Proper Time and the Epistemic Arrow: From Cosmological Boundary to Thermodynamic Throughput to Persistent Identity

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February 17, 2026

Abstract

We propose a record-centered account of the arrow of time grounded in a covariant Page–Wootters/refined algebraic quantization (PW/RAQ) framework in which an observer's internal degrees act as a physical clock. Under admissibility conditions, the relational parameter selected by conditioning is unique up to monotone reparametrization and—after calibration—is realized by the observer's center-of-mass (COM) proper time. On that parameter, we define an *epistemic arrow* as the inclusion order of a physically realized record algebra. Because forming and maintaining reliable records require dissipation (Landauer-type costs and information-thermodynamic bounds), the expected information content of the record algebra grows under positive average dissipation, yielding a directed order in proper time. A low-entropy cosmological boundary (Past Hypothesis) together with entanglement typicality and ETH explains why local subsystems exhibit thermodynamic behavior that sustains the free-energy throughput enabling record formation; thus cosmological $\Rightarrow$ thermodynamic $\Rightarrow$ epistemic arrows. Philosophically, we align the temporally extended self-model—the "me"—with Parfit's notion of *what matters*: psychological continuity/connectedness realized as the maintenance (within operationally defined tolerances (ε, L)) and growth of reliable records. In a timeless description, present reliable records sharply retrodict a narrow set of histories that contain them; the redundancy and concordance of those records *require* a Past-Hypothesis–type low-entropy boundary. Technical proofs and RAQ details appear in a companion note.

1 Introduction: records, identity, and what matters

Parfit's reductionism treats diachronic identity in terms of *psychological continuity and connectedness* rather than any further fact (Parfit, 1984). We make this identification explicit: the temporally extended self-model—the *"me"*—is the pattern of *reliable* internal records and the inferences they support. On our account, an agent *persists* insofar as those records are maintained within design tolerances and expanded by learning. This connects a live problem in philosophy of identity directly to concrete thermodynamic and information-theoretic constraints.

A second thread concerns *which* parameter structures this story. In a timeless, constrained description, Page–Wootters recovers dynamics from correlations; what selects the parameter for an *embodied* observer? We adopt a covariant PW/RAQ construction in which the observer's internal degrees function as a clock coupled (via a single constraint) to COM motion. Under admissibility conditions—minimal observer viability requirements (scalarity, calibration, unitarity, regular gauge, monotonicity)—the relational parameter is unique up to reparametrization and, after calibration, realized by COM proper time; we use that result as a theorem-level input and relegate proofs to appendices and a companion note.[1]

Kant and Wheeler (specific, methodological). We invoke two guideposts without further metaphysical commitments. (i) *Kant*: time as the *form of inner sense* structuring appearances, together with the role of temporal schemata in applying concepts (Kant, 1998). Our PW/RAQ parameter plays this structuring role for an embodied observer. (ii) *Wheeler*: a minimal "It-from-Bit" reading where public objectivity supervenes on *redundant, intersubjectively available* records (Wheeler, 1990). Our meetings construction gives this operational content.

Related work and positioning

Our RAQ/PW construction complements recent classical-limit progress on Page–Wootters (PW) time via generalized coherent states, which recover both quantum and classical equations from a single relational parameter (Foti et al., 2021). Laboratory illustrations of PW retrodiction using entangled photons support the basic conditioning picture (Moreva et al., 2014). We are interpretation-agnostic: unlike Relational Quantum Mechanics (RQM), we do not posit primitive "relative facts"; recent GHZ-style no-go results therefore do not target our framework (Lawrence et al., 2023). Instead, our perspective-relative assignments align with the Quantum Reference Frames (QRF) program, where descriptions (and even entanglement) are frame-dependent but related by perspective-switching maps (Giacomini et al., 2019; Vanrietvelde et al., 2020). Relativistic extensions predict superpositions of time dilations, dovetailing with our proper-time emphasis (Apadula et al., 2024). Recent work by Vuyst et al. (2025) demonstrates that different QRF choices yield different observable algebras and hence different entropies, making gravitational entropy itself observer-dependent—a result directly relevant to our claim that the record algebra is constituted by the observer's frame choice. Fields et al. (2022) reformulate the Free Energy Principle in spacetime-background-free quantum information theory, identifying Markov blankets with holographic screens and agents with QRF-deploying systems; the connection between their abstract framework and the specific PW/RAQ construction developed here is explored in a companion paper (Anonymous, 2025a). On the information-thermodynamic side, our record-growth results mesh with analyses linking correlations/entanglement to thermodynamic asymmetries and with experiments reversing heat flow via quantum correlations (Jennings and Rudolph, 2010; Micadei et al., 2019).

Timeless retrodiction and a participatory reading

In a timeless Hilbert-space description with time-reversal-symmetric microdynamics, explanation need not mirror causation. Because reliable records are physical encodings of past microfacts, the present *logically constrains* the set of compatible pasts. Two points are helpful.

Existence (cheap). In a high-dimensional Hilbert space, for any finite family of present-day record variables there typically exist many microhistories whose coarse-grainings contain those records. That is, the compatibility set $\mathcal{H}(R_\tau)$ of histories consistent with the current record algebra is generically nonempty and often large.

Sharpness (earned). Redundant, (ε, L)-reliable records plus appropriate priors produce *posterior concentration* onto a narrow coarse-grained past. Our proposal makes this precise by (i) defining reliability in operational terms (tolerances (ε, L) and a readout channel M), (ii) linking record creation/maintenance to dissipation (Landauer-type costs), and (iii) showing that under positive average dissipation the expected inclusion of the record algebra grows along the proper-time

[1] Companion technical note cited as Anonymous (2025b).

parameter selected by PW/RAQ. On this picture, observers are not passive: the energy budgets that sustain their memories are part of what makes temporal experience emerge in proper time.

Retrodictive sufficiency as an information bound. Let H be a coarse-grained past macro-history with finite alphabet $\mathcal{H}$, and let $\hat{R}_\tau$ be the classical readout of the present record algebra $R(\tau)$. For any estimator $\widehat{H}(\hat{R}_\tau)$ and any prior over H, Fano's inequality yields

$$P_{\text{err}}\big(H \neq \widehat{H}(\hat{R}_\tau)\big) \;\geq\; \frac{H(H \mid \hat{R}_\tau) - 1}{\log(|\mathcal{H}| - 1)}\,, \tag{1}$$

so achieving error $\leq \delta$ requires

$$I\Big(H; \hat{R}_\tau\Big) \;\geq\; H(H) - h_2(\delta) - \delta \log(|\mathcal{H}| - 1). \tag{2}$$

Because each (ε, L)-reliable record contributes a mutual-information floor, the total present-day content $I_R(\tau)$ sets a quantitative lower bound on how sharply the past can be recovered. Thus the rhetoric—that present reliable records "sharply retrodict a narrow set of histories"—is equivalent to $I(H; \hat{R}_\tau)$ exceeding an explicit threshold, which our dissipation-funded growth results make plausible in nonequilibrium regimes (Prop. 1).

Scope and limitations. The formal results of this paper and its companion technical note assume massive observers on flat or static backgrounds, with no backreaction. These assumptions are stated explicitly in the companion note and cover essentially all current earth-bound metrological settings; they fail for genuinely dynamical regimes (cosmological expansion, binary inspirals) or when the spacetime itself is in superposition. Observers are physical systems with internal memory and readout—no appeal to consciousness is required. The present paper concerns the temporally extended self-model (the "me" realized in records) rather than the transient subject of experience (the "I"); the latter belongs to a different investigation. A companion paper (Anonymous, 2025a) develops the connection between the present framework and the Free Energy Principle, showing that the admissibility conditions are dynamically maintained by systems engaged in active inference and drawing out consequences for the Boltzmann brain problem, the robustness of the epistemic arrow, and the extension to dynamic spacetimes.

2 Relational dynamics without external time (summary)

Kinematically $H_{\text{kin}} = H_{\text{COM}} \otimes H_{\text{int}} \otimes H_{\text{ext}}$. A single first-class constraint couples internal energy to inertial mass; refined algebraic quantization (RAQ) with a regulated rigging map defines H_{phys}. Conditioning on an admissible scalar clock yields reduced dynamics for a relational parameter.

Theorem (Proper-time uniqueness; informal). *If $\hat{\Theta}$ is an admissible scalar clock (Lorentz-scalar completeness; stationary/static calibration; self-adjoint reduced dynamics; regular gauge; monotonicity), then there exists a strictly increasing f with $\hat{\Theta} = f(\hat{T})$, where $\hat{T}$ is the COM proper-time scalar constructed from the mass shell. After calibration, $\theta \equiv \tau$.* (Anonymous, 2025b)

3 Records, reliability, and the epistemic arrow

3.1 Operational primitives and definitions

Fix a readout channel M (a CP instrument with classical outcomes). For design tolerances (ε, L) in a given operating context, a discrete record X written at τ is (ε, L)-*reliable* if repeated queries over $[\tau, \tau+L]$ recover X with error $\leq \varepsilon$. By Fano's inequality each reliable record contributes a positive mutual-information floor to $I(X;\hat{X})$ (Cover and Thomas, 2006). Let $R(\tau)$ be the Boolean algebra generated by reliable records at τ; write $\tau_1 \preceq \tau_2$ iff $R(\tau_1) \subseteq R(\tau_2)$.

3.2 Monotonicity in expectation under dissipation

Proposition 1 (Coarse-grained, expected)**.** *Assume: (i) net positive average dissipation rate* $\dot{Q}_{\text{diss}}(\tau) > 0$ *over intervals of interest; (ii) stationary noise for the memory substrate; (iii) writing/refreshing* k *additional* (ε, L)*-reliable bits requires at least* $c_{\text{dev}}\, k\, k_B T \ln 2$ *(Landauer bound including overhead). Then for coarse-graining windows large compared to device cycle times,*

$$\frac{d}{d\tau}\,\mathbb{E}[I_R(\tau)] \geq 0, \qquad \textit{and} \qquad \mathbb{E}[\mathbf{1}_{R(\tau)}] \textit{ is nondecreasing in } \tau, \tag{3}$$

up to localized forgetting events whose total contribution over any interval is bounded by the integrated deficit of dissipation relative to the minimal maintenance cost.

An important clarification: the monotonicity is in expectation over coarse-graining windows, not pointwise along individual trajectories. Individual histories may exhibit local decreases in $I_{\mathcal{R}}$ (forgetting events—degradation of specific records due to noise, metabolic interruption, or environmental disruption). What the proposition guarantees is that, averaged over windows large compared to device cycle times, dissipation-funded growth dominates fluctuation-driven loss. The "localized forgetting events" clause makes this explicit: the framework accommodates temporary decreases, bounded by the integrated dissipation deficit.

Limits and caveats. The bound does not claim that *every* microscopic step must dissipate: near-reversible logic can reduce marginal costs. However, maintaining (ε, L)-reliability at finite temperature and noise requires logically irreversible operations (e.g., syndrome extraction and ancilla reset in error correction), whose erasure cost enforces a nonzero *average* dissipation over windows $\gg$ device cycles. Thus, while efficiency factors can push $\eta \to 1$ in quasi-static limits, the long-run maintenance budget cannot vanish for finite L and nonzero noise.

3.3 Toy model

Single-bit memory with spontaneous flip rate α; periodic refresh every δ (each refresh costs $\geq c_{\text{dev}} k_B T \ln 2$). Choose δ so $p_e(\delta) \leq \varepsilon$. Writing new bits at rate β yields $\mathbb{E}[\Delta I_R] \gtrsim (\beta - \alpha_{\text{eff}})\,\Delta\tau \cdot \iota_{\varepsilon,2}$ provided $\dot{Q}_{\text{diss}} \geq c_{\text{dev}} k_B T \ln 2\,(\beta + \delta^{-1})$.

3.4 Record-centric fitness over histories

For coarse-grained, decoherent history segments $\Gamma|_{[\tau,\tau+\Delta\tau]}$, define

$$F_{\text{rec}}(\Gamma;\tau,\Delta\tau) := \frac{1}{\Delta\tau}\Big(\mathbb{E}[I_R(\tau+\Delta\tau) \mid \Gamma] - \mathbb{E}[I_R(\tau) \mid \Gamma]\Big). \tag{4}$$

Weak selection bound. *There exists* $0 < \eta \leq 1$ *such that*

$$\mathbb{E}[\Delta I_R \mid \Gamma] \;\leq\; \eta\,\frac{\Delta S_{\text{env}}[\Gamma]}{\ln 2}, \qquad \Delta S_{\text{env}} = \frac{Q_{\text{diss}}[\Gamma]}{k_B T}. \tag{5}$$

The bound is understood in expectation over coarse-grained intervals in stationary regimes. *Idea.* Each reliable write/refresh costs $\geq k_B T \ln 2$ of entropy production, so reliable information gain is bounded by the entropy budget up to device efficiencies (Bennett, 2003; Bérut et al., 2012; Landauer, 1961; Parrondo et al., 2015; Sagawa and Ueda, 2012; Toyabe et al., 2010). In stationary continuous-time Markov settings, Thermodynamic Uncertainty Relations imply precision/irreversibility trade-offs that bound fluctuations of successful refresh/write counts and hence constrain ΔI_R at fixed ΔS_{env} (Barato and Seifert, 2015; Gingrich et al., 2016; Horowitz and Gingrich, 2019).

4 From cosmological to thermodynamic to epistemic arrows

A low-entropy early-universe boundary (Past Hypothesis) fixes a cosmological arrow. Entanglement typicality and ETH show that, for global pure states in high-dimensional energy shells, small subsystems *typically* exhibit thermal behavior without ensemble averaging (Deutsch, 2018; Goldstein et al., 2006; Linden et al., 2009; Popescu et al., 2006; Reimann, 2007; Srednicki, 1994). This explains why local nonequilibrium and structure formation—and hence sustained dissipation—are generic, supplying the free-energy throughput that funds reliable record creation/maintenance.

4.1 Why the cascade matters philosophically

The cascade clarifies: (i) *Explanatory asymmetry*: boundary explanation of local thermodynamics; (ii) *Epistemic asymmetry*: nonequilibrium free-energy throughput enables reliable record growth, aligning the direction of knowledge with proper time; (iii) *Modal support*: typicality/ETH provide counterfactual stability underpinning scientific inference.

Retrodictive sufficiency from record redundancy. In regimes with sustained dissipation, agents produce highly redundant, (ε, L)-reliable records. Redundancy breaks time-symmetric descriptive ambiguity by making the present an information-rich fixed point for Bayesian retrodiction: almost all microhistories compatible with the current record algebra agree on the same coarse-grained past.

4.2 Retrodictive necessity of a Past Hypothesis

Claim (Retrodictive necessity; abductive). *If present records routinely support retrodictive sufficiency (i.e., present reliable records select an effectively unique coarse-grained past with high probability), then the underlying measure over microhistories must concentrate on histories with a low-entropy past boundary (a Past-Hypothesis–type condition).* Here "measure" refers to the physically relevant weighting induced by the cosmological boundary condition together with typicality in high-dimensional energy shells, not a subjective prior over histories. This is an inference to the best explanation, not a deductive entailment: the claim is that a low-entropy boundary is required as part of the best account of why concordant, retrodiction-licensing records are ubiquitous rather than miraculous.

Rationale. Absent a special low-entropy boundary, typical global microstates are near equilibrium; high redundancy of concordant records is then overwhelmingly atypical and generically swamped by incompatible "Boltzmann-fluctuation" pseudo-records. The observed ubiquity of redundant, cross-validated records that license stable retrodiction therefore entails a low-entropy boundary as part of the best explanation of our world's data. With a Past Hypothesis in place, entanglement typicality and ETH make that redundancy generic, closing the cosmological ⇒ thermodynamic ⇒ epistemic chain (Callender, 2016; Deutsch, 2018; Goldstein et al., 2006; Linden et al., 2009; Popescu et al., 2006). The "Boltzmann-fluctuation" pseudo-records mentioned above are developed into a categorical exclusion of standard Boltzmann brains from observer-hood in Anonymous (2025a), where the operational record definition provides a principled, non-*ad hoc* basis for the exclusion; see also objection (O4) below.

5 Why the arrow is in proper time

(i) *Rest-frame thermodynamics.* Landauer-type costs $k_B T \ln 2$ and power budgets are defined in the memory's rest frame; write/refresh rates are thus bounded per unit *proper* time of that hardware. (ii) *Covariant selection.* Our RAQ/PW construction picks a Lorentz-scalar parameter for relational dynamics (proper time up to reparametrization); defining the epistemic arrow on the same scalar avoids gauge-dependent formulations (Anonymous, 2025b). (iii) *Empirical separability.* In redshift/dilation scenarios with identical lab schedules, record-growth differences appear when plotted vs. coordinate time but collapse when replotted vs. each device's calibrated proper time (Protocol A below).

6 Identity and experience: the "me" as Parfitian continuity

We distinguish the transient subject of experience (the "I") from the temporally extended self-model (the "me") realized in an agent's internal records. In Parfit's sense, *what matters* is psychological continuity/connectedness (Parfit, 1984). We make the correspondence explicit and operational.

Parfit–Records Correspondence (operational). Fix a readout M and tolerances (ε, L). Let $R(\tau)$ be the algebra of (ε, L)-reliable records at proper time τ, and define its information content $I_R(\tau) = \sum_{X \in R(\tau)} I(X; \hat{X}_\tau)$.

- *Continuity threshold.* The *retained information fraction*

$$\Xi(\tau, \Delta\tau) := \frac{\sum_{X \in R(\tau) \cap R(\tau+\Delta\tau)} I(X; \hat{X}_{\tau+\Delta\tau})}{\sum_{X \in R(\tau)} I(X; \hat{X}_\tau)} \tag{6}$$

  captures connectedness; for device-dependent $\Xi_\star \in (0,1)$, we say the "me" *persists* from τ to $\tau + \Delta\tau$ when $\Xi \geq \Xi_\star$.

- *Branching cases.* For successors A_i with reliable algebras R_{A_i} at $\tau + \Delta\tau$, define a *degree of persistence*

$$\mathrm{Pers}(\tau \to A_i) := \frac{\sum_{X \in R(\tau) \cap R_{A_i}(\tau+\Delta\tau)} I(X; \hat{X}_{A_i})}{\sum_{X \in R(\tau)} I(X; \hat{X}_\tau)}. \tag{7}$$

  This realizes Parfit's graded connectedness: fission undermines numerical identity but can preserve what matters to varying degrees.

Under positive average dissipation, $\mathbb{E}[I_R(\tau)]$ is nondecreasing (Prop. 1), so continuity (in the above sense) is typically maintainable; gaps in experience (sleep, anesthesia) correspond to suspended updating while $R(\tau)$ remains within tolerances (Cover and Thomas, 2006).

7 Operational intersubjectivity and perspective-relative states

Perspective-relative states ("personal wave functions") and shared reality

Our formalism is compatible with two equivalent readings. On one reading (useful for PW/RAQ derivations), there is a single global stationary state; conditioning on an admissible clock yields relational dynamics (Page and Wootters, 1983). On another (QRF-inspired) reading, each embodied observer A carries a *perspective-relative* assignment $\rho^{(A)}_{S|\tau_A,R_A}$ to the rest of the world, defined relative to A's clock reading τ_A and record algebra $R_A(\tau_A)$ (Giacomini et al., 2019; Vanrietvelde et al., 2020). These assignments are not solipsistic: at reunion events, a normalized meeting POVM and associated inter-observer isometry enforce consistency on the overlap of accessible observables (companion note). The two readings are intertranslatable and make identical empirical predictions; our claims are phrased to be independent of this choice. They are compatible with relativistic QRF transformations, including superpositions of time dilations (Apadula et al., 2024).

Born-rule coherence at meetings (lemma). Let $\mathcal{A}$ be the overlap algebra of observables accessible to A and B at a reunion. If the meeting channel is $\mathcal{E}(\rho) = U_{A\to B}\rho U^\dagger_{A\to B}$ with $U_{A\to B}$ the isometry defined by the meeting POVM and inter-observer swap, then for all $O \in \mathcal{A}$,

$$\mathrm{Tr}[\rho_A\, O] \;=\; \mathrm{Tr}[\mathcal{E}(\rho_A)\, O] \;=\; \mathrm{Tr}[\rho_B\, O]\,. \tag{8}$$

Sketch. $U_{A\to B}$ intertwines the spectral measures of the two clocks on the support of the meeting effect, so Born probabilities agree on $\mathcal{A}$. Details are given in the companion note.

From individuals to a shared temporal order (networked observers). Let observers $\{A_i\}$ meet along a connected reunion graph and apply the meeting isometry at each edge. The induced consistency map on the family $\{R_{A_i}\}$ has fixed points corresponding to stable, redundantly shared records. Under sustained positive dissipation along the network, the expected information content of the shared subalgebra is nondecreasing in each node's proper time, yielding an intersubjective epistemic arrow without appeal to consciousness. Intuitively, shared records are those that survive cross-checking at reunion events: when two observers compare notes, the records on which they agree form a stable core that neither observer's subsequent experience can unilaterally revise. The shared subalgebra grows because each reunion event can add concordant records but cannot (under the meeting isometry) remove ones already established.

8 Empirical anchors and prospects

What differs from "GR+thermo"? Our selection and monotonicity bounds hold *per proper time of the memory device.* Hence, at fixed lab-frame schedules of power delivery and environment, observers on distinct worldlines (redshift/dilation) will display different *record-growth rates* when plotted against a common coordinate time but the *same* rates when plotted against each device's proper time. This is a direct, parameter-level prediction beyond a mere reinterpretation.

Protocol A (gravitational redshift, static). Place two otherwise identical memory arrays (same hardware, same temperature bath, same coordinate-time power schedule) at heights $h_1 \neq h_2$. Read out I_R at equal lab times t. Prediction: $\frac{d}{dt}\mathbb{E}[I_R]$ scales with the redshift factor $N(x)$; when re-plotted against each device's calibrated proper time τ_i, the slopes agree (Chou et al., 2010).

Protocol B (kinematic, relativistic-QRF variant). Prepare a register whose motional state is a superposition of small rapidities. Condition on the branch-resolved proper times $\tau_\pm$ and measure the branch-conditioned growth of I_R. Prediction: growth rates track $\tau_\pm$; any interference penalty is bounded by the TUR-refined constraint (Apadula et al., 2024; Horowitz and Gingrich, 2019).

Platform tests (thermodynamic coupling).

(i) *Mesoscopic memories* with tunable refresh/write power; (ii) *information engines* with finite memories. Both correlate $\dot{Q}_{\mathrm{diss}}$ with growth in I_R and test the bounds above (Parrondo et al., 2015; Sagawa and Ueda, 2012; Toyabe et al., 2010).

9 Objections and replies (brief)

(O1) "Isn't this just RQM?" No. We use perspective-relative assignments for presentation; predictions remain those of standard QM (Born rule). Our meeting isometry enforces cross-perspective agreement on the shared subalgebra, avoiding GHZ-style contradictions raised for RQM (Lawrence et al., 2023).

(O2) "Loschmidt reversibility." Microscopic reversibility coexists with macroscopic asymmetry via boundary conditions and typicality/ETH; practically, *positive average dissipation in proper time* is what funds reliable record growth (Prop. 1). Localized forgetting events are expected and bounded.

(O3) "No new empirical bite." Protocols A/B separate proper-time predictions from coordinate-time schedules; memory and information-engine platforms test the selection bound where dissipation and reliability are tunable.

(O4) "What about Boltzmann brains?" In cosmological scenarios permitting eternal expansion or recurrence, random thermal fluctuations could produce configurations instantaneously resembling observers with coherent-seeming memories. Our operational definition of records provides a principled response: a Boltzmann brain may instantiate a pattern resembling an observer's internal states, but it does not instantiate a record algebra, because (ε, L)-reliability requires stable readout under repeated querying over the interval $[\tau, \tau + L]$—not instantaneous structural resemblance—and transient thermal fluctuations cannot satisfy this condition. The exclusion is not *ad hoc*; it follows from the same operational definition of records that grounds the epistemic arrow. A detailed treatment, including the boundary case of fluctuation-produced systems that subsequently enter a sustained maintenance regime, appears in Anonymous (2025a).

10 Conclusion: the chain that matters

The central lesson is the **cosmological** ⇒ **thermodynamic** ⇒ **epistemic** chain. A *cosmological low-entropy boundary* makes local nonequilibrium and structure formation *generic*; this sustains *thermodynamic throughput* that funds the creation and maintenance of reliable records; and on the *proper-time* parameter selected by PW/RAQ, this yields a directed *epistemic arrow* (record inclusion). In short:

$$\text{Past Hypothesis} \implies \text{Local Thermodynamics} \implies \text{Epistemic Arrow in Proper Time.}$$

Within this chain, the Parfitian *what matters* is realized operationally by the maintenance and growth of reliable records: persistent personal identity is just sustained continuity/connectedness of the "me" as a record algebra. Retrodictive sufficiency—that the present effectively selects its past—is thereby *explained* and, we have argued, *requires* a Past-Hypothesis boundary to be generic rather than miraculous. The accompanying selection and TUR-type bounds turn this philosophical picture into a program of measurable constraints linking dissipation, proper time, and the growth of knowledge.

A companion paper (Anonymous, 2025a) extends this program in three directions: it identifies the Markov blanket of the Free Energy Principle with the quantum reference frame of the PW/RAQ construction, showing that active inference maintains the admissibility regime; it develops the Boltzmann brain exclusion into a categorical dissolve grounded in the operational record definition; and it proposes a strategy for relaxing the static-background assumption by replacing global symmetry assumptions with local, observer-accessible regularity conditions. The direction of time, on this account, is neither a cosmic given nor a subjective imposition, but the inclusion order of the records by which knowers constitute themselves as such.

Appendix (statements only; proofs in companion note)

PW/RAQ setup and admissible clocks. Statements as in the body; proofs, domains, ordering, noise→dephasing, and meetings in Anonymous (2025b).
Monotonicity and selection bounds. Thermodynamic accounting via Landauer–Bennett and information-thermodynamics inequalities; TUR-refined constraints in stationary Markov regimes.

Acknowledgments

The author acknowledges the extensive contributions provided by large language models from Anthropic and OpenAI.

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