Emergent Time and Measurement as Irreversible Constraints on the Space of Accessible Futures

Abstract

A thermodynamic framework is developed in which time and measurement arise jointly from irreversible entropy-driven dynamics on the probability simplex. No external time parameter or stochastic collapse postulate is assumed. Instead, temporal ordering and classical outcomes emerge from the monotone reduction of accessible futures induced by entropy production. The framework preserves the Born rule, forbids signaling and deterministic outcome control, and applies uniformly to microscopic and macroscopic regimes. Measurement is identified not as a dynamical selection mechanism, but as a structural restriction on future realizability.

1 Entropy-Drift Dynamics on the Probability Simplex

Let $w(t)$ denote a diagonal weight associated with a projector P, defined as

$$w = \mathrm{Tr}(P\rho),$$

and evolving on the open interval $w \in (0,1)$. The dynamics is governed by an entropy-gradient drift of the form

$$\dot{w} = -\Gamma\, w(1-w)\, \partial_w S(w),$$

where $S(w)$ is a reduced entropy functional and $\Gamma > 0$ a dissipation constant.

The drift vanishes at $w = 0, 1$ and at stationary points of S. Away from these points, the dynamics is strictly irreversible.

2 Entropy Production and Monotonicity

The entropy production rate induced by the drift is

$$\frac{dS}{dt} = \partial_w S\, \dot{w} = -\Gamma\, w(1-w)\, (\partial_w S)^2 \leq 0.$$

Entropy production vanishes if and only if $\dot{w} = 0$. The drift therefore induces a partial ordering on state-space trajectories via monotone entropy decrease.

3 Internal Time as Consumed Decision Budget

Definition (Internal Time). The internal time variable τ is defined as a functional of the entropy-drift trajectory:

$$\boxed{\tau(t) := \int_0^t \mathcal{D}\big(w(t')\big)\, dt', \qquad \mathcal{D}(w) := \kappa\, w(1-w)\, |\partial_w S(w)|}$$

with $\kappa > 0$ setting the entropy-to-time conversion scale.

Internal time increases if and only if entropy is irreversibly produced. Laboratory time t appears solely as a parametrization.

The internal time rate satisfies

$$\frac{d\tau}{dt} \propto \sqrt{-\frac{dS}{dt}},$$

establishing a direct correspondence between temporal flow and entropy production.

4 Information Geometry and Temporal Distance

The Fisher information metric on the simplex is

$$F(w) = \frac{1}{w(1-w)}.$$

Using this metric, the internal time increment admits a geometric representation:

$$\boxed{d\tau^2 = \frac{\kappa^2}{4}\, F(w)\, dw^2}$$

Time is thus identified with the metric length of irreversible trajectories in information space. Near classical attractors, $dw \to 0$ and entropy production ceases, leading to temporal saturation.

5 Measurement as Restriction of Accessible Futures

No individual outcome is dynamically selected by the entropy-drift equation. Instead, the drift constrains the set of physically accessible future states.

Principle.

> *Measurement corresponds to the irreversible reduction of accessible futures induced by entropy production.*

This restriction is structural rather than causal: the geometry of probability space is reshaped, while individual realizations remain uncontrollable.

6 No-Go Results

No-Go I: No Deterministic Outcome Fixation. A drift of the form $\dot{w} = f(w)$ determines ensemble evolution only. It yields no control over individual events and no deterministic future selection.

No-Go II: Born Weights as Unstable Fixed Points. Symmetry points of $S(w)$ satisfy $\partial_w S = 0$ but are generically unstable. The Born rule arises as a geometric symmetry of entropy, not as an attractor of the dynamics.

No-Go III: No-Signaling. Since no controllable steering of outcomes exists, entropy-driven time flow cannot transmit usable information without classical channels.

No-Go IV: No Unitary Simulation. Purely dissipative drift dynamics cannot reproduce coherent unitary evolution, but only its irreversible boundary regime.

7 Classical Limit

In the limit $w \to 0, 1$,

$$\dot{w} \to 0, \qquad \frac{d\tau}{dt} \to 0,$$

and entropy production ceases. Classicality corresponds to exhaustion of the available decision budget and saturation of internal time.

8 Scaling, Coherence Volume, and Thermodynamic Bounds on Time Flow

Consider a composite system with entropy-drift variables $\{w_i\}_{i\in\mathcal{I}}$ evolving on a high-dimensional probability simplex. Not all degrees of freedom contribute equally to irreversible evolution. Classical ($w_i = 0, 1$) and fully delocalized variables do not generate entropy drift and therefore do not contribute to internal time.

Definition (Active Coherence Volume). The *active coherence volume* is defined as

$$\boxed{\mathcal{V}_{\mathrm{coh}} := \{\, i \in \mathcal{I} \mid 0 < w_i < 1 \,\}}$$

and collects precisely those degrees of freedom undergoing irreversible information fixation.

A direct summation of entropy-drift contributions over $\mathcal{I}$ would lead to an extensive internal time rate and unphysical acceleration for macroscopic systems. To obtain an intensive notion of time, the internal time rate is normalized by the size of the active coherence volume:

$$\boxed{\frac{d\tau}{dt} = \frac{\kappa}{|\mathcal{V}_{\mathrm{coh}}|} \sum_{i\in\mathcal{V}_{\mathrm{coh}}} w_i(1-w_i)\,|\partial_{w_i} S|}$$

This normalization ensures that systems with comparable coherence densities exhibit comparable temporal rates, independent of total system size. Macroscopic classical objects, for which $|\mathcal{V}_{\mathrm{coh}}|/|\mathcal{I}| \ll 1$, therefore do not experience arbitrarily rapid internal time flow.

Thermodynamic Bound. Entropy production is constrained by the available dissipated power P_{diss} at temperature T. Using the Landauer principle, the total entropy production rate satisfies

$$\dot{S} \le \frac{P_{\mathrm{diss}}}{T}.$$

Since internal time is generated exclusively by irreversible entropy production, the internal time rate obeys the bound

$$\boxed{\frac{d\tau}{dt} \le \frac{P_{\mathrm{diss}}}{k_B T \ln 2}}$$

This inequality constitutes a thermodynamic upper limit on temporal flow. Regions of reduced dissipation or lower effective coupling to entropy sinks exhibit slower internal time rates. In the limit $P_{\mathrm{diss}} \to 0$ or $T \to 0$, entropy drift stalls and internal time ceases to advance.

Consequences.

- Temporal rates depend on local entropy production densities rather than global system size.
- Time dilation corresponds to reduced access to entropy sinks and diminished irreversible information export.

- Gravitational or environmental redshifts may be interpreted as variations in effective dissipation capacity.
- Classicality corresponds to vanishing coherence volume and saturation of internal time.

9 Conclusion

Time and measurement emerge jointly from irreversible entropy production on the probability simplex. Temporal ordering reflects the cumulative restriction of accessible futures rather than the evolution of a background parameter. The framework preserves quantum statistics, forbids signaling and deterministic control, and provides a thermodynamic resolution of the measurement problem without introducing additional postulates.