Kernel Dynamics: Irreversibility from Algebraic Access

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Abstract

We present *Kernel Dynamics*, a structural framework in which physical reality is defined as a quotient of a unitary history space by the kernel induced by an observer's accessible algebra. In this formulation, irreversibility, entropy growth, and emergent physical distinctions do not arise from non-unitary dynamics or stochastic laws, but from time-dependence and insufficiency of observer access. We formalize entropy as kernel volume, show that apparent information loss corresponds to algebraic contraction or mismatch with state support, and demonstrate that standard thermodynamic and informational paradoxes admit a unified resolution. A sequence of stress tests—Maxwell's Demon, quantum error correction, autonomous information engines, and reversible computation—confirms the internal consistency of the framework and clarifies the operational role of access upgrades.

1. Ontological Basis: Reality as a Quotient

1.1. Unitary History Space

Axiom 1 (Unitary History)**.** Let $\mathcal{X}$ denote the *history-augmented configuration space* of a closed physical system. Evolution in $\mathcal{X}$ is strictly unitary, deterministic, and information-preserving.

Remark 1. No fundamental irreversibility is assumed at the level of $\mathcal{X}$. Apparent irreversibility must therefore be induced by the observation channel.

1.2. Observer Access and Observable Algebra

Axiom 2 (Observer Access)**.** An observer is modeled by an accessible observable algebra

$$\mathcal{O} \subset \mathcal{B}(\mathcal{X}),$$

where $\mathcal{B}(\mathcal{X})$ denotes bounded operators on $\mathcal{X}$ (or on the corresponding Hilbert space representation when applicable). The algebra is (i) coarse, in the sense $\dim(\mathcal{O}) \ll \dim(\mathcal{X})$, and (ii) potentially time-dependent, $\mathcal{O} = \mathcal{O}(t)$, reflecting access upgrades or access loss.

1.3. Kernel Equivalence and Physical Reality

Definition 1 (Kernel Equivalence)**.** Two histories $x, x' \in \mathcal{X}$ are *physically indistinguishable relative to* $\mathcal{O}$ if they induce identical statistics for all observables accessible to the observer. This defines an equivalence relation

$$x \sim_{\mathcal{O}} x' \quad \Longleftrightarrow \quad \forall A \in \mathcal{O},\ \langle A \rangle_x = \langle A \rangle_{x'} .$$

The *kernel* $\mathcal{K}_{\mathcal{O}}$ is the partition of $\mathcal{X}$ into equivalence classes under $\sim_{\mathcal{O}}$.

Axiom 3 (Physical Reality as Quotient)**.** The observer-relative physical state space is the quotient

$$\mathcal{R} \;=\; \mathcal{X}\,/\,\mathcal{K}_{\mathcal{O}} \;\cong\; \mathcal{X}/{\sim_{\mathcal{O}}}\,.$$

Distinctions lying in $\mathcal{K}_{\mathcal{O}}$ are operationally unresolvable to the observer and behave as gauge redundancies or hidden structure.

2. Entropy as Kernel Volume

2.1. Kernel Volume and Thermodynamic Entropy

Definition 2 (Entropy as Kernel Volume)**.** Let $[\![x]\!]_{\mathcal{O}}$ denote the equivalence class of $x \in \mathcal{X}$ under $\sim_{\mathcal{O}}$. Thermodynamic entropy is defined as a monotone of the "size" of kernel classes—e.g., dimension, measure, or logarithmic volume:

$$S_{\mathcal{O}}(x) \;\propto\; \log \mathrm{Vol}\big([\![x]\!]_{\mathcal{O}}\big),$$

with the understanding that the precise notion of volume depends on the model (finite-dimensional, measure-theoretic, or information-geometric).

Remark 2. This definition separates ontology from estimation: $S_{\mathcal{O}}$ is a structural property of the quotient induced by access, not a primitive dynamical quantity.

2.2. Algebra Contraction Principle

Theorem 1 (Algebra Contraction Principle)**.** *In a unitarily evolving closed system, apparent information loss (entropy growth as perceived by the observer) occurs if and only if the observer's accessible algebra contracts in time or becomes insufficient to resolve distinctions carried by the evolving state support. Equivalently, entropy increases when distinctions migrate from $\mathcal{R}$ into $\mathcal{K}_{\mathcal{O}(t)}$.*

Remark 3 (Operational reading). Even if $\rho(t)$ evolves unitarily in $\mathcal{X}$, the induced evolution on $\mathcal{R}$ can be non-invertible whenever $\mathcal{K}_{\mathcal{O}(t)}$ grows.

3. Kernel Dynamics Theorem

Theorem 2 (Origin of Irreversibility)**.** *All physically observable irreversible phenomena arise solely from the time-dependence of the observer's accessible algebra $\mathcal{O}(t)$ relative to the spreading support of the unitary history.*

Proof sketch. Let $\rho(t)$ denote the (unitary) state in $\mathcal{X}$.

(i) If $\mathcal{O}(t)$ is invariant and sufficiently rich ("God's-eye" access), then $\mathcal{K}_{\mathcal{O}(t)}$ is constant in time and entropy is conserved.

(ii) If $\rho(t)$ spreads into degrees of freedom orthogonal to $\mathcal{O}(t)$ (scrambling beyond access), or if $\mathcal{O}(t)$ contracts (loss of accessible generators), then $\mathcal{K}_{\mathcal{O}(t)}$ grows.

(iii) Kernel growth induces a many-to-one effective evolution on $\mathcal{R}$, making the inverse map from $\mathcal{R}$ to $\mathcal{X}$ singular in the observer's description. The observer therefore perceives irreversible loss of data despite unitary evolution in $\mathcal{X}$.

□

4. Corollaries: Emergence of Physical Structure

4.1. Identity as Gauge

Corollary 1 (Identity as Kernel Gauge). *If $\mathcal{O}$ is invariant under a symmetry group G acting on $\mathcal{X}$ (e.g., permutation symmetry S_N on particle labels), then G-related histories lie in the same kernel class. Thus identity labels acted upon by G are gauge choices on the history fiber rather than intrinsic objects in the quotient.*

4.2. Time Orientation as an Emergent Observable

Corollary 2 (Time as Emergent Observable). *If an observer's access is memoryless (Markov-0), time direction can lie in the kernel. An access upgrade that introduces memory and feedback can break this kernel symmetry, rendering the arrow of time physically distinguishable for that observer class.*

4.3. Reality as Correlation in Access-Limited Regimes

Corollary 3 (Correlation-First Quotient). *In regimes where local particle-number operators are not well-defined or are access-forbidden (e.g., cosmology without asymptotia, Unruh/Hawking contexts), the robust quotient content is given by correlation observables (e.g., n-point functions, symplectic invariants) rather than particle counts.*

5. Stress Tests of Kernel Dynamics

5.1. Maxwell's Demon

Setup. Let the closed universe factor as

$$\mathcal{X} \;=\; \mathcal{X}_S \otimes \mathcal{X}_M \otimes \mathcal{X}_E,$$

representing system, demon memory, and environment. The demon has accessible algebra $\mathcal{O}_D$ acting on $\mathcal{X}_S$ and its memory degrees of freedom.

Kernel shrinkage (measurement). A measurement is an *access upgrade* $\mathcal{O}_{\text{coarse}} \to \mathcal{O}_{\text{fine}}$ that adds new projectors distinguishing previously hidden distinctions, shrinking the system kernel:

$$\mathcal{K}_{S,\text{after}} \subset \mathcal{K}_{S,\text{before}}.$$

This permits a local entropy decrease in the system relative to the demon's upgraded access.

Kernel growth (erasure / reset). To operate cyclically, the demon must reset memory to a standard "ready" state, implementing a many-to-one map on observable memory states. This corresponds to an effective algebra contraction on the memory degrees of freedom and requires exporting entropy to $\mathcal{X}_E$ as heat.

Theorem 3 (Kernel–Landauer Inequality (Structural Form)). *In a closed unitary system, net kernel shrinkage in one sector over a complete cycle requires compensating kernel growth elsewhere. In particular, cyclic operation implies a heat cost that lower-bounds the information erased from the demon's memory.*

5.2. Quantum Error Correction (QEC)

Mechanism. A QEC code expands physical degrees of freedom to create orthogonal syndrome subspaces. Syndrome measurement is an access upgrade that converts error entanglement into readable syndrome information, while ancilla reset exports entropy:

$$\text{(noise)} \Rightarrow \text{(syndrome info)} \Rightarrow \text{(unitary correction)} \Rightarrow \text{(entropy export)}.$$

Kernel Dynamics interprets QEC as *active kernel management*: maintaining a small kernel for logical observables by pumping kernel volume into ancilla/environment degrees of freedom.

5.3. Autonomous Demons and Saturation

Infinite memory. If the demon writes measurement outcomes to an unbounded, initially blank memory tape, it can reduce system entropy indefinitely by continuously expanding accessible recorded distinctions; disorder is transferred from system to memory.

Finite/thermalizing memory. With finite capacity or thermalization, the demon's memory saturates; further operation forces many-to-one overwrites, i.e., kernel growth. Saturation is the generic form of Landauer: when the algebra's capacity to retain distinctions is exhausted, further interaction pushes information into the kernel and generates heat.

5.4. Reversible Computing

Kernel neutrality. A reversible computation implements a bijection on computational basis states (e.g., Toffoli/Fredkin). If the observer tracks the full computational state, kernel dimension is constant and dissipation is not required:

$$\Delta \log \mathrm{Vol}(\mathcal{K}) = 0 \quad \Rightarrow \quad \Delta S = 0.$$

Irreversible gates. Irreversible logic (AND/OR) performs many-to-one maps on logical states, necessarily increasing kernel volume; the corresponding entropy must be exported as heat to maintain reliability for subsequent cycles.

6. Discussion

Kernel Dynamics unifies thermodynamics, information processing limits, and measurement-induced emergence under a single algebraic mechanism: *apparent entropy production is the shadow of distinctions entering the kernel*. The framework shifts the explanatory burden from postulated irreversibility to explicit access structure. Classical irreversibility, decoherence, and computation heat costs are reinterpreted as consequences of evolving or insufficient observable algebras acting on an otherwise unitary history space.

7. Conclusion

Physical reality is not the full unitary history space, but its observer-relative quotient. Entropy is not primitive disorder, but hidden distinction. Irreversibility is not fundamental, but induced by kernel growth under access constraints. The stress tests considered here confirm that Kernel Dynamics reproduces standard second-law behavior while providing a structural generalization that naturally encompasses measurement, feedback, coding, and computation within a single quotient-algebra formalism.

Status. Ontology: complete. Governing dynamics: formalized. Stress tests: consistent. The framework is prepared for external review.