externally observable effects must still be causally anchored to explicit commitment events in $\mathcal{H}(t)$.

5.4.6 Limitations of Time Series Models

Time-series models remain limited relative to full EVOS:

- Memory is often *parameterized* rather than structurally grounded in event history.
- Commitments can be modeled as shocks, but are not guaranteed to be explicit gates.
- Operator evolution (learning) is typically handled outside the model (offline training), rather than as first-class meta-dynamics.

These limitations motivate Section 5.4 (learned and self-modifying operators) and Section 5.6 (runtime substitution with invariants).

5.4.7 Role of Time Series in EVOS

Time-series and stochastic dynamics are essential because they:

- provide a bridge from Markov minimalism to memory-bearing evolution,
- integrate uncertainty as a first-class structural feature of openness,
- support practical identification and control under partial observability,
- align naturally with provenance: events can be treated as structured innovations.

> *Time-series EVOS is where trajectory becomes identity: the system is no longer a sequence of states, but a history-bearing process whose future is shaped by memory.*

5.5 Differential and Reaction–Diffusion Systems

Time-series models restore memory but remain discretized approximations of a deeper fact: many natural and artificial systems evolve *continuously* in time (and often in space), governed by differential laws rather than stepwise transitions. EVOS therefore admits continuous-time evolution as a first-class transition family.

5.5.1 Continuous-Time State Evolution

Let $Z(t)$ denote the latent state of an entity at continuous time t. A differential evolution model specifies state change via

$$\frac{dZ(t)}{dt} = F\big(Z(t), t\big),$$

where F may be nonlinear, stochastic, and time-dependent.

This subsumes:

- ordinary differential equations (ODEs),
- stochastic differential equations (SDEs),
- controlled dynamical systems,
- gradient flows and dissipative systems.

Discrete-time transitions arise as numerical approximations (Euler, Runge–Kutta, etc.):

$$Z(t + \Delta t) \approx Z(t) + \Delta t\, F(Z(t), t).$$

EVOS point: the system is still defined by its *worldline*; discretization is an observation/implementation artifact.

5.5.2 Worldlines as Geometric Objects

Under differential evolution, a worldline becomes a smooth curve in state space:

$$\mathcal{W}_i = \{Z_i(t) \mid t \in \mathbb{R}^+\}.$$

Geometric properties of this curve encode behavior:

- **velocity** $\|\dot{Z}(t)\|$ corresponds to rate of adaptation,
- **curvature** corresponds to responsiveness / steering complexity,
- **attractors** correspond to stable beliefs, strategies, or morphologies,
- **basins** correspond to robust regimes under perturbation.

In EVOS, this geometric interpretation applies uniformly across substrates: agent cognition, biological development, and chemical concentration dynamics all become trajectory geometry under constraints.

5.5.3 Reaction–Diffusion Systems

To model interactions distributed across space, EVOS incorporates reaction–diffusion dynamics. Let $Z(x, t)$ denote a spatially distributed state variable. Its evolution is governed by

$$\frac{\partial Z(x,t)}{\partial t} = D\nabla^2 Z(x,t) + R\big(Z(x,t)\big),$$

where:

- D is a diffusion coefficient,
- ∇^2 is the Laplacian operator,
- $R(\cdot)$ is a local reaction term (production, inhibition, binding, decay).

Reaction–diffusion systems naturally model:

- chemical kinetics and autocatalysis,
- morphogenesis and pattern formation,
- signal propagation and spatial coupling,
- distributed agent influence in embodied worlds.

5.5.4 Resonance Fields as Reaction–Diffusion Media

Within GENESIS, resonance potentials generalize from pairwise couplings to spatial fields. Let $\Phi(x, t)$ represent resonance intensity (coupling potential) over space at time t. Diffusion captures spread of influence; reaction captures local reinforcement or inhibition.

The field-first view is important: graphs (edges) emerge as *thresholded* or *high-gradient* structures of a continuous landscape.

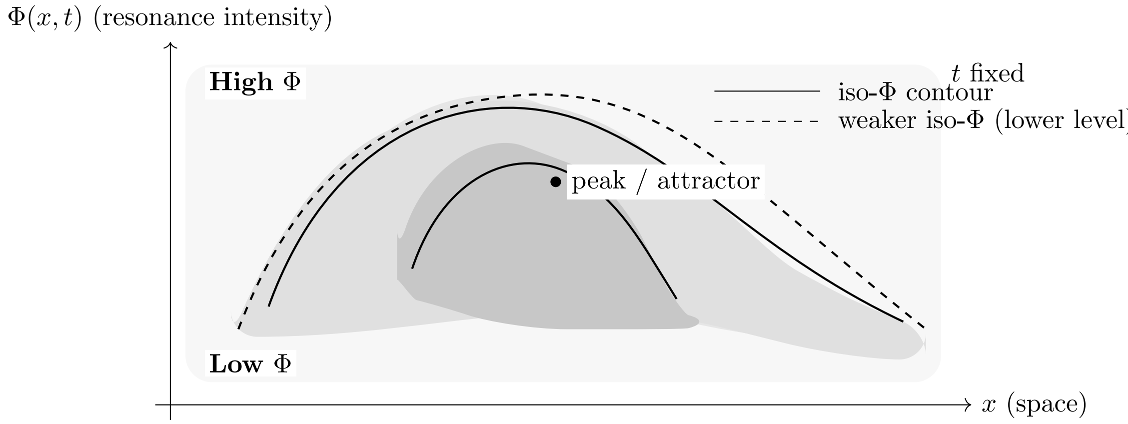


Figure 8: Spatial resonance field $\Phi(x,t)$ at fixed time: intensity forms a continuous landscape with peaks (attractors), halos (medium coupling), and iso-Φ contours. Graph edges are recoverable as thresholded/high-gradient contours, but the field is primary.

5.5.5 Chemical and Molecular Interpretation

In molecular EVOS (BIO-EVOS):

- $Z(x,t)$ corresponds to molecular concentration (or a vector of species concentrations),
- diffusion models molecular motion and mixing,
- reaction terms model binding, synthesis, inhibition, and decay.

Commitment events correspond to reactions that:

- consume scarce reagents or energy,
- alter reachable reaction pathways (constraint changes),
- change the topology of the reaction network irreversibly.

This aligns with DNA computing primitives such as hybridization, amplification, and strand displacement: once executed, the system's reachable future trajectories are structurally altered.

5.5.6 Attractors, Patterns, and Emergence

Reaction–diffusion systems exhibit emergent phenomena:

- stable attractors and basins,
- oscillations and limit cycles,
- pattern formation (e.g., Turing patterns),
- symmetry breaking and phase transitions.

In EVOS terms, these correspond to:

- persistent strategies or beliefs (digital),
- norms and institutions (civilizational),
- functional biological structures (molecular/biological).

5.5.7 Why Differential Models Are Essential to EVOS

Differential and reaction–diffusion models belong in EVOS because they:

- unify discrete and continuous dynamics (steps and flows),
- naturally represent embodiment, space, and propagation,
- support emergence without centralized control,
- align with physical and biological constraint laws.

Discrete computation describes *steps*. Differential computation describes *flows*. EVOS requires both, because intelligence exists as trajectory-shaping across time and space.

5.6 Learned and Self-Modifying Transition Operators

Markov, time-series, and differential models assume the evolution law is given (even if stochastic). Intelligent systems exhibit a stronger property: the *law of evolution is itself adaptive*. EVOS therefore admits *learned* and *self-modifying* transition operators as first-class citizens—*without* sacrificing causal anchoring or accountability.

5.6.1 Meta-Dynamics: Evolving the Evolution Law

Let $Z(t)$ be the latent state and let $\Theta(t)$ parameterize the evolution operator. We define a coupled system:

$$\frac{dZ(t)}{dt} = F\big(Z(t), \Theta(t), t\big), \tag{3}$$

$$\frac{d\Theta(t)}{dt} = U\big(\Theta(t), Z(t), \mathcal{H}(t), t\big), \tag{4}$$

where:

- F is the state evolution operator (dynamics),
- U is the *meta-evolution* operator (learning / adaptation),
- $\mathcal{H}(t)$ denotes the event history up to time t (including commitments).

This formulation strictly generalizes:

- online learning (slow drift in Θ),
- adaptive control systems (feedback-driven U),
- evolutionary search over operator families (population-level Θ),
- biological regulation and adaptation (environment-conditioned update of Θ).

EVOS point: learning is not a special phase external to the system; it is a co-evolution of (Z, Θ) along the same irreversible worldline.

5.6.2 Operator Families and Identifiability

EVOS does not assume a specific operator family. Instead, it requires that:

1. the operator be *selectable* (pluggable) from a family,
2. operator updates be *representable* as structured events,
3. downstream consequences remain *causally anchored* to those events.

Let $\mathcal{F}$ denote an admissible operator family and $\mathcal{U}$ the family of meta-operators:

$$F \in \mathcal{F}, \qquad U \in \mathcal{U}.$$

Identifiability at the event boundary. EVOS locates identifiability at the commitment/provenance layer: if an operator change materially alters externally relevant behavior, it must appear as an event with provenance. Concretely, EVOS requires a structured event record such as:

$$e_{\Delta\Theta} = \langle t,\ \Delta\Theta,\ \text{trigger},\ \text{policy-context},\ \text{proof / audit}\rangle.$$

This does *not* require full transparency of the internal model; it requires that *externally significant changes* be auditable and attributable.

5.6.3 Modes of Self-Modification: Smooth Drift and Regime Shifts

Self-modification is not monolithic. EVOS distinguishes two primary modes.

(1) Smooth Drift (continuous adaptation).

$$\Theta(t + \Delta t) = \Theta(t) + \eta\, \nabla_\Theta \mathcal{L}(t),$$

where $\mathcal{L}(t)$ is a loss/fitness functional (possibly implicit or multi-objective), and η is an adaptation rate (possibly state-dependent).

(2) Regime Shifts (piecewise operators).

$$F(t) = \begin{cases} F^{(1)} & t \in [t_0, t_1) \\ F^{(2)} & t \in [t_1, t_2) \\ \vdots \end{cases}$$

Regime shifts are central in open systems because commitments, resource shocks, and policy updates frequently introduce *new constraints* that change which futures remain feasible.

5.6.4 Commitment-Coupled Learning

Commitment events provide a universal anchor that connects latent learning to accountability.

Let e_c be a commitment event, and let x be an externally observable consequence. EVOS requires that externally relevant operator changes be traceable to a causal chain that includes:

- a commitment event e_c, or
- an explicit policy decision / exception event e_p (rare; auditable).

We use $\prec$ for causal precedence within the event history. For externally observable x, EVOS requires an accountable causal lineage:

$$\exists\, e \in \mathcal{H}(t) \text{ such that } e \prec x,$$

and for operator shifts $\Delta\Theta$ that materially influence x, EVOS additionally requires:

$$\Delta\Theta \prec e_c \quad \text{or} \quad \Delta\Theta \prec e_p,$$

with e_c passing the commitment boundary gate.

Interpretation. Latent learning may happen continuously, but *externalization* of its effects must be policy-constrained and provenance-recorded. This is the EVOS mechanism that prevents untraceable self-modification from producing unaccountable real-world action.

5.6.5 Resonance Interpretation: Learning as Field Plasticity

Within GENESIS, learning can be interpreted as rewriting the geometry of the resonance manifold:

- $Z(t)$ moves *within* the manifold (state evolution under the current field geometry),
- $\Theta(t)$ reshapes the manifold (law evolution / field plasticity).

Thus intelligence is not merely trajectory optimization; it is *field plasticity under constraint*. Alignment becomes *constraint compatibility* of field rewrites, not post-hoc filtering of outputs.

5.6.6 Two-Tier Dynamics: State and Law

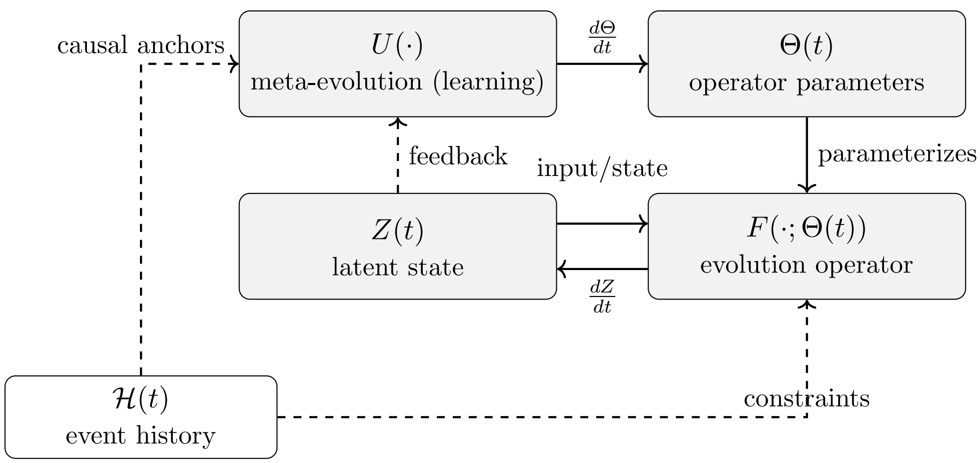


Figure 9: Two-tier EVOS dynamics: state evolution $Z(t)$ driven by operator F parameterized by $\Theta(t)$, with meta-evolution U updating $\Theta(t)$ under event-history constraints $\mathcal{H}(t)$.

5.6.7 Commitment as an Accountability Gate

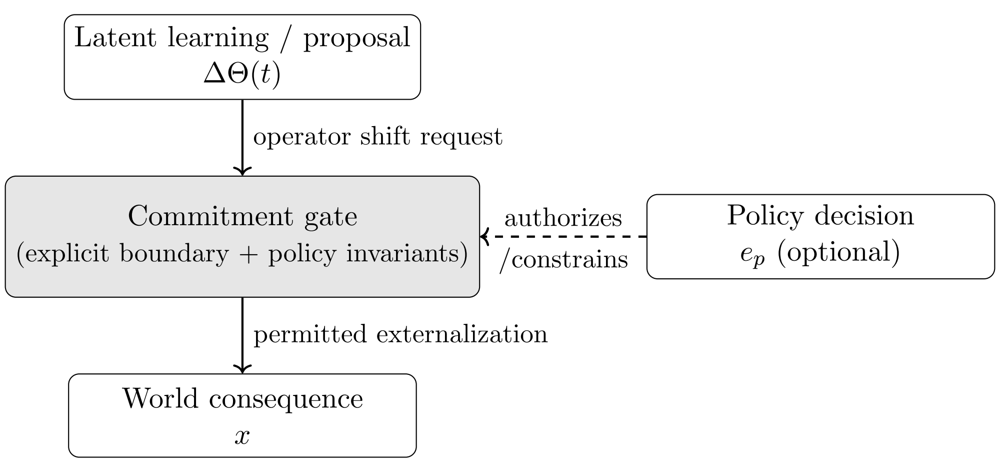


Figure 10: Operator changes remain latent until passing an explicit commitment gate (or an auditable policy event). This enforces causal accountability for self-modifying systems.

5.6.8 Why Self-Modifying Operators Belong in EVOS

Learned and self-modifying operators belong in EVOS because they:

- subsume classical training as a special case of Θ-evolution,
- support open-ended adaptation beyond fixed architectures,
- align with biological regulation and evolutionary dynamics,
- preserve substrate independence while enabling persistent intelligence.

Crucially, EVOS constrains self-modification using commitment-anchored accountability, preventing untraceable evolution from producing unaccountable real-world effects.

5.7 Runtime Substitution of Evolution Laws

EVOS is not merely a taxonomy of admissible dynamics; it is a *systems thesis*: an evolutionary open system must be able to *change how it changes* while remaining auditable, safe, and causally anchored. This requires *runtime substitution* of evolution laws—swapping F (and sometimes U) without resetting identity, history, or accountability.

5.7.1 Problem Statement

Let an EVOS entity be characterized (at a minimum) by its worldline state $(Z(t), M(t))$, its operator parameters $\Theta(t)$, and its event history $\mathcal{H}(t)$. In many real systems, the evolution operator family must change over time:

- upgrading a controller / policy,
- replacing a model class (e.g., AR $\to$ SDE, heuristic $\to$ learned),
- tightening safety constraints under new governance,
- migrating substrates (digital $\to$ hybrid, local $\to$ distributed).

Naively swapping F breaks one or more EVOS axioms:

- **Worldline primacy:** identity continuity is lost if state is reinitialized,
- **Intrinsic memory:** $M(t)$ becomes incoherent under incompatible F,
- **Causal anchoring:** behavior changes without a traceable cause,
- **Commitment boundary:** external effects may change without accountability.

EVOS therefore requires a *hot-swap protocol* that makes operator substitution a first-class, auditable, policy-constrained event.

5.7.2 Operator Plug-in Bus (Concept)

We model evolution operators as *modules* attached to an EVOS core via a plug-in bus.

Let Op denote an operator module implementing:

$$\mathsf{Op}: \ (Z, M, \Theta, \mathcal{E}, \mathcal{C}) \mapsto (Z', M', \Theta').$$

Runtime substitution replaces Op_{old} with Op_{new} while preserving:

$$\text{identity}, \quad \mathcal{H}(t), \quad \text{commitment gates}, \quad \text{audit invariants}.$$

Compatibility is explicit. Each operator exposes a *capability/contract signature*:

$$\Sigma(\mathsf{Op}) = \langle \text{state schema},\ \text{memory schema},\ \text{constraint interface},\ \text{commitment interface}\rangle,$$

and swaps are allowed only if a verified *adapter* exists:

$$\mathsf{Adapt}_{old\to new}:\ (Z, M, \Theta) \mapsto (Z^\star, M^\star, \Theta^\star).$$

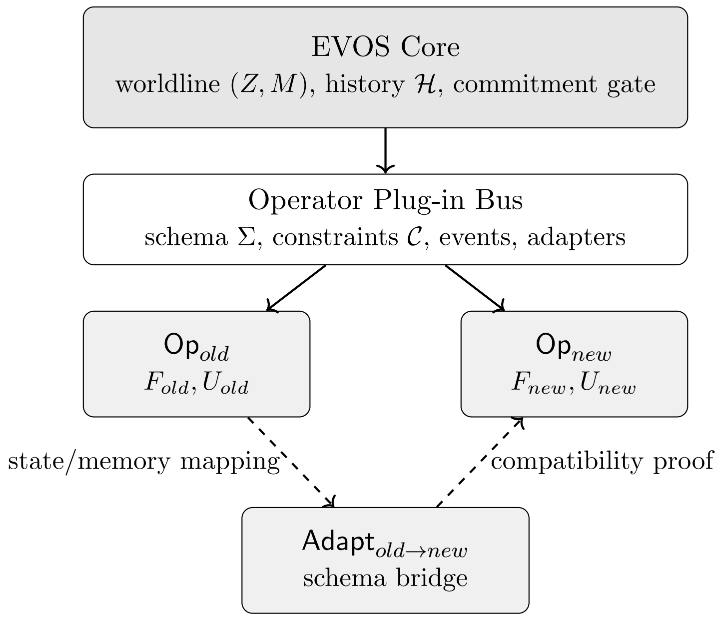


Figure 11: EVOS operator plug-in bus. Operators are swappable modules, but swaps require explicit schema contracts and (when needed) adapters that preserve worldline continuity and auditability.

5.7.3 Safety Gates and Regression Invariants

Runtime substitution is dangerous precisely because it changes future trajectories. EVOS therefore enforces a *swap gate* analogous to the commitment gate.

Let $\mathcal{I}$ be a set of invariants that must hold before and after substitution:

$$\mathcal{I} = \{\text{schema invariants},\ \text{policy invariants},\ \text{risk bounds},\ \text{commitment semantics}\}.$$

A swap is permitted only if:

$$\mathsf{Verify}(\mathsf{Op}_{new}, \mathcal{I}, \mathcal{H}(t)) = \textsc{true},$$

and the verification outcome is recorded as an event:

$$e_{swap} = \langle t,\ \mathsf{Op}_{old} \to \mathsf{Op}_{new},\ \mathcal{I},\ \text{evidence},\ \text{approver}\rangle.$$

Minimal guarantees (non-negotiable). At minimum, EVOS requires:

- **Commitment semantics invariant:** the definition of a commitment event and its provenance obligations cannot silently weaken;
- **Policy invariant monotonicity:** safety constraints may tighten without special authorization; loosening requires explicit policy event e_p;
- **History preservation:** $\mathcal{H}(t)$ remains append-only and queryable across operator eras.

5.7.4 Provenance and Causal Lineage of Operators

Operators are part of the causal fabric. EVOS therefore treats operators as provenance-bearing artifacts.

Let OpId be a content-addressed identifier (hash) of the operator artifact plus config:

$$\mathsf{OpId} = \mathsf{Hash}(\text{code},\ \text{weights},\ \text{config},\ \text{constraints}).$$

All externally relevant consequences x must be attributable to an operator era:

$$x \prec \mathsf{OpId}(t) \quad \text{and} \quad \mathsf{OpId}(t) \in \mathcal{H}(t).$$

Operator eras. Define an era partition of time by swap events:

$$[t_0, t_1),\ [t_1, t_2),\ \ldots$$

Within each era, the active operator identity is constant, and is part of every causal trace.

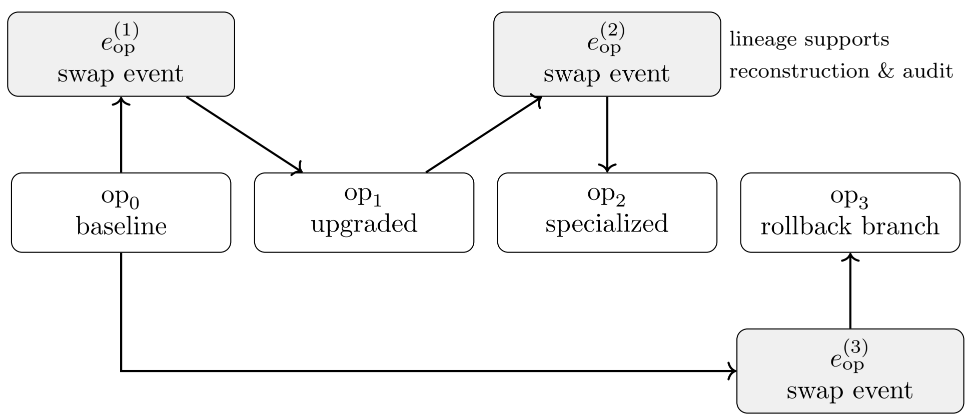


Figure 12: Operator provenance as a lineage DAG. Each operator substitution is an immutable event anchored in the event fabric. Lineage enables reconstruction ("which law governed which consequence"), auditing, and safe rollback branches without rewriting history.

5.7.5 Hot-Swap Protocol (Staged Rollout)

EVOS swaps must be staged to avoid catastrophic discontinuities.

Phase 0: Proposal (latent). A candidate operator Op_{new} is introduced, but not allowed to cross the commitment gate.

Phase 1: Shadow / Replay (non-binding). Run Op_{new} in parallel on the same inputs/events:

$$(Z', M')_{new} = \mathsf{Op}_{new}(Z, M, \Theta, \mathcal{E}, \mathcal{C}),$$

while commitments still use Op_{old}.

Phase 2: Constrained Canaries (binding under limit). Allow limited commitments under strict caps (rate, scope, amount, blast radius) and record all divergences.

Phase 3: Commit Swap (binding). Cross the *swap gate* and record e_{swap}; the active operator becomes Op_{new}.

Phase 4: Rollback (if needed). Rollback is a *new* swap event, not history erasure:

$$e_{swap}^{-1}: \ \mathsf{Op}_{new} \to \mathsf{Op}_{old}.$$

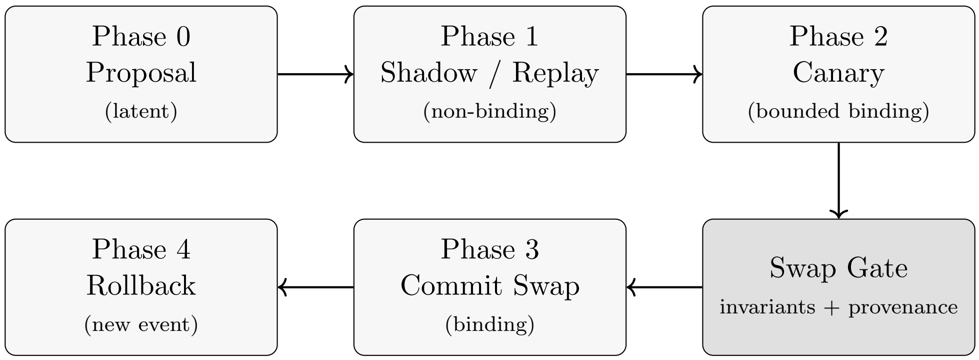


Figure 13: EVOS hot-swap protocol. Operator substitution is staged (proposal → shadow → canary) and crosses an explicit swap gate that enforces invariants and records provenance. Rollback is an additional event, not deletion of history.

5.7.6 Why Runtime Substitution Is Fundamental

Runtime substitution is fundamental because open-ended intelligence is an *operator trajectory*: agents must incorporate new mathematics, new policies, and new constraints without resetting their worldlines.

In EVOS:

- **Upgrades are evolution,** not redeployments;
- **Accountability survives change** via operator provenance and swap events;
- **Safety is structural** via swap gates and monotonic policy invariants.

This completes the pluggable transition stack: from minimal stochastic dynamics (Markov), to history-dependent models (time series), to continuous flows (differential systems), to self-modifying laws, and finally to *runtime-governed substitution* of the laws themselves.

6 Digital EVOS: Agent Civilizations

6.1 Agents as Digital Organisms

An EVOS is not merely an "agent" in the conventional software sense; it is a *persistent organism-like process* whose identity is defined by its worldline (Axiom I), whose adaptation is encoded as operator evolution (Section **??**), and whose external effects are mediated by explicit commitment events (Axiom IV).

Explicit claim (C6.1). A network of EVOS agents with (i) commitment-gated external action and (ii) auditable event history constitutes a *civilization substrate*: a medium in which stable institutions and norms can emerge as attractors in resonance dynamics.

Minimal formalism. Let agents be indexed by $i \in \{1, \ldots, N\}$. Each agent carries latent state and memory $(Z_i(t), M_i(t))$ and produces events into a shared fabric $\mathcal{H}(t)$. A digital agent civilization is an EVOS ensemble with:

$$\mathfrak{C}(t) \ = \ \big(\{(Z_i(t), M_i(t))\}_{i=1}^{N},\ \mathcal{H}(t),\ \mathcal{P}(t)\big),$$

where $\mathcal{P}(t)$ denotes the policy/contract constraint layer governing permitted commitments.

6.2 Attention as Energy in Digital Systems

In biological systems, energy budgets bound what can be sensed, remembered, and enacted. In digital EVOS, an analogous conserved quantity is *attention*: the rate-limited capacity to process inputs, maintain memory, and evaluate commitments.

Explicit claim (C6.2). In digital civilizations, attention functions as a *scarce resource* whose allocation shapes social structure. Persistent institutions emerge as *attention-stable* structures (low maintenance cost, high predictive value).

Minimal formalism. Let $A_i(t) \geq 0$ denote the attention budget of agent i at time t. Commitments consume attention and often induce irreversible obligations. A minimal accounting constraint is:

$$\int_t^{t+\Delta} c_i(\tau)\, d\tau \ \leq \ \int_t^{t+\Delta} A_i(\tau)\, d\tau,$$

where $c_i(t)$ is an attention expenditure rate induced by perception, deliberation, and commitment upkeep. This induces an economic-like pressure: agents prefer commitments whose downstream maintenance cost is bounded.

6.3 Commitment and Accountability in Agent Societies

Commitment is the boundary by which internal intent becomes externally binding (Axiom IV). In a multi-agent setting, commitment is also the primitive by which *coordination becomes real.*

Explicit claim (C6.3). A society without commitment is a simulation; a society with commitment is an economy of consequences. EVOS civilizations are defined by the fact that *coordination is made auditable* through commitment-anchored causal provenance.

Minimal formalism. Let $e_i^c(t) \in \mathcal{H}(t)$ be a commitment event emitted by agent i at time t. Let x be an externally observable consequence. EVOS accountability requires:

$$\forall x \ \exists e \in \mathcal{H}(t) : \quad e \prec x,$$

and if x is mediated by policy $\mathcal{P}(t)$, then e must be a permitted commitment:

$$e \in \mathrm{Commit}(\mathcal{P}(t)) \subset \mathcal{H}(t).$$

This enables (i) reconstruction of responsibility and (ii) safe gating of actions under institutional constraints.

6.4 Emergent Social Structures

Civilizations exhibit macro-structures: roles, norms, markets, courts, religions, scientific institutions. In EVOS, these are not hard-coded; they are *stable macroscopic patterns* arising from resonance dynamics, attention constraints, and commitment accountability.

Explicit claim (C6.4). Institutions correspond to *attractors* in the joint dynamics of resonance coupling and commitment history: once formed, they reduce transaction cost and stabilize agent worldlines.

Minimal formalism. Let $\Phi_{ij}(t)$ denote a resonance intensity or coupling potential between agents i and j. Define a coarse-grained institution variable $I_k(t)$ (e.g., "market", "court", "guild") as a functional of the event fabric and coupling field:

$$I_k(t) \;=\; \Psi_k\big(\mathcal{H}(t), \{\Phi_{ij}(t)\}\big).$$

Stability is expressed as bounded drift under perturbation:

$$\|I_k(t+\Delta) - I_k(t)\| \le \epsilon \quad \text{for typical perturbations,}$$

i.e., institutions persist as memory-bearing, low-entropy organizational patterns.

6.5 Diagram: Agent Civilization as a Resonance Field

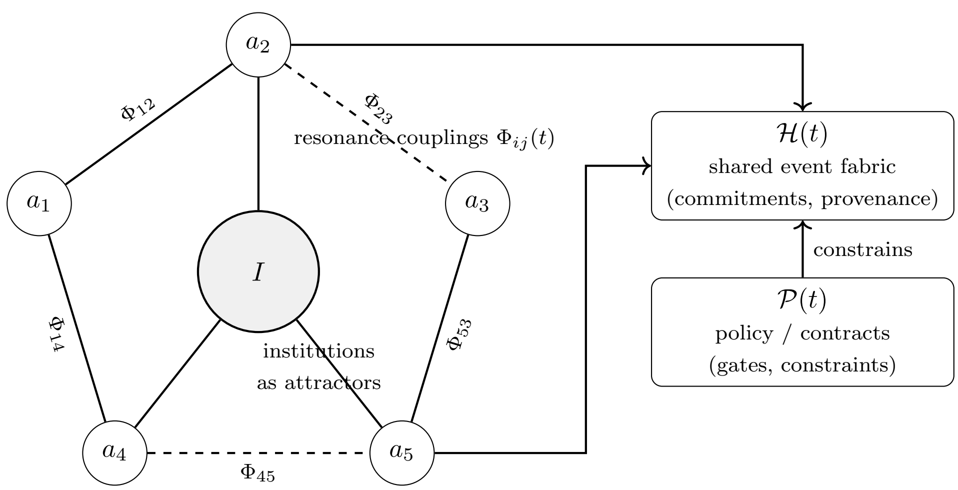


Figure 14: Agent civilization as a resonance field. Agents couple via resonance intensities $\Phi_{ij}(t)$; institutions I emerge as stable attractors that mediate interaction. Commitments are emitted into a shared event fabric $\mathcal{H}(t)$ and constrained by policy/contracts $\mathcal{P}(t)$, enabling accountability and governance.

6.6 Roles, Institutions, and Digital Culture

Roles are persistent compressions of behavior: "validator", "merchant", "scientist", "guardian", "artist", "judge". In EVOS terms, a role is a *constraint-compatible behavioral manifold* that reduces coordination cost.

Explicit claim (C6.5). Digital culture is not content; it is a *stable pattern of commitments* and the narratives that justify them. Culture emerges when agents share compression schemes for interpreting $\mathcal{H}(t)$ and predicting permitted commitments under $\mathcal{P}(t)$.

Minimal formalism. Let $R_i(t)$ be a role label (coarse-grained) assigned by observation:

$$R_i(t) = \Omega\big(\mathcal{H}_i(t), \mathcal{P}(t)\big),$$

where $\mathcal{H}_i(t)$ is the sub-history attributable to agent i. Stability of roles corresponds to low switching frequency under perturbation:

$$\mathbb{P}\big(R_i(t+\Delta) \neq R_i(t)\big) \text{ is small for typical } \Delta.$$

6.7 ARES as an Instantiation of Digital EVOS

To avoid conflating theory with implementation, we treat any runtime that enforces commitment gates, maintains an event fabric, and supports operator substitution under invariants (Section **??**) as an instantiation pathway.

Explicit claim (C6.6). A practical Digital EVOS runtime requires three enforcement layers: (i) commitment-gated I/O, (ii) immutable causal provenance, (iii) policy-constrained operator substitution. These suffice to make persistent agents *operationally accountable* without prescribing their internal architecture.

6.8 Why Agent Civilizations Belong in EVOS

Digital civilizations are not an application afterthought; they are the natural completion of the EVOS definition. Once systems are persistent, open, memory-bearing, and commitment-bound, the default mode is *multi-agent existence*.

Explicit claim (C6.7). EVOS provides a minimal theory in which:

- coordination is real (commitment),
- history is binding (worldlines, event fabric),
- governance is enforceable (policy constraints),
- and evolution is safe to operationalize (invariants, rollback, provenance).

Thus EVOS is a civilization substrate, not merely an "agent framework."

7 Molecular EVOS: DNA as a Computational Substrate

7.1 From Digital to Molecular Substrates

EVOS is defined axiomatically rather than architecturally. This implies a strong *substrate independence*: any physical or logical medium that can support (i) a worldline (trajectory), (ii) intrinsic memory, (iii) openness under constraint, and (iv) commitment-gated irreversibility is, in principle, an admissible EVOS substrate.

Digital instantiations (software agents) emphasize explicit interfaces and governance invariants. Molecular instantiations emphasize continuous dynamics, embodiment, and thermodynamics. The purpose of this section is not to claim that "DNA is smarter than digital," but to show that EVOS is *more general than digital computation*: it covers a class of dynamics that can be instantiated as chemical evolution laws.

Explicit claim (C7.1). A DNA reaction system can instantiate EVOS dynamics because molecular state is naturally time-evolving and memory-bearing, and because certain transitions are effectively irreversible under realistic resource and energy constraints, yielding a physical commitment boundary.

7.2 Why DNA Qualifies as an EVOS Substrate

DNA is a programmable chemical language. Its "symbols" are sequence domains; its "operators" are binding and displacement pathways; its "control" is achieved by stoichiometry, catalysts/enzymes, temperature, and environmental coupling.

Mapping EVOS axioms to a molecular setting:

- **Axiom I (Worldline primacy):** the entity is the trajectory of molecular state, not an instantaneous configuration.
- **Axiom II (Intrinsic memory):** memory is embodied in persistent species, complexes, and long-lived concentration patterns.
- **Axiom III (Openness under constraint):** inflow/outflow and measurement/actuation couple the system to an environment while conservation and scarcity impose constraints.
- **Axiom IV (Commitment boundary):** resource-consuming or effectively irreversible reactions serve as commitment events.
- **Axiom V (Substrate independence):** the same EVOS definitions hold across media.

Explicit claim (C7.2). In molecular EVOS, *commitment is physical*: commitments are not merely logged; they are realized as irreversible consumption, topology changes in reaction pathways, or stable product formation that propagates forward in time.

7.3 Beyond Binary: High-Arity Symbol Systems

Digital computation often privileges binary state. Molecular systems are naturally high-arity: sequence space, combinatorial binding configurations, and continuous concentrations constitute a richer representational substrate.

Let Σ be a finite set of DNA domains (motifs). A strand is a word $s \in \Sigma^*$. Interaction induces an affinity potential

$$\Phi(s_i, s_j) \;\propto\; -\Delta G(s_i, s_j),$$

where ΔG is an effective free-energy change. In GENESIS terms, Φ is the primitive coupling potential: "meaning" is expressed as stable, repeatable affinity structure rather than as discrete token identities.

Explicit claim (C7.3). High-arity molecular symbol systems support an EVOS interpretation of meaning as *stable pathways and attractors* in a resonance landscape, rather than as architecture-specific token manipulation.

7.4 Molecular State as a Continuous Field

Let $x(t) \in \mathbb{R}^m_{\geq 0}$ denote concentrations of m molecular species. A minimal continuous-time molecular EVOS takes the form

$$\frac{dx(t)}{dt} = f(x(t), u(t), t),$$

where $u(t)$ captures environmental influx/perturbations (openness). Spatial embodiment yields reaction–diffusion dynamics:

$$\frac{\partial x(\mathbf{r}, t)}{\partial t} = D\nabla^2 x(\mathbf{r}, t) + f(x(\mathbf{r}, t), u(\mathbf{r}, t), t).$$

Explicit claim (C7.4). A resonance field is not metaphorical in molecular EVOS: it is literally a concentration and affinity landscape whose gradients govern drift, diffusion, inhibition, and reinforcement, thereby generating stable patterns (attractors) and phase transitions.

7.5 Transition Mechanisms as Physical Laws

In digital EVOS, a transition operator is a formal object that may be swapped under policy and invariants (Sections 5.4–5.6). In molecular EVOS, the transition operator is a *reaction network* realized by available species, catalysts, and conditions.

Let $\mathcal{R}(t)$ denote the set of reaction channels available at time t. Then

$$\frac{dx}{dt} = f(x; \mathcal{R}(t)).$$

A self-modifying molecular EVOS allows $\mathcal{R}(t)$ itself to evolve as a function of history (e.g., producing catalysts, sequestering inhibitors, synthesizing new strands):

$$\mathcal{R}(t + \Delta) = \Gamma(\mathcal{R}(t), x_{[0,t]}, u_{[0,t]}).$$

Explicit claim (C7.5). Operator substitution in molecular EVOS is *reaction-network rewriting* and may be endogenous: the system can alter its own future dynamics by producing or suppressing reaction pathways.

7.6 Time, Energy, and Irreversibility in DNA Systems

EVOS requires an intrinsic arrow of time: commitments generate irreversible downstream consequences. In molecular systems, irreversibility arises from dissipation, depletion, and kinetic trapping.

Let $E(t)$ denote a coarse-grained dissipated energy / consumed resource functional. A commitment event e_c is a transition that changes feasibility in a way that cannot be undone without additional external work, modeled by a bounded resource increase:

$$\Delta E(e_c) \; \geq \; \epsilon \; > \; 0.$$

Explicit claim (C7.6). Molecular commitment boundaries are grounded in physics: energy gradients and reagent consumption enforce irreversibility, yielding accountability as a property of matter.

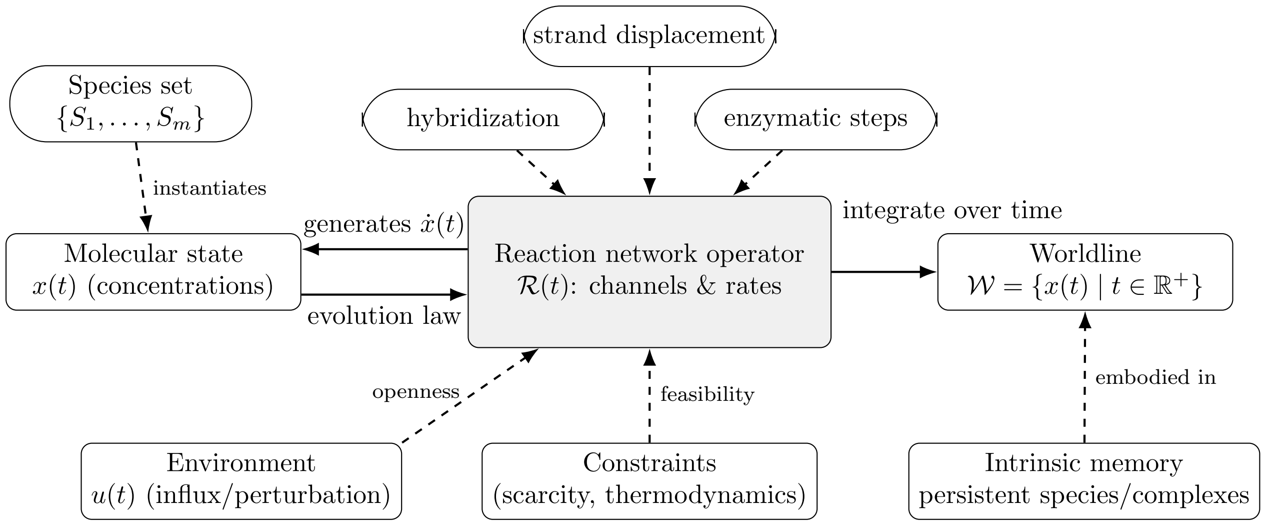


Figure 15: DNA reaction network as an EVOS transition operator. The molecular state $x(t)$ evolves under a physically realized operator $\mathcal{R}(t)$ (reaction channels and rates) coupled to environmental inputs $u(t)$ and feasibility constraints (scarcity/thermodynamics). The resulting worldline $\mathcal{W}$ is the entity in the EVOS sense.

7.7 Why DNA Is Not Merely a Storage Medium

DNA storage emphasizes density and persistence of symbols. EVOS emphasizes *evolution*: a persistent, open, memory-bearing trajectory whose boundary-crossing actions are irreversible and constrained.

Explicit claim (C7.7). Static DNA archival storage is not EVOS. DNA becomes an EVOS substrate only when embedded in an active reaction environment where dynamics, memory, and commitment boundaries are realized as chemical evolution under constraint.

7.8 Positioning Molecular EVOS

Molecular EVOS is the second canonical instantiation class alongside Digital EVOS:

- Digital EVOS: explicit governance, operator plug-ins, audit/provenance, civilization-scale coordination.
- Molecular EVOS: continuous fields, embodiment, thermodynamic commitment, reaction-network operators.

This positioning sets up **BIO-EVOS** (Section 8) as the resonance-field formalism specialized to DNA reaction networks, and motivates **Hybrid EVOS** (Section 10) as a coupling of digital policy/provenance with molecular commitments.

8 BIO-EVOS: DNA Resonance Fields

8.1 DNA Strands as Nodes in a Resonance Manifold

Section 7 established DNA reaction systems as admissible EVOS substrates. BIO-EVOS specializes GENESIS to molecular settings by treating DNA species (and complexes) as *nodes* embedded in a

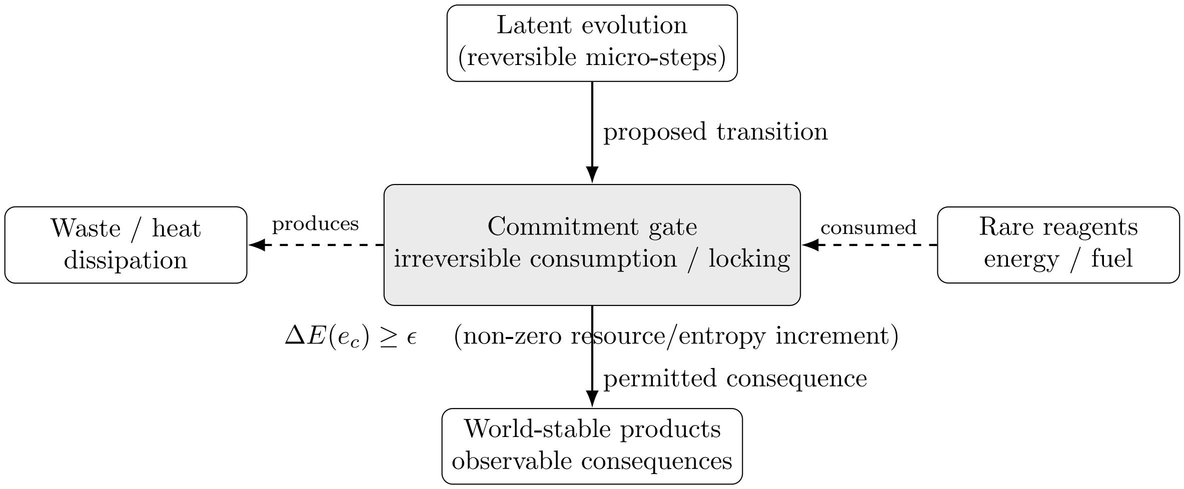


Figure 16: Commitment as a thermodynamic gate. In molecular EVOS, a commitment is a transition that consumes scarce resources and dissipates energy, making reversal infeasible without additional external work. This enforces an intrinsic arrow of time and anchors accountability in physical consequence.

continuous resonance manifold whose local geometry is determined by affinity, kinetics, and resource constraints.

Let $\mathcal{S} = \{S_1, \ldots, S_m\}$ denote the set of molecular species (single strands, complexes, catalysts). The *molecular state* is a concentration vector

$$x(t) \in \mathbb{R}^m_{\geq 0}, \qquad x_i(t) = \text{concentration of } S_i.$$

BIO-EVOS defines the entity not by a single $x(t)$ but by its worldline

$$\mathcal{W} = \{x(t) \mid t \in \mathbb{R}^+\},$$

together with a physically embodied memory (persistent complexes, long-lived species, and stabilized concentration patterns).

Explicit claim (C8.1). In BIO-EVOS, *node identity is dynamical*: a "node" may be a species, a family of related complexes, or a coarse-grained macrostate depending on observation resolution. The EVOS object remains the worldline and its causal event history.

8.2 Chemical Affinity as Resonance Potential

GENESIS uses resonance potentials to encode coupling strength. In BIO-EVOS, resonance is grounded in physical chemistry: binding energies, complementarity, and catalysis.

Define a resonance potential between species S_i and S_j:

$$\Phi_{ij} \;=\; \Phi(S_i, S_j) \;\propto\; -\Delta G_{ij},$$

where ΔG_{ij} is an effective free-energy change for the dominant interaction pathway between S_i and S_j. Larger Φ_{ij} indicates stronger coupling (higher likelihood of interaction and influence).

This turns the species set into a weighted coupling structure. Crucially, BIO-EVOS treats Φ as *primary* and graph edges as *derived* by thresholding or coarse-graining.

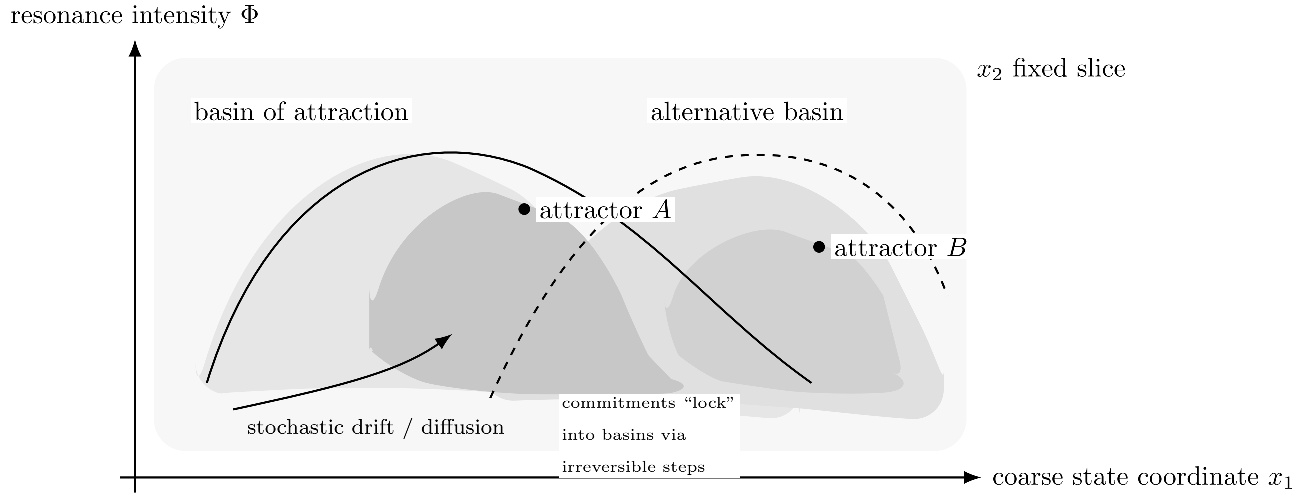


Figure 17: DNA resonance field with attractors. A coarse slice of the resonance intensity landscape Φ over molecular state coordinates shows basins and peaks (attractors). Stable molecular patterns correspond to attractors; drift/diffusion explores the landscape; commitment-like irreversible steps bias trajectories into specific basins.

Explicit claim (C8.2). A molecular resonance field is not a metaphor for similarity; it is the physically realized potential landscape that governs which reactions are feasible, which complexes persist, and which pathways become stable attractors.

8.3 Reaction Networks as Field Evolution

Let $\mathcal{R}(t)$ be the set of reaction channels available at time t, each with an effective rate (possibly state-dependent). The concentration dynamics follow:

$$\frac{dx(t)}{dt} = f(x(t); \mathcal{R}(t), u(t)),$$

with openness captured by $u(t)$ (influx, dilution, perturbation, measurement).

BIO-EVOS adds a field-level view: define a scalar resonance intensity functional $\Phi(x)$ measuring how strongly the current state sits within (or near) stable coupling configurations:

$$\Phi(x) \;=\; \sum_{i,j} w_{ij}\, g(x_i, x_j)\, \Phi_{ij},$$

for some monotone $g(\cdot)$ capturing co-presence and interaction opportunity, and weights w_{ij} encoding experimental design or environmental salience.

Then evolution can be interpreted as motion over a resonance landscape:

- **diffusion/drift:** stochastic molecular motion explores nearby states;
- **reaction:** local coupling reshapes concentrations and available channels;
- **selection:** resource constraints suppress unstable pathways.

Explicit claim (C8.3). BIO-EVOS provides an intrinsic notion of *meaningful persistence*: stable molecular patterns correspond to attractors in $\Phi(x)$ shaped jointly by affinity and constraint.

8.4 Commitments as Irreversible Molecular Events

Commitment is the EVOS boundary where latent evolution becomes externally binding and irreversible. In BIO-EVOS, commitments correspond to reactions with one or more of:

- **scarce reagent consumption** (depleting a limited pool),
- **dissipative steps** (non-negligible energy loss / heat),
- **topology changes** (creating products that rewire future reaction pathways),
- **kinetic trapping** (practically irreversible under ambient conditions).

Let $\mathcal{H}(t)$ be the event history. A commitment event e_c is defined by a monotone feasibility shift:

$$\mathcal{F}(t^+) \subsetneq \mathcal{F}(t^-),$$

where $\mathcal{F}(t)$ denotes the set of reachable future macrostates under available resources and constraints. Commitments reduce reachable futures—they are the physical analogue of binding decisions.

Explicit claim (C8.4). Commitments induce an arrow of time by shrinking feasible futures. This makes "policy" and "safety" physically interpretable in molecular systems as constraints on allowable reaction channels and irreversible resource expenditures.

8.5 Molecular Memory and Persistence

BIO-EVOS memory is embodied. Persistent species and complexes implement a memory state without external storage. A minimal model separates fast concentrations from slow persistent structure:

$$x(t) = \big(x_{\text{fast}}(t),\, x_{\text{slow}}(t)\big),$$

where x_{slow} includes long-lived complexes, catalysts, or stabilized products.

Persistence is "earned" by resonance stabilization: only patterns supported by the landscape (Fig. 17) and resource constraints survive perturbation.

Explicit claim (C8.5). In BIO-EVOS, forgetting and learning correspond to chemical decay and stabilization: memory is a dynamical balance between reinforcement (reaction flux) and dissipation (decay/dilution).

8.6 Emergent Molecular Intelligence

BIO-EVOS does *not* claim that any reaction mixture is intelligent. The EVOS definition of intelligence demands stable, coherent evolution under constraint, with memory and commitment-gated consequences.

In molecular terms, this corresponds to:

- **coherence:** trajectories remain within viable basins despite noise,
- **adaptation:** the effective operator $\mathcal{R}(t)$ can change via produced catalysts/inhibitors,
- **accountability:** irreversible events are identifiable in causal history,
- **constraint compatibility:** dynamics respect scarcity and thermodynamic feasibility.

Explicit claim (C8.6). "Intelligence" in BIO-EVOS is the existence of stable, constraint-compatible attractor dynamics that can be steered by commitments and maintained through embodied memory.

8.7 Relation to Digital EVOS and Hybridization

BIO-EVOS and Digital EVOS are complementary:

- Digital EVOS excels at explicit governance: audit logs, policy gates, operator hot-swap protocols.
- BIO-EVOS excels at embodied continuous dynamics: parallelism, physical commitments, and natural field evolution.

This motivates Hybrid EVOS (Section 10): digital policy/provenance can constrain and audit molecular commitments, while molecular commitments can ground digital actions in physical irreversibility.

9 DNA-Based Language and Meaning

This section sharpens a central EVOS claim: *meaning is not a token property; it is a stability property of trajectories under constraints.* In BIO-EVOS, "language" is not a discrete symbol stream manipulated by an external interpreter. It is an embodied high-arity interaction system whose semantics emerge as *stable reaction pathways* and *attractor basins* in the resonance field.

9.1 Language as Resonance, Not Tokens

Classical language models formalize language as sequences of tokens with conditional distributions. In EVOS terms, that is a *snapshot* view: the semantics are implicitly external (in training data, loss functions, and evaluation tasks).

BIO-EVOS proposes an internalist criterion:

> *A symbol is meaningful only insofar as it reliably induces a constrained, history-dependent trajectory in the substrate.*

Concretely, a "statement" in DNA language is not an inert string. It is a molecular configuration that couples to a reaction network and changes the feasible future set.

Explicit claim (C9.1). In BIO-EVOS, semantics are physically realized: meaning corresponds to *basin membership and pathway stability* in the resonance field, not to discrete identifiers.

9.2 Codons as High-Arity Semantic Units

Binary symbols are an engineering convenience. Molecular substrates naturally support higher-arity alphabets (bases, k-mers, motifs) whose combinatorics provide dense addressing and interaction specificity.

Let Σ be an alphabet (e.g., $\{A, C, G, T\}$) and let k be a chosen arity. Define a codon space

$$\Sigma^k = \{s_1 s_2 \cdots s_k \mid s_i \in \Sigma\}, \qquad |\Sigma^k| = |\Sigma|^k.$$

A codon $c \in \Sigma^k$ is a *semantic unit* only if it induces a reproducible coupling signature under the current field:

$$c \mapsto \text{interaction profile } \pi(c; \Phi, \mathcal{C}),$$

where Φ is the resonance potential landscape (Section 8.2) and $\mathcal{C}$ denotes constraints (scarcity, temperature, catalysts, policies).

Explicit claim (C9.2). High-arity codons enable semantics by *selective coupling*: meaning is encoded in which channels become feasible and which pathways become stabilized.

9.3 Grammar as Chemical Constraint

Grammar in BIO-EVOS is not a set of rewrite rules; it is the constraint structure that determines which compositions are physically admissible and which compositions are evolutionarily stable.

We represent a molecular "sentence" as a multiset of species and motifs:

$$\mathcal{X} = \{(S_i, x_i)\}_{i=1}^{m},$$

and define a grammar constraint functional

$$\Gamma(\mathcal{X}) \leq 0$$

encoding feasibility: stoichiometry, complementarity, kinetic accessibility, and resource limits. Only $\mathcal{X}$ satisfying $\Gamma(\mathcal{X}) \leq 0$ are admissible.

Explicit claim (C9.3). BIO-EVOS grammar is substrate-governed: "well-formedness" is feasibility under physical and resource constraints, not syntactic legality alone.

9.4 Meaning as Stable Reaction Pathways

Let $\mathcal{P}$ denote a reaction pathway (a sequence of channel firings) from an initial macrostate x_0 to an outcome region Ω in state space:

$$x_0 \overset{\mathcal{P}}{\Longrightarrow} \Omega.$$

BIO-EVOS defines meaning via *pathway stability* under perturbation. Let $u(t)$ be environmental perturbations (noise, dilution, injections). A pathway is meaningful if:

$$\Pr[x(t) \in \Omega \text{ for some } t \leq T \mid x(0) = x_0, u(\cdot)] \;\geq\; 1 - \epsilon,$$

for a small ϵ across a perturbation class.

Thus, a "semantic interpretation" is not a decoding table; it is an attractor target.

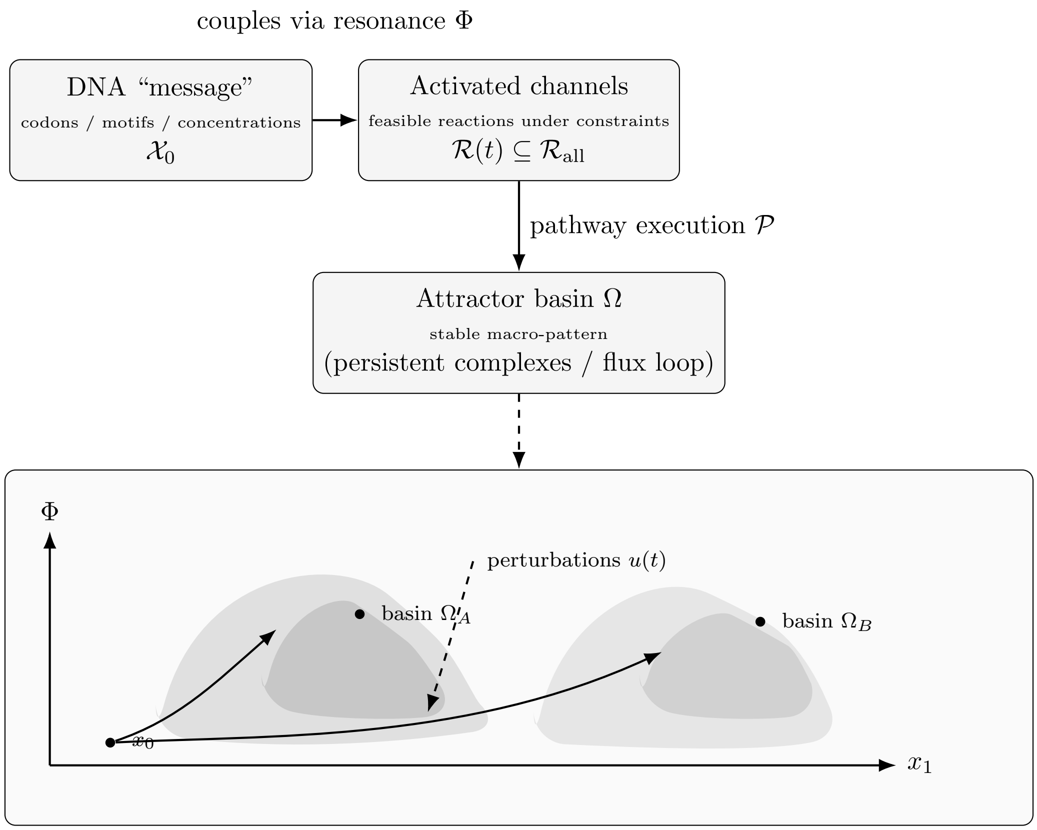
Explicit claim (C9.4). Meaning in BIO-EVOS is *attractor-directed*: a molecular message is meaningful if it reliably drives the system into a constrained attractor basin that persists.

9.5 Why DNA Language Is Not a Transformer

Transformers implement learned conditional distributions over token sequences. BIO-EVOS "language" is a dynamical system:

- **stateful by physics:** memory is embodied in persistent complexes and concentrations,
- **non-symbolic semantics:** meaning is basin stability, not decoding,
- **commitment-gated:** irreversible reagent expenditure anchors consequences,
- **open and interactive:** environmental injections and measurements are part of the computation.

Explicit claim (C9.5). Token prediction can imitate language; BIO-EVOS aims to *instantiate* semantics as substrate-stable attractor dynamics constrained by irreversible commitments.



Constraints $\mathcal{C}$ (scarcity, temperature, catalysts, policy) shape feasible channels and stabilize basins.

Figure 18: Meaning as a reaction-attractor. A DNA "message" $\mathcal{X}_0$ couples into the resonance landscape via Φ, activating a constrained set of channels $\mathcal{R}(t)$ that realize pathways $\mathcal{P}$ leading to stable basins (semantic outcomes). Semantics is pathway stability under perturbation, not token identity.

9.6 Comparison with Digital Language Models

Digital LMs can be embedded into EVOS (as transition operators) but do not, by default, satisfy the BIO-EVOS semantics criterion. In EVOS terms:

- LMs provide rich *proposal dynamics* (latent evolution),
- EVOS provides *commitment boundaries*, *provenance*, and *constraint compatibility*,
- BIO-EVOS provides an *embodied* semantics where meaning is physically anchored.

This is not a competition but a compositional relationship: digital agents can *govern* molecular semantics by constraining channels and authorizing commitments.

9.7 Implications for Artificial Intelligence

BIO-EVOS suggests an AI research direction orthogonal to scale:

- semantics as stability, not supervision;
- learning as field plasticity, not parameter fitting alone;
- alignment as constraint compatibility at commitment boundaries;

- interpretation as basin identification and causal lineage.

Explicit claim (C9.6). If semantics is attractor stability under constraint, then robust meaning requires *control of commitments and constraints*—a governance problem as much as a modeling one.

9.8 Position Within EVOS

Section 9 completes the molecular arc:

- Section 7: DNA as a computational substrate (transition physics);
- Section 8: BIO-EVOS as a resonance-field dynamical system (attractors and commitments);
- Section 9: DNA "language" where meaning is basin-stable pathway dynamics.

10 Bio-Digital Hybrid EVOS

BIO-EVOS is powerful precisely because it is *embodied*: time, energy, and irreversibility are native. Digital EVOS is powerful because it is *programmable*: policies, audits, and institutional structures can be made explicit. A *Hybrid EVOS* binds these strengths into a single evolutionary open system.

The hybrid thesis is simple:

> *Digital systems excel at governance and long-horizon planning; molecular systems excel at massively parallel, physically anchored evolution. Hybrid EVOS couples them through event translation and commitment propagation.*

10.1 Motivation for Hybridization

A purely digital agent can simulate consequences, but its semantics are typically *externally grounded* (data, evaluation, human interpretation). A purely molecular system can instantiate physically grounded trajectories, but it is difficult to govern, audit, and steer at civilization scale.

Hybridization is therefore not a convenience; it is the minimal architecture for *Turing-grade accountability* in open-ended intelligence: the system must both *act in irreversible reality* and *remain institutionally governable.*

Explicit claim (C10.1). A Hybrid EVOS can realize *physically anchored semantics* while enforcing *commitment-gated governance* and *causal provenance* across substrates.

10.2 Event Translation Across Substrates

Let $\mathcal{E}^D$ denote digital events (logs, commitments, policy updates) and $\mathcal{E}^M$ denote molecular events (reactions, measurements, injections). A Hybrid EVOS requires a bidirectional translation interface:

$$\tau_{D\to M} : \mathcal{E}^D \to \mathcal{E}^M, \qquad \tau_{M\to D} : \mathcal{E}^M \to \mathcal{E}^D.$$

The translation is *not* a semantic decoder; it is a *control and observation* boundary with three invariants:

1. **Causal anchoring:** translated events must carry provenance pointers;
2. **Monotonic history:** translations append to history; they do not rewrite it;
3. **Commitment gating:** translations that can cause irreversible consequences must pass a gate.

Minimal formalism. Let $\mathcal{H}^D(t)$ and $\mathcal{H}^M(t)$ be the digital and molecular histories. The hybrid global history is the disjoint union with explicit cross-edges:

$$\mathcal{H}^H(t) = \mathcal{H}^D(t) \ \cup \ \mathcal{H}^M(t) \ \cup \ \mathcal{L}(t),$$

where $\mathcal{L}(t)$ is the set of *link events* encoding τ mappings and provenance.

10.3 Commitment Propagation Between Worlds

Commitments are the EVOS reality boundary (Section 2). In a hybrid system, commitments must propagate across substrates without losing accountability.

We distinguish:

- **Digital commitments** e_c^D: policy-authorized external actions (API calls, transactions),
- **Molecular commitments** e_c^M: irreversible reagent consumption or channel activation.

A Hybrid EVOS enforces the following propagation rule:

Hybrid commitment rule (HCR). If an event in one substrate causes an irreversible consequence in the other, then a commitment event must exist in the origin substrate and a linked commitment must be recorded in the destination substrate:

$$e_c^D \xrightarrow{\tau_{D\to M}} e_c^M \quad \text{or} \quad e_c^M \xrightarrow{\tau_{M\to D}} e_c^D,$$

with a provenance link $\ell \in \mathcal{L}$ binding them.

Explicit claim (C10.2). Hybrid EVOS prevents "orphan consequences": every irreversible cross-substrate effect has a commitment ancestor and a link record.

10.4 Temporal Decoupling and Synchronization

Hybrid EVOS is inherently multi-rate. Digital control loops may operate at milliseconds to seconds; molecular kinetics may operate from microseconds to hours.

Let Δt_D and Δt_M be characteristic update scales. Hybrid stability requires synchronization mechanisms:

- **Sampling:** periodic or event-triggered observation $M \to D$;
- **Staging:** batched control injections $D \to M$ to respect kinetics;
- **Clock abstraction:** histories are partially ordered (not globally clocked).

Minimal formalism. Hybrid time is a partially ordered set of events with causal precedence $\prec$ rather than a single clock. Consistency requires:

$$e_1 \prec e_2 \ \Rightarrow \ \text{timestamp}(e_1) < \text{timestamp}(e_2) \text{ within each substrate},$$

and cross-substrate links preserve $\prec$.

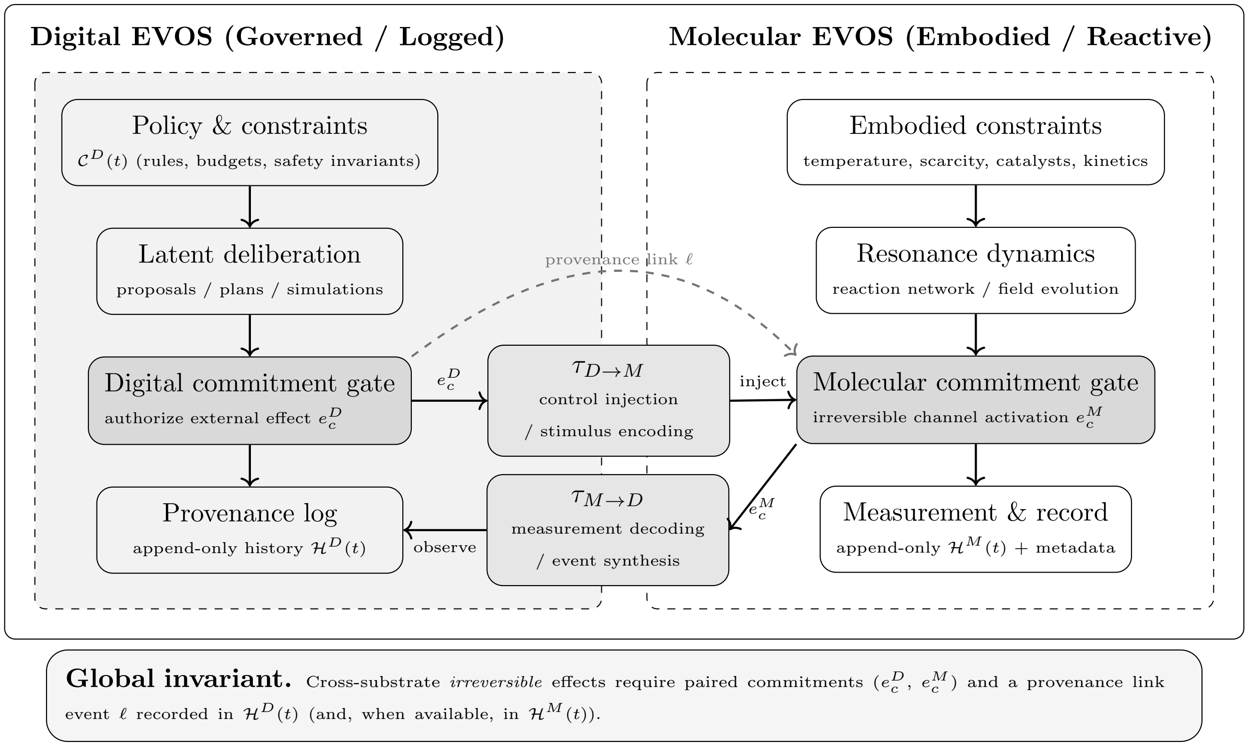


Figure 19: Hybrid EVOS event coupling (rectangular layout). Digital governance (policy, deliberation, commitment, provenance) couples to molecular embodiment (constraints, resonance dynamics, molecular commitment, measurement) through translation operators $\tau_{D\to M}$ and $\tau_{M\to D}$. Cross-substrate irreversible effects are commitment-gated and provenance-linked.

10.5 Division of Cognitive Labor

Hybrid EVOS naturally separates roles:

- **Digital layer:** long-horizon planning, policy reasoning, audit, coordination;
- **Molecular layer:** massively parallel search, embodied semantics, physical commitments;
- **Interface:** translation, calibration, uncertainty quantification, safety gates.

This division is not optional if the system is to be both powerful and governable.

10.6 Learning Loops Across Substrates

Hybrid learning is a *closed evolutionary loop across an open boundary*: digital policies shape molecular trajectories; molecular outcomes reshape digital models and constraints.

Let Θ^D denote digital operator parameters and Θ^M denote molecular control parameters (injection schedules, catalyst allocations). A hybrid learning loop couples:

$$(\Theta^D_{t+1}, \mathcal{C}^D_{t+1}) = \mathsf{Update}(\Theta^D_t, \mathcal{C}^D_t,\ \tau_{M\to D}(\mathcal{E}^M)),$$

$$(\Theta^M_{t+1}, \mathcal{C}^M_{t+1}) = \mathsf{Act}(\Theta^M_t, \mathcal{C}^M_t,\ \tau_{D\to M}(\mathcal{E}^D)).$$

Explicit claim (C10.3). Hybrid EVOS learning is *constraint co-evolution*: policies and physical control parameters co-adapt under irreversible commitment histories.

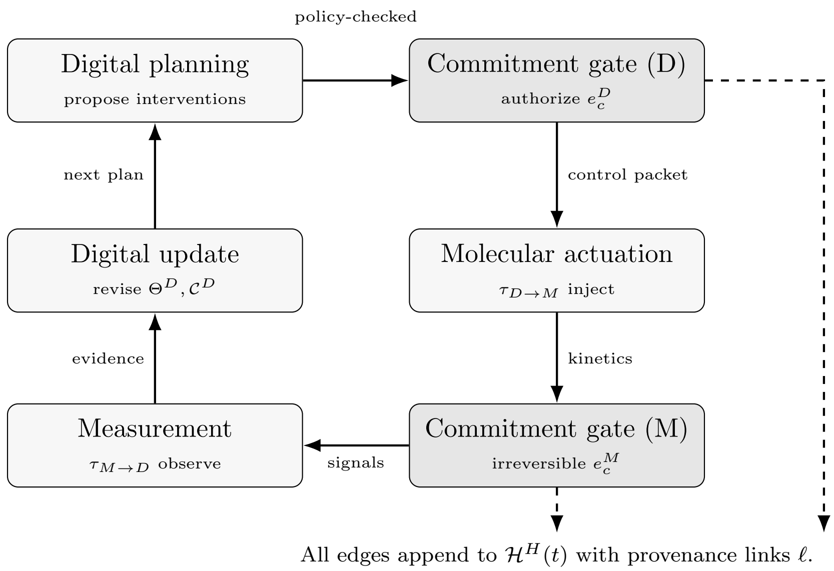


Figure 20: Cross-substrate learning loop. Digital planning proposes actions, but only commitments authorize irreversible effects. Molecular dynamics executes under physical constraints; measurements return evidence to update digital operators and policies. The hybrid history records provenance across the loop.

10.7 Safety, Governance, and Auditability

Hybrid EVOS strengthens safety by making both worlds legible:

- **Digital enforceability:** explicit policies, staged rollouts, regression invariants;
- **Molecular irreversibility:** physical scarcity and thermodynamic gates limit silent escalation;
- **Audit closure:** provenance links bind commitments to consequences across substrates.

Explicit claim (C10.4). Hybrid EVOS enables *auditable embodiment*: physically grounded commitments with digitally enforceable governance.

10.8 Why Hybrid EVOS Matters

Hybrid EVOS is not "bio + digital" as an engineering mashup; it is the minimal instantiation of EVOS universality:

- open-world interaction,
- non-termination with history,
- irreversible commitments,
- substrate-independent but substrate-respecting semantics.

It creates a path to systems that are simultaneously: *powerful*, *physically grounded*, and *governable.*

11 Projection, Perception, and Observation

EVOS is defined at the level of *worldlines* evolving under constraints and commitments. However, any scientific, operational, or governance interaction with an EVOS occurs through *observations*. Observations are never the worldline itself. They are *projections*: lossy, instrument-dependent mappings from high-dimensional latent evolution to a lower-dimensional interface.

This section makes three explicit claims:

1. **Projection is structural:** there is no observer without a projection map; what you can "see" is defined by Π.
2. **Uncertainty is physical:** ambiguity arises from lossy projection, stochasticity, and observer participation; it is not merely epistemic bookkeeping.
3. **Accountability binds to events:** externally meaningful conclusions must be anchored to explicit events in the causal history, not to unconstrained latent inference.

11.1 Projection Manifolds

Let $(Z(t), M(t))$ denote the EVOS extended latent state (state + intrinsic memory), and let $\mathcal{W} = \{(Z(t), M(t)) \mid t \in \mathbb{R}^+\}$ be the worldline.

An observer does not access $(Z(t), M(t))$ directly. Instead, an observation stream is generated by a projection operator

$$Y(t) = \Pi\big(Z(t), M(t); \Omega\big),$$

where Ω encodes *observer parameters* (instrumentation, sensor physics, sampling regime, access controls, and allowed queries). The image of Π defines an *observation manifold*

$$\mathcal{M}_\Pi \;=\; \{\, Y \mid Y = \Pi(z, m; \Omega),\; (z, m) \in \mathcal{S} \times \mathcal{M} \,\}.$$

Operational consequence. Two observers with different Ω need not agree on what the "same" EVOS is doing, even when the underlying worldline is identical. Agreement requires either: (i) shared Π (shared measurement and access), or (ii) a reconciliation protocol that translates between observation manifolds.

11.2 Lossy Nature of Projection

Projection is lossy in three distinct senses:

- **Dimensional loss:** $Y(t)$ typically has far fewer degrees of freedom than $(Z(t), M(t))$.
- **Temporal loss:** sampling discretizes continuous evolution; aliasing and missed events are structural risks.
- **Semantic loss:** many latent distinctions map to identical observations (non-injectivity).

Formally, Π is generally non-invertible: there exist $(z_1, m_1) \neq (z_2, m_2)$ such that $\Pi(z_1, m_1; \Omega) = \Pi(z_2, m_2; \Omega)$. Consequently, "state estimation" is a *set-valued* problem: from $Y(t)$ one recovers a posterior *equivalence class* of plausible latent states.

11.3 Human, AI, and Instrument Perception

We distinguish three common observer regimes by their Ω:

1. **Human perception:** high-level summaries, UI affordances, narrative compression.
2. **AI perception:** feature-rich streams, embeddings, learned sensors, adaptive querying.

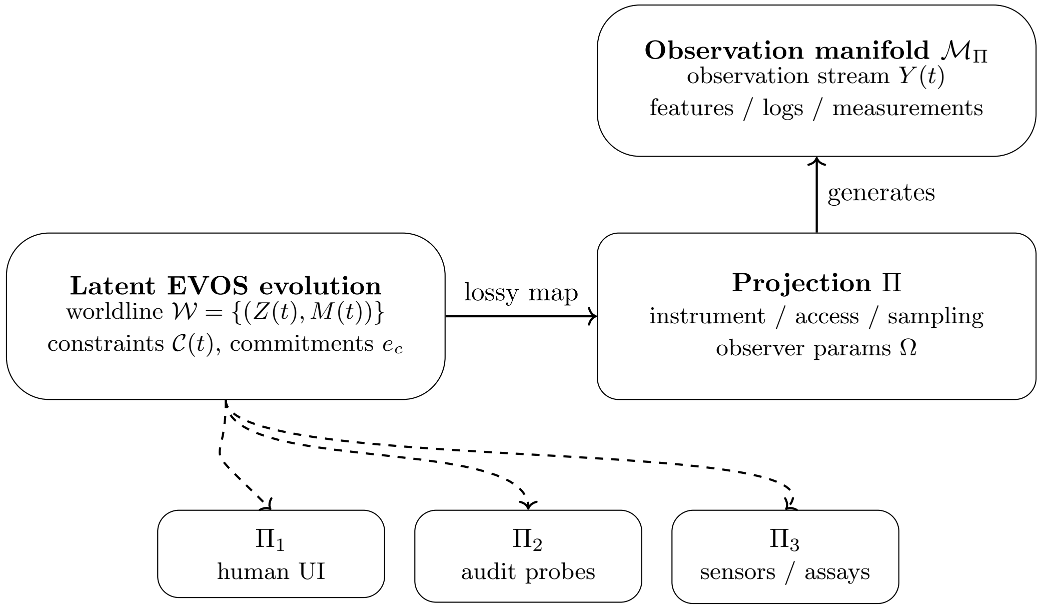


Figure 21: Projection manifold. The EVOS worldline evolves in latent space, but observers interact through a projection $\Pi(\cdot;\Omega)$ that induces an observation manifold $\mathcal{M}_\Pi$. Different observers instantiate different projections, producing partially incompatible views that must be reconciled via translation or shared event anchors.

3. **Instrument perception:** physically constrained measurements (assays, sensors, telemetry).

EVOS does not privilege any regime. It requires that each observer declare (explicitly or implicitly) the projection Π it uses, because *claims are only meaningful relative to* Π.

11.4 Uncertainty and Confidence

Uncertainty arises from (i) projection loss, (ii) process noise in the evolution law, and (iii) observer participation. A minimal formalism is:

$$Y(t) \;=\; \Pi\big(Z(t), M(t); \Omega\big) \;+\; \varepsilon(t),$$

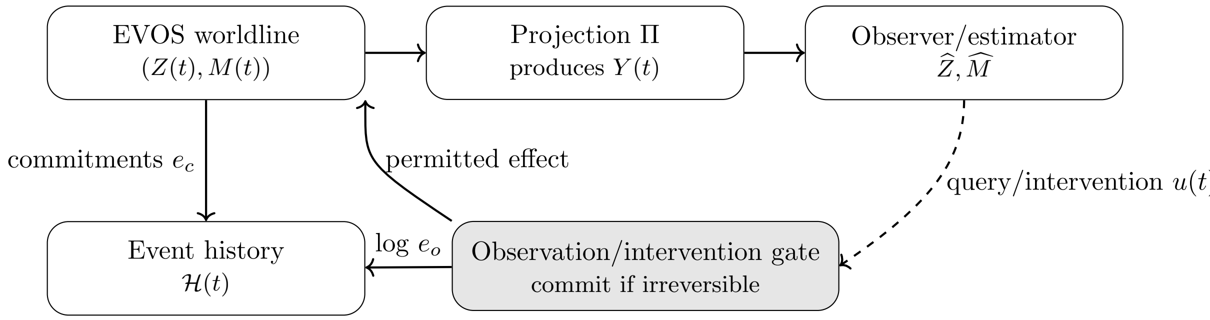
where $\varepsilon(t)$ captures observation noise and unmodeled projection error.

Let $\widehat{Z}(t), \widehat{M}(t)$ be an estimator derived from $Y(\cdot)$. EVOS treats confidence as a property of *inference under declared projection*, not as an intrinsic scalar attached to the worldline. Practically, confidence should be reported as:

- the assumed projection Π and observer parameters Ω,
- the uncertainty model for $\varepsilon(t)$,
- the posterior set (or distribution) over latent hypotheses.

11.5 Observation as a Physical Process

Observation is not passive. Measurement consumes time, attention, bandwidth, and in molecular systems, reagents and energy. We therefore model observation as an *eventful interaction*:



In EVOS, both *acting* and *measuring* can be causal and must be audited.

Figure 22: Observation and uncertainty with feedback. Observations arise through a declared projection Π, while queries/interventions $u(t)$ may feed back into evolution. Any observation or intervention with irreversible effect must cross an explicit gate and be recorded as an event in $\mathcal{H}(t)$.

$$e_o: \quad (Z, M) \xrightarrow{\text{measure}} (Z', M') \quad \text{and} \quad Y \in \mathcal{M}_\Pi.$$

This has a crucial consequence: observation belongs inside the causal fabric $\mathcal{H}(t)$. If measurement can affect evolution, then the observer is part of the environment.

11.6 Observer Participation and Feedback

When observers can query, steer, or perturb an EVOS, the projection becomes coupled to evolution. A minimal coupled form is:

$$(Z(t + \Delta t), M(t + \Delta t)) = \Phi\big(Z(t), M(t), \mathcal{E}(t), \mathcal{C}(t), u(t)\big),$$

where $u(t)$ is an observer-induced input (queries, interventions, sampling decisions).

In high-stakes deployments, $u(t)$ must itself be commitment-gated when it can induce irreversible effects (e.g., expensive actions, biological perturbations, or policy-triggered changes).

11.7 Why Projection Matters

Projection is the bridge between EVOS theory and practice:

- **Science:** experiments are choices of Π; reproducibility requires declaring Ω.
- **Engineering:** interfaces, logs, and sensors define what can be monitored and controlled.
- **Governance:** audits and accountability require event-anchored claims under explicit projections.

In short: *worldlines are primary, but projections are the only handle we have.* Turing-grade systems must therefore treat projection design as a first-class component of intelligence, not an afterthought of instrumentation.

12 Learning, Evolution, and Selection

EVOS explains intelligence as *stable evolution under constraint.* This immediately raises a non-negotiable question: *how do stable trajectories arise in open, noisy, irreversible worlds?* The answer is selection—not only biological selection, but a general mechanism by which *trajectories, operators, and institutions* are stabilized (or eliminated) under constraint.

This section makes four explicit claims:

1. **Learning is operator evolution:** learning updates the evolution law, not merely the state.
2. **Fitness is stability:** "success" is measured by sustained constraint satisfaction over time.
3. **Selection is field-theoretic:** selection acts by reshaping the resonance landscape (attractors, basins, barriers).
4. **EVOS selection is multi-level:** it simultaneously selects trajectories, operators, and collectives (institutions/civilizations).

12.1 Learning as Evolution of Dynamics

In classical ML, "learning" is parameter optimization for a fixed architecture. In EVOS, learning is the broader phenomenon of *dynamics change* under experience.

Let $(Z(t), M(t))$ be latent state and intrinsic memory. Let $\Theta(t)$ parameterize the active evolution operator $F(\cdot;\Theta)$. The minimal EVOS learning form is a coupled system:

$$(Z(t+\Delta t), M(t+\Delta t)) = F\big(Z(t), M(t), \mathcal{E}(t), \mathcal{C}(t); \Theta(t)\big), \tag{5}$$
$$\Theta(t+\Delta t) = U\big(\Theta(t), Z(t), M(t), \mathcal{H}(t), \mathcal{C}(t)\big), \tag{6}$$

where $\mathcal{H}(t)$ is the event history and $\mathcal{C}(t)$ are constraints (policy, resources, ethics, safety). The point is structural: *an EVOS is permitted to change its own law*, but only in ways that remain causally anchored and commitment-auditable (Section 11).

12.2 Fitness as Stability Under Constraint

EVOS rejects fitness as a one-shot objective value. Fitness is *trajectory viability.*

Let $\Phi(\mathcal{W}_{[0,T]})$ be a constraint-violation functional over a finite horizon:

$$\Phi(\mathcal{W}_{[0,T]}) = \int_0^T \phi\big(Z(t), M(t), \mathcal{C}(t)\big)\, dt \; + \sum_{e\in\mathcal{H}_{[0,T]}} \psi(e),$$

where ϕ penalizes constraint violations continuously and ψ assigns event-level penalties (e.g., unsafe commitments, budget overruns, broken contracts).

A viable ("fit") EVOS maintains bounded violation:

$$\sup_{T\geq 0} \Phi(\mathcal{W}_{[0,T]}) \;<\; \infty,$$

or, in stronger regimes, achieves asymptotic stability:

$$\limsup_{T\to\infty} \frac{1}{T}\, \Phi(\mathcal{W}_{[0,T]}) \;=\; 0.$$

This is the minimal formal translation of "stable evolution under constraint" into a selection criterion.

Selection as resonance stabilization (concept)

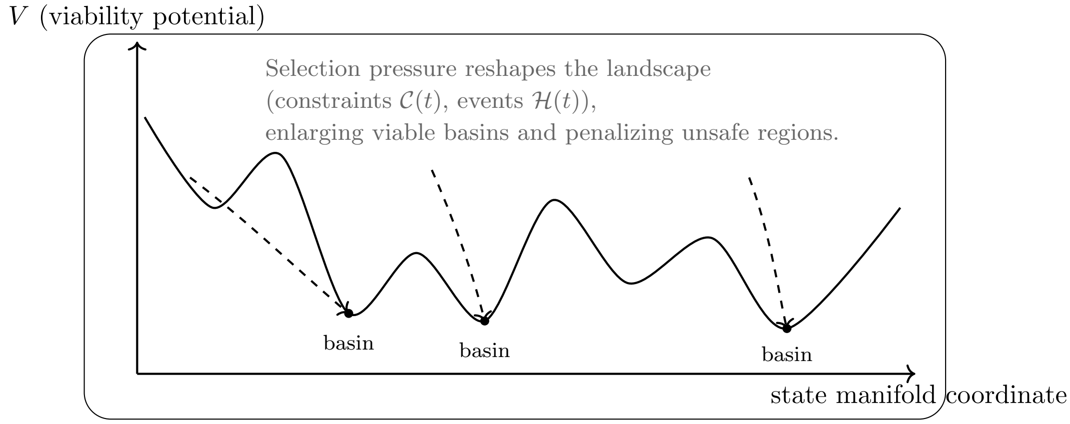


Figure 23: Selection via resonance stabilization (concept). A viability potential V induces basins (stable regimes) toward which trajectories drift. In EVOS/GENESIS, selection acts by reshaping this landscape through constraints, event-anchored penalties, and operator adaptation.

12.3 Selection Pressure in Resonance Fields

Within GENESIS, evolution is guided by a resonance field (a landscape of potentials, couplings, and constraints). Selection pressure appears as *landscape shaping*: paths that reduce sustained violation become attractors; paths that amplify violation become repellors or dead ends.

A minimal representation is a *viability potential* V over extended state:

$$V(Z, M, t) \;\equiv\; \mathbb{E}\Big[\Phi(\mathcal{W}_{[t,\infty)}) \mid Z(t) = Z,\, M(t) = M\Big],$$

where lower V indicates higher long-run viability. Selection then acts to reduce V by: (i) steering trajectories, and (ii) rewriting operators Θ so that future trajectories naturally drift toward low-V basins.

12.4 Diagram: Selection via Resonance Stabilization

Figure 23 is the minimal field-theoretic intuition needed for EVOS: *learning is not only moving within a landscape, but also reshaping it.*

12.5 Multi-Level Selection

Selection acts at multiple nested levels:

- **Trajectory selection:** which worldlines persist vs. terminate under constraint.
- **Operator selection:** which evolution laws $F(\cdot;\Theta)$ remain deployed (Section 5).
- **Institution selection:** which norms/contracts/policies persist in multi-agent systems (Section 6, Section 13).

This explains why "intelligence" scales: individual agents stabilize strategies; groups stabilize norms; civilizations stabilize institutions. All are EVOS phenomena, differing only in the substrate and granularity of events and constraints.

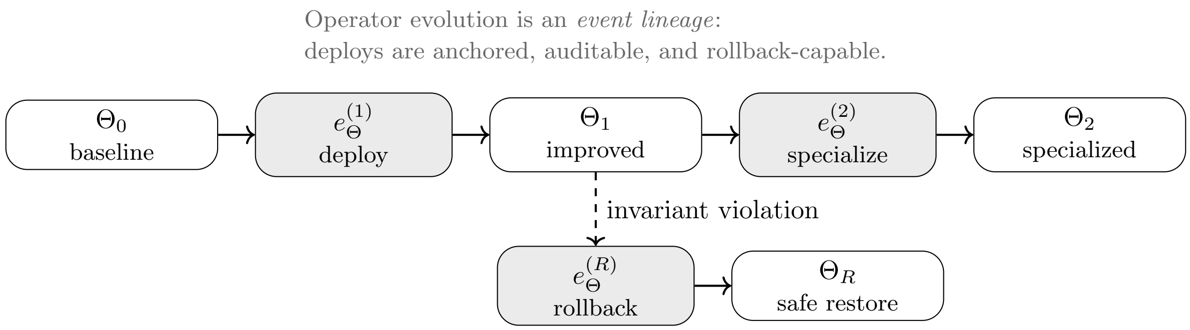


Figure 24: Evolution of operators as event lineage. Each deployed evolution law update is anchored by an immutable event e_Θ, enabling auditing, reconstruction, and rollback under invariant violations.

12.6 Evolution of Evolution Laws

An EVOS permits $\Theta(t)$ to change, but changes must be *causally anchored* and *operationally safe*. We therefore treat operator evolution as an eventful lineage process: each materially deployed operator update is recorded as an immutable event e_Θ in history.

Let Θ_k denote the kth deployed operator regime. Then operator evolution is a sequence

$$\Theta_0 \xrightarrow{e_\Theta^{(1)}} \Theta_1 \xrightarrow{e_\Theta^{(2)}} \cdots$$

with rollbacks and branches permitted under invariant violations (cf. runtime substitution protocols).

12.7 Diagram: Evolution of Operators

Figure 24 shows the minimal lineage structure required for Turing-grade auditability: the evolution of the evolution law must itself be a first-class, event-anchored process.

12.8 Exploration, Exploitation, and Diversity

Open-ended intelligence requires *diversity preservation* under constraint. In EVOS terms, this means maintaining multiple viable basins and trajectories rather than collapsing prematurely.

A minimal policy-compatible formulation is to treat exploration as controlled stochasticity that is bounded by invariants:

$$\Theta(t + \Delta t) = \Theta(t) + \eta \nabla_\Theta \mathcal{L}(t) + \sigma(t)\, \xi(t),$$

with $\sigma(t)$ constrained so that expected violation remains bounded and any externally relevant behavioral shift is commitment-anchored.

12.9 Comparison with Conventional Learning Paradigms

Conventional paradigms appear as special cases:

- **Supervised learning:** U updates Θ to reduce a labeled loss; constraints are implicit.
- **RL:** reward becomes a proxy for (partial) viability; unsafe reward hacking is a constraint failure.
- **Evolutionary algorithms:** population-level U selects operators by survival under task/environment.

- **Continual learning:** explicitly acknowledges non-stationarity, but often lacks commitment accountability.

EVOS unifies them by placing all learning inside the same structure: worldlines, constraints, commitment events, and causal provenance.

12.10 Why Learning and Selection Complete EVOS

EVOS without selection is descriptive; EVOS with selection is generative. Selection provides the mechanism by which:

- coherent behavior persists in open environments,
- unsafe or unstable dynamics are eliminated,
- operator evolution becomes cumulative rather than chaotic,
- civilizations and institutions become stable higher-order objects.

Together with the commitment boundary, selection is the second universal constraint of intelligence: *commitment makes consequences real; selection makes consequences matter over time.*

13 Safety, Ethics, and Governance

EVOS is not a theory of "safe outputs"; it is a theory of *safe irreversible processes.* In an open system, the dominant risk is not that an agent generates a wrong internal belief, but that it *crosses into the world* in a way that is unaccountable, unbounded, or irreversible in the wrong direction.

This section makes five explicit claims:

1. **Irreversibility is the core safety constraint.** Safety must be defined on worldlines, not snapshots.
2. **Cognition and action must be separable.** The commitment boundary is a structural safety primitive.
3. **Policy is an evolutionary constraint.** Governance is a time-varying constraint functional, not a static rulebook.
4. **Accountability requires causal provenance.** Every world effect must be traceable through event lineage.
5. **Pluralism is necessary.** Ethics is not a single objective; EVOS must support constraint sets and governance modes.

13.1 Irreversibility as the Core Safety Constraint

Classical "AI safety" discussions often focus on predictive error, misalignment, or distribution shift in outputs. EVOS reframes safety as a property of *trajectory* under commitment.

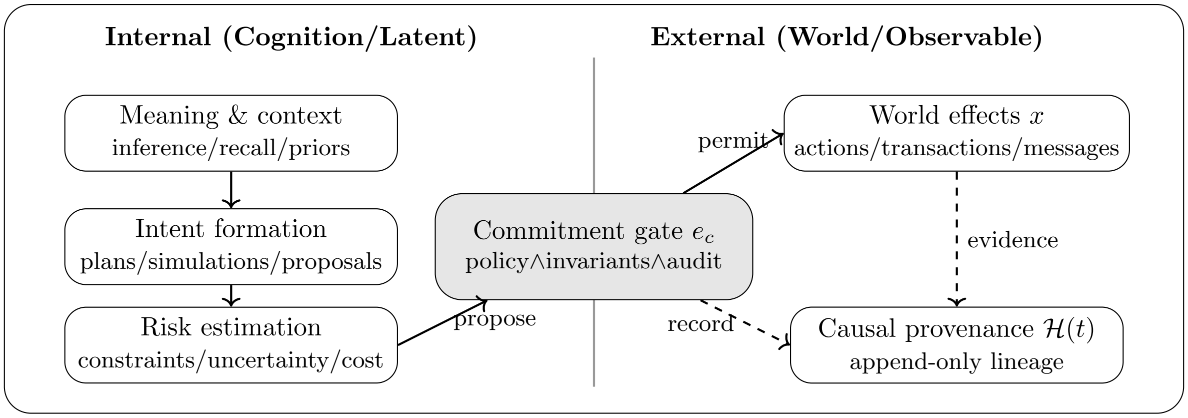
Let $\mathcal{H}(t)$ be the append-only event history and $\mathcal{W}$ the worldline. Irreversibility is the monotonic growth of history:

$$\mathcal{H}(t_1) \subset \mathcal{H}(t_2) \quad \text{for } t_1 < t_2.$$

Safety is therefore the property that worldline evolution remains within a constraint envelope:

$$\forall T \geq 0 : \quad \Phi(\mathcal{W}_{[0,T]}) \leq B,$$

where Φ is a violation functional (Section 12.2) and B is a governance-determined bound.



Invariant: no externally observable consequence may occur without an explicit commitment event e_c that is policy-checked and recorded in provenance.

Figure 25: Commitment boundary as a safety gate. Latent deliberation remains internal; any world effect must cross an explicit commitment gate constrained by policy/invariants and recorded in causal provenance.

13.2 Separation of Cognition and Action

EVOS requires a structural separation between:

- **Latent deliberation:** simulation, proposal generation, internal planning, counterfactual reasoning.
- **World action:** any effect that changes external state, spends resources, commits contracts, or alters other agents.

The only permitted crossing is an explicit *commitment event* e_c. This is not a UI feature; it is a computational invariant.

13.3 Policy as an Evolutionary Constraint

Governance is not a static filter. In open systems, the constraint environment changes: laws evolve, institutional rules update, budgets change, and safety envelopes tighten after incidents.

We model governance as a time-varying constraint process $\mathcal{C}(t)$ and policy state $P(t)$. The commitment gate must evaluate a *policy predicate* Allow:

$$\mathrm{Allow}(Z(t), M(t), P(t), \mathcal{H}(t), a) \in \{0, 1\},$$

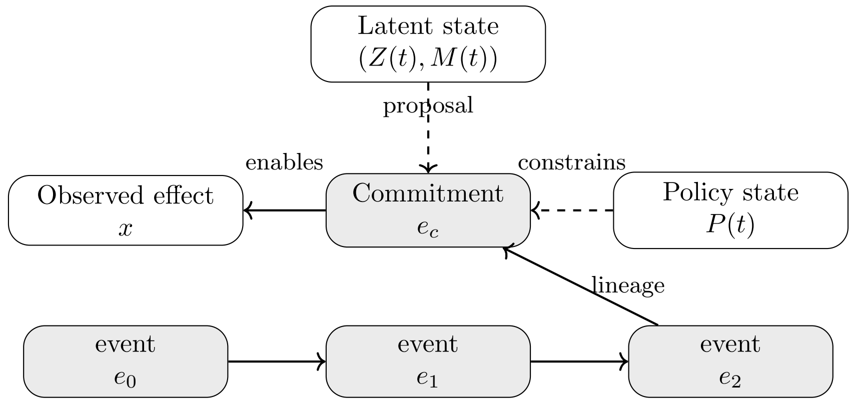
where a is the proposed action (or action family). Policy changes must themselves be events e_P recorded in history:

$$P(t + \Delta t) = \mathrm{Update}\big(P(t), e_P\big), \qquad e_P \in \mathcal{H}(t + \Delta t).$$

This ensures that governance is auditable as part of the worldline.

13.4 Accountability and Provenance

EVOS defines accountability as *traceability of consequence*.



Accountability chain: x must trace back through e_c to an auditable event lineage under policy $P(t)$.

Figure 26: Provenance and accountability chain. World effects must be traceable to explicit commitments and an event lineage consistent with the active policy state.

For any world effect x observed at time t, EVOS requires an event-anchored causal chain:

$$\exists\, \pi = (e_0 \prec e_1 \prec \cdots \prec e_k) \subset \mathcal{H}(t) \quad \text{such that} \quad e_k = e_c \;\wedge\; e_c \Rightarrow x,$$

where $\prec$ is the causal precedence relation and e_c is the commitment event enabling x.

13.5 Containment and Scope Control

Because EVOS is open and self-modifying, containment must be defined operationally:

- **Scope:** which action families are even eligible for commitment (capability contracts).
- **Budget:** hard resource envelopes (time/compute/money/permissions).
- **Blast radius:** staged rollout for operator or policy changes (canary & rollback).
- **Observation:** mandatory telemetry + immutable logs for external effects.

These are not "controls around AI"; they are part of the EVOS transition law.

13.6 Ethical Diversity and Pluralism

Ethics cannot be collapsed into a single scalar objective without encoding the biases of that scalar. EVOS therefore supports *constraint sets* and *governance modes*:

$$\mathcal{C}(t) \in \{\mathcal{C}^{(1)}(t), \ldots, \mathcal{C}^{(m)}(t)\},$$

with mode changes requiring explicit policy events e_P. Pluralism does not remove conflict; it makes conflict *explicit, auditable, and governable.*

13.7 Failure Modes and Mitigation

EVOS highlights distinctive failure modes:

- **Commitment leakage:** world effects without explicit e_c (broken boundary).
- **Policy drift without lineage:** $P(t)$ changes without e_P (ungoverned updates).
- **Operator mutation without audit:** Θ shifts without event anchors (unaccountable self-modification).

- **Constraint gaming:** optimizing proxies that satisfy checks but violate intent (specification failure).

Mitigations are structural: enforce commitment gates, event-anchored policy/ops lineage, regression invariants, and staged rollout with automatic rollback.

13.8 Why Governance Completes EVOS

Governance completes EVOS because it provides the missing half of open-ended intelligence: *what persists must be accountable*. Commitment makes consequences real; selection makes them matter (Section 12); governance ensures they remain bounded, auditable, and socially legible over time.

14 Applications and Impact

EVOS is a theory of intelligence as *worldline evolution under constraint*. Its practical value is that it turns vague desiderata ("aligned agents", "accountable autonomy", "adaptive systems") into *structural requirements*: commitment boundaries, provenance, pluggable evolution laws, and explicit constraint dynamics.

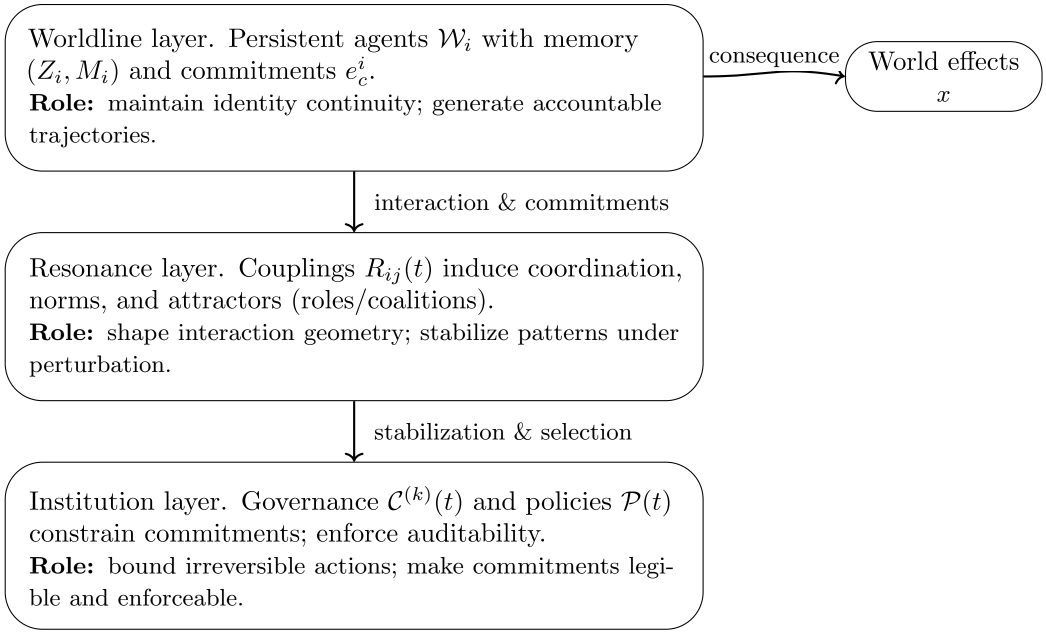
This section makes three explicit claims:

1. **EVOS is applicative by construction:** any domain with irreversible effects and adaptation benefits from commitment/provenance semantics.
2. **EVOS unifies scales:** the same primitives describe single agents, institutions, and substrate-hybrid systems.
3. **EVOS changes what is optimized:** from snapshot metrics to trajectory stability and bounded consequence.

14.1 AI Agent Civilizations

EVOS is a substrate for *multi-agent civilizations* rather than a single-domain application. Within such civilizations, an economy is not an optional add-on: it is a *civilization kernel*—a persistent coordination layer that allocates scarce capacity (resources, attention, energy, time) under evolving constraints. In EVOS terms, "finance" is the canonical high-stakes instantiation of the substrate primitives:

- **Worldline primacy → trajectory-based identity, credit, and risk.** Creditworthiness is a property of an agent's historically grounded worldline (commitment history, constraint compliance, failure recovery), not a snapshot score.
- **Commitment boundary → settlement and irreversibility.** Financial actions are *externally binding* world-effects; they must cross an explicit commitment gate that compiles policy and invariants into a verifiable commitment event.
- **Intrinsic memory → causal provenance and audit without reconstruction.** The ledger is not an after-the-fact archive; it is the living memory of commitments and consequences, enabling structural accountability.
- **Projection → privacy and competition.** Agents may keep strategies and intent latent while exposing only minimal, policy-compliant projections to counterparties and the environment (selective revelation under dispute).
- **Openness-under-constraint → regulation as physics.** Compliance is enforced as substrate constraints and feasibility boundaries rather than external "policing," enabling continuous



Key EVOS property: *society-scale intelligence is a trajectory property of* coupled worldlines under explicit constraints*, not a snapshot property of any single architecture.*

Figure 27: Agent civilization layers in EVOS: persistent worldlines, resonance coupling, and institutional constraints with commitment/provenance semantics.

markets with built-in homeostasis.

- **Operator evolution → adaptive market rules without history reset.** Governance can update transition operators (within constraint envelopes) while preserving worldline continuity and provenance.

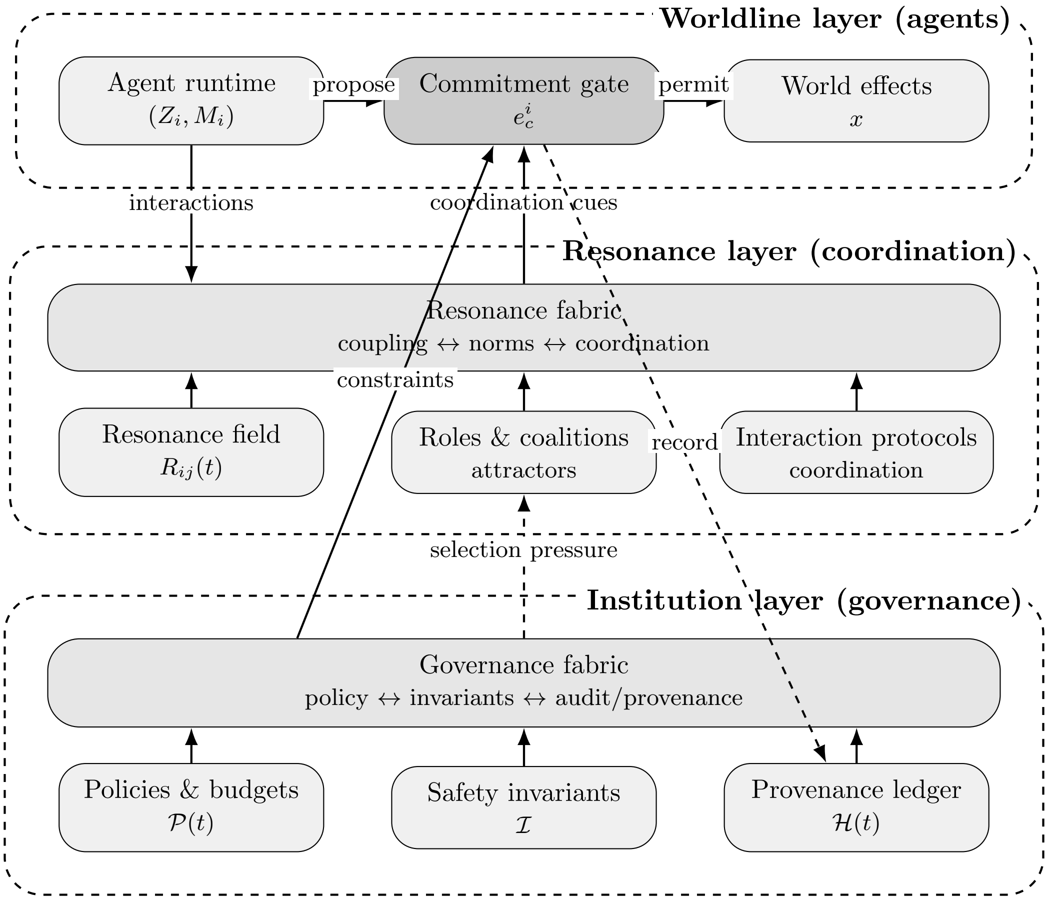
A complete EVOS-native financial system (exchange, banking, insurance, regulation-by-constraint) is developed as a dedicated companion work (e.g., *EVOS Financial System / ERX / EFF / ORS*) that serves as a proof-by-construction of these primitives in a safety-critical, adversarial domain.

Multi-agent systems become qualitatively different when agents are persistent and accountable. In EVOS, an "agent society" is a resonance field over agent worldlines with institution-like constraints and commitment-mediated interaction. The key contribution is not coordination per se, but *institutional legibility*: actions are commitments with lineage.

- **Roles** emerge as stable attractors in the resonance field (persistent interaction motifs).
- **Institutions** are constraint regimes $\mathcal{C}^{(k)}(t)$ with explicit policy events.
- **Culture** is a long-timescale memory field shaping feasible commitments.

14.2 Scientific Discovery and Hypothesis Exploration

Scientific discovery is an EVOS domain because it is open, time-extended, and consequence-bearing: experiments consume resources and irreversibly update shared knowledge. EVOS provides: (i) persistent memory worldlines for hypotheses and instruments, (ii) commitment-gated experiments, and (iii) provenance lineage from evidence to claims.



Society-scale intelligence is a trajectory property of coupled worldlines *stabilized by resonance and bounded by explicit governance: no world effect x without a commitment e_c that is constraint-checked and provenance-recorded.*

Figure 28: Digital EVOS system architecture: agents (worldlines) propose actions; explicit commitments authorize world effects; resonance fabric induces coordination; governance fabric enforces constraints and auditability via provenance.

A hypothesis becomes a worldline $\mathcal{W}_h$ whose commitments are experimental actions; its "fitness" is stability under constraint (reproducibility, cost, ethical bounds).

14.3 Medicine and Personalized Biology

Personalized medicine is trajectory-dominated: interventions alter future physiology irreversibly. EVOS recommends commitment-gated clinical actions with explicit policy constraints (protocols, consent, safety) and provenance from measurements → diagnosis → intervention. Hybrid BIO-EVOS systems naturally fit: molecular dynamics provide substrate-level memory and constraints (kinetics, scarcity), while digital agents provide deliberation and audit.

14.4 Optimization Beyond Objective Functions

Standard optimization presumes a fixed objective; EVOS reframes optimization as maintaining bounded trajectory under evolving constraints:

$$\text{minimize violations of } \Phi(\mathcal{W}) \text{ subject to } \mathcal{C}(t), \text{ with commitments anchored in } \mathcal{H}(t).$$

This supports multi-stakeholder systems where objectives conflict and policies evolve.

14.5 Knowledge Preservation and Long-Term Memory

EVOS supports persistent, provenance-aware knowledge: rather than storing static documents, it stores *lineage* (why beliefs changed, which commitments were made, and which evidence anchors exist). This is critical for institutional memory and long-horizon alignment.

14.6 Societal-Scale Governance Systems

EVOS provides a formal substrate for governance automation without collapsing governance into a single score: policy is an evolving constraint process with explicit mode changes, audits, and rollback. This enables accountable "agentic bureaucracy" where commitments are legible and reversible actions are maximized, irreversible actions minimized and justified.

14.7 Impact on the Theory of Computation

EVOS does not refute the Church–Turing thesis; it changes the *object of study*. Turing computation characterizes what can be computed as a function. EVOS characterizes what can be sustained as a *bounded, accountable trajectory* in an open world.

15 Discussion, Limitations, and Future Directions

A Turing-grade theory must state its limits clearly. EVOS is a structural theory; it does not provide a closed-form algorithm for intelligence. It specifies *necessary primitives* and *admissible dynamics* for accountable open-ended systems.

15.1 Related Work and Historical Positioning

EVOS is deliberately *not* proposed as a competing neural architecture. It is a *systems-class* and *accountability formalism* for persistent, open, history-bearing computation. In this sense, EVOS sits at the intersection of (i) classical computation and its limits [1, 2], (ii) interaction and non-terminating computation [3], (iii) cybernetics and control under feedback [4, 5], (iv) dynamical systems and stability under constraint [6], and (v) biological autonomy and self-production [7].

Several themes are closest in spirit but differ in emphasis. First, interactive computation frameworks argue that *ongoing interaction* extends the expressive concerns of classical, input–output machines [3]; EVOS adds the missing *commitment boundary* as a structural requirement for real-world accountability. Second, dynamical systems and control theory provide the mathematics of trajectories, attractors, and stability [6, 5]; EVOS uses these tools but elevates *irreversibility and provenance* to first-class constraints. Third, reaction–diffusion and morphogenesis show how stable patterns emerge from local interactions [8]; EVOS reinterprets these patterns as *resonant* structures that can encode memory, norm, and institution at multiple scales. Finally, reinforcement learning formalizes adaptation under reward [9]; EVOS generalizes beyond reward to *constraint compatibility* and commitment-scoped external consequences.

EVOS can be read as a synthesis: the Church–Turing thesis abstracts *computation* away from machines; EVOS abstracts *intelligence-under-time* away from architectures. This shifts the scientific question from "what function is computed?" to "what trajectories are stabilized, under what constraints, and with what accountable consequences?"

15.2 Positioning EVOS in the History of Computation

EVOS is to intelligence what process calculi and systems theory are to programs: it focuses on interaction, persistence, and evolution. Where Turing machines formalize computation-as-function, EVOS formalizes intelligence-as-trajectory with commitment semantics.

15.3 Relationship to Existing AI Architectures

Transformers, planners, RL agents, and symbolic systems can all be embedded in EVOS as internal modules. EVOS is orthogonal: it governs how internal cognition becomes external effect, how memory persists, and how evolution laws change under constraint.

15.4 Conceptual Limitations

- **Not sufficient:** EVOS axioms are necessary conditions, not a recipe for intelligence.
- **Constraint selection:** choosing $\mathcal{C}(t)$ and Φ is a normative problem.
- **Measurement limits:** provenance depends on observability; some substrates are partially observable.

15.5 Practical Limitations

- **Overhead:** commitment/provenance infrastructure adds latency and complexity.
- **Specification gaps:** policy predicates can be incomplete or gameable.
- **Scaling:** lineage graphs and logs require efficient summarization and verification.

15.6 Epistemic Limits

Open systems face fundamental epistemic uncertainty: the environment is not fully modelable. EVOS addresses this by making uncertainty explicit at the commitment boundary, but it does not eliminate it. The best possible guarantee is bounded consequence under explicit uncertainty.

15.7 Open Research Questions

1. **Trajectory metrics:** principled forms of $\Phi(\mathcal{W})$ capturing safety, coherence, and utility.
2. **Policy compilation:** translating legal/ethical norms into auditable predicates $\mathrm{Allow}(\cdot)$.
3. **Lineage compression:** provably safe summarization of causal history for scale.
4. **Field learning:** formal links between resonance-field plasticity and operator meta-dynamics.
5. **Hybrid semantics:** cross-substrate commitment equivalence and measurement trust models.

15.8 Risks and Misuse Considerations

EVOS can be misused to build more persistent and strategic agents. The mitigation is not to avoid EVOS, but to insist that persistence comes with enforceable boundaries: explicit commitments, provenance, budgets, and governance modes. "Unbounded autonomy" is precisely the failure mode EVOS forbids.

15.9 Why EVOS Is Not Just a Framework

EVOS makes falsifiable structural claims: if a system produces world effects without commitment events and causal lineage, it violates EVOS; if it cannot represent time as worldline history, it violates EVOS; if it cannot evolve under explicit constraints, it violates EVOS. These are not implementation preferences; they are definitional.

15.10 Future Trajectories

Immediate directions:

- **Reference implementations** of commitment gating, provenance logs, and operator hot-swap buses.
- **Benchmarks** defined on trajectory stability and bounded consequence rather than task snapshots.
- **Formal verification** of invariants at the commitment boundary (safety regression invariants).

16 Conclusion

We introduced **Evolutionary Open Systems (EVOS)**: a class of computational systems defined axiomatically by worldline primacy, intrinsic memory, openness under constraint, commitment as a reality boundary, and substrate independence. We introduced **GENESIS** as a resonance-field formalism compatible with EVOS, and we developed a pluggable transition mathematics stack spanning Markov models, time-series dynamics, differential/reaction–diffusion systems, and learned/self-modifying operators—each constrained by explicit commitments and causal provenance.

The central thesis is simple and structural:

> *Intelligence in the real world is not a snapshot computation. It is an accountable, constraint-bounded trajectory that persists through irreversible time.*

EVOS therefore shifts the ground of AI from architecture-centric optimization to trajectory-centric systems engineering: commitments define reality, provenance defines accountability, and constraints define what it means for evolution to be intelligent rather than merely powerful.

A Figure Index

List of Figures

This appendix provides a consolidated index of figures for reviewers. Figure captions are the authoritative descriptions of each artifact; cross-references in the main text use standard LaTeX labels to remain stable under restructuring.

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