Physical Distinction Carriers and Erasure Maps: Accounting Boundaries, Distinction-to-Noise Ratio, and Thermodynamic Implementation

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The FDS formal core distinguishes formal distinctions from physically realized distinctions. A formal distinction is a partition or relation. A physical distinction must be carried by a substrate, read out with bounded error, retained over a task window, and thermodynamically accounted for when it is irreversibly reused. FDS-P1 develops the first paper in the Physical Bridge Ladder. It defines physical distinction carriers, accounting boundaries, side records, distinction-to-noise ratio (DNR), record-stability windows, erasure maps, dissipative projection, refresh cost, and full-boundary thermodynamic accounting. The central boundary statement is conservative: a mathematical projection does not dissipate heat by itself; a physical irreversible implementation by reset, overwrite, many-to-one compression, or garbage collection does. Reversible computation does not evade the ledger; it relocates preimage information into side records, memory-fill pressure, externalization, or later cleanup. The paper separates maintenance and refresh costs from Landauer-style erasure costs, and it clarifies how apparent sub-bound operations can arise when side records, feedback memories, reservoirs, or work sources are omitted from the accounting boundary. Deterministic simulations illustrate DNR-controlled readout error, thermal retention and refresh cost, accounting-boundary side records, logical versus dissipative projection, refresh-versus-erasure ledgers, full energy-flow accounting, and the interface between register-time resolution and physical turnover. The paper does not claim that every distinction dissipates heat, that every measurement is erasure, that Landauer's principle is newly derived, or that mathematical coarse-graining alone produces thermodynamic cost. Its contribution is a physical accounting interface between finite distinctions and thermodynamic implementation.

Scope and Boundary of the Theory. This paper is a physical bridge, not a derivation of thermodynamics from the distinction primitive. It does not assert that every formal distinction is physical, costly, or entropic. It does not assert that reading, copying, sensing, measurement, or reversible computation necessarily pays a Landauer erasure cost. It claims only that task-available physical distinctions require carriers, readout reliability, retention windows, and accounting boundaries; and that physically implemented logically irreversible reset, overwrite, many-to-one compression, or garbage collection requires generalized Landauer accounting under the relevant thermodynamic conditions.

Claim-status summary

Table I summarizes the central FDS-P1 claims, their epistemic status, and the conditions under which they should be weakened or rejected.

Keywords: physical distinction carriers; accounting boundary; distinction-to-noise ratio; finite records; Landauer principle; erasure maps; dissipative projection; refresh cost; record stability; reversible computation; side records; housekeeping dissipation; information thermodynamics; active finite distinction systems.

INTRODUCTION

Why P1 is needed

The FDS formal core starts from distinctions, but it explicitly separates a purely formal distinction from a physically realized record. A formal distinction is a logical separation. A realized distinction in an active finite system is an operational state maintained under finite capacity, update, noise, and resource constraints [1]. P1 is needed because later FDS papers use projections, registers, erasure, overflow, and invariant persistence. Without a physical accounting layer, those words can be misread as a category error: treating a mathematical map as a heat engine.

The P1 bridge is

$$\begin{aligned} &\text{formal distinction} \to \text{carrier} \to \text{record} \\ &\to \text{accounting boundary} \to \text{erasure map} \\ &\to \text{thermodynamic ledger.} \end{aligned} \tag{1}$$

This chain is narrower than the full FDS core. It does not treat life, cognition, geometry, topology, or social systems. It supplies the physical compliance layer needed for P2 on bounded-memory reversible computation, P5 on entropy production in active finite systems, O3 on finite-memory Second-Law channels, and P7 on invariant-supported persistence.

TABLE I. Central FDS-P1 claims, epistemic status, and failure or demotion conditions.

Claim	Status	What would weaken or falsify it
Task-available physical distinctions require carriers, readout reliability, and retention windows.	Operational definition	A finite physical system uses a distinction for a task without any carrier state, readable trace, retention interval, or external record.
Readout reliability is controlled by distinction-to-noise ratio and carrier-state overlap.	Testable bridge	Readout error remains invariant as state separation, noise variance, temperature, drift, or bandwidth are varied under controlled measurement.
The accounting boundary determines whether missing preimage information is erasure, side memory, externalization, or hidden-reservoir correlation.	Accounting principle	Full-boundary audits show that preimage information can be absent, stored, erased, and externalized without any boundary-dependent difference.
Many-to-one maps lose preimage information $H(X\|Y)$ unless side records are included.	Formal theorem	A non-injective deterministic map preserves enough information in its output alone to reconstruct every input under all nontrivial priors.
Mathematical projection is not heat; dissipative projection is a physical implementation claim.	Boundary statement	Not a direct empirical claim; it separates abstract maps from physical implementations.
Refresh cost and erasure cost are distinct ledger terms.	Testable accounting claim	Holding, refresh, clocking, isolation, and reset costs prove inseparable in every controlled implementation.
Reversible logging delays erasure by increasing memory-fill, synchronization, and later cleanup burden.	Conditional physical bridge	Bounded-memory reversible systems sustain unbounded updates indefinitely without memory growth, externalization, compression, cleanup, or failure.

Main boundary statement

The central boundary statement is

$$\begin{gathered}\text{mathematical projection is not heat;}\\ \text{irreversible physical implementation is.}\end{gathered} \tag{2}$$

A map $\pi : X \to Z$ may be many-to-one as an abstract description. That fact alone does not imply that a device has dissipated heat. Heat enters only when a physical substrate performs a logically irreversible operation such as reset, overwrite, many-to-one compression, or garbage collection under the physical assumptions of Landauer-style accounting.

This boundary is essential because FDS-O1, FDS-O2, and FDS-T3 all use finite projection and non-injective update [2–5]. P1 specifies when those projections become thermodynamic events.

Contributions

This paper makes eight contributions.

1. It defines physical distinction carriers and task-available records.
2. It introduces DNR as a measurable carrier-qualification variable.
3. It defines accounting boundaries as sets of physical degrees of freedom included in the ledger.
4. It distinguishes erasure, side-record memory growth, externalization, and reservoir correlation.
5. It defines logical projection versus dissipative projection.
6. It separates refresh, holding, clocking, and isolation costs from Landauer-style erasure costs.
7. It states the O2 interface: sharper register time requires higher physical turnover and, when irreversible reuse is involved, higher housekeeping power.
8. It provides deterministic synthetic simulations and reproducible code.

RELATED WORK

Information, records, and capacity

Shannon information theory provides the language of distinguishable messages, channel limits, and coding [6, 9]. Rate-distortion theory specifies how much information is needed to represent a source at tolerated distortion [7, 8]. FDS uses these tools operationally: a finite system can only use distinctions that are carried by finite records and processed through finite channels.

Landauer, Bennett, and information thermodynamics

Landauer's principle links logically irreversible erasure to heat generation in a physical substrate [10]. Bennett showed that computation can in principle be arranged reversibly when adequate memory and garbage management are available [11]. Experiments and modern information thermodynamics refine this relation under feedback, finite-time protocols, correlations, and nonequilibrium conditions [13–19]. Recent many-body experiments further emphasize that generalized Landauer accounting depends on the chosen system–environment partition and on mutual-information and relative-entropy contributions [20]. P1 follows the conservative reading: erasure cost attaches to physical logically irreversible implementation, not to all information processing.

FDS core and the physical bridge

The FDS core defines logical erasure per update by

$$b_t = H(M_t \mid M_{t+1}, Y_t), \tag{3}$$

and under a physical Landauer bridge gives the informational heat-rate floor

$$\dot{Q}_{\text{info}} \geq \frac{k_{\text{B}} T \ln 2}{\tau} H(M_t \mid M_{t+1}, Y_t). \tag{4}$$

It also separates informational heat from physical losses such as control, coupling, leakage, friction, error correction, clocking, isolation, and transport [1]. P1 is the standalone paper that spells out the carrier, boundary, erasure-map, and implementation assumptions behind Eq. (4).

PHYSICAL DISTINCTION CARRIERS

Definition 1 (Formal distinction)**.** *A formal distinction is a nontrivial separation of alternatives in a possibility space, such as a partition* $\mathcal{D} = \{A_i\}_{i=1}^n$ *with* $n \geq 2$.

Definition 2 (Physical distinction carrier)**.** *A physical distinction carrier for a distinction value* $d \in \{1, \dots, n\}$ *is a family of physical states* $\{s_d\}$ *and a readout procedure* R *such that*

$$\mathbb{P}(R(s_d) = d) \geq 1 - \varepsilon \tag{5}$$

within a specified task interval, physical boundary, and measurement context.

A distinction is therefore not task-available merely because a formal partition exists. It is task-available only when a physical carrier can be read and retained with sufficient reliability.

Distinction-to-noise ratio

For scalar readout with two equal-variance Gaussian carrier states, define

$$\text{DNR} = \frac{|\mu_1 - \mu_0|}{\sigma}. \tag{6}$$

More generally, for vector readout with covariance Σ,

$$\text{DNR}^2 = (\mu_1 - \mu_0)^T \Sigma^{-1} (\mu_1 - \mu_0). \tag{7}$$

For equal priors and equal-variance scalar readout, the Bayes error is

$$P_e = \Phi\left(-\frac{\text{DNR}}{2}\right) = \frac{1}{2}\,\text{erfc}\left(\frac{\text{DNR}}{2\sqrt{2}}\right), \tag{8}$$

where Φ is the standard normal cumulative distribution.

Criterion 1 (Carrier qualification by DNR)**.** *For a task with tolerated readout error* ε*, a binary carrier satisfies the DNR qualification if* $P_e(\text{DNR}) \leq \varepsilon$ *under the specified readout model. In non-Gaussian cases, the DNR may be replaced by the optimal classifier error or another preregistered distinguishability margin.*

DNR is not a new physical law. It is a diagnostic interface between formal distinctions and physical readout. When thermal noise, drift, overlap, or bandwidth limitations reduce DNR, a carrier can lose task availability even though the formal partition still exists.

Record stability and retention window

Definition 3 (Record stability window)**.** *A physical distinction carrier has a record stability window* $\tau_{\text{rec}}(\varepsilon)$ *if*

$$\mathbb{P}(\hat{d}(t') = d \mid \hat{d}(t) = d) \geq 1 - \varepsilon \quad \textit{for all } 0 \leq t' - t \leq \tau_{\text{rec}}(\varepsilon). \tag{9}$$

It is task-available over a task window τ_{task} *only if* $\tau_{\text{rec}}(\varepsilon) \geq \tau_{\text{task}}$ *or if refresh, error correction, or external records supply an equivalent retention function.*

A simple thermal-barrier model gives

$$\tau_{\text{rec}} \approx \tau_0 \exp(E_b / k_{\text{B}} T), \tag{10}$$

where E_b is an effective barrier and τ_0 a microscopic timescale. This is a toy retention model, not a universal law. It makes one point explicit: a record is physical only relative to stability under noise. Device-level memory studies likewise show that retention is a physical carrier property, controlled by material stability, diffusion, and thermodynamic phase structure rather than by abstract bit labels alone [21].

Proposition 1 (Carrier criterion)**.** *A distinction is physically task-available only relative to a carrier, readout tolerance, task window, and accounting boundary.*

Proof. If there is no carrier, no physical state differs between alternatives. If there is no reliable readout, the alternatives cannot be operationally used. If the carrier does not remain stable or refreshed over the task window, the distinction is unavailable when needed. If the accounting boundary excludes the carrier or its side records, the distinction may be physically present elsewhere but unavailable to the system under that boundary. □

ACCOUNTING BOUNDARIES AND SIDE RECORDS

Definition 4 (Accounting boundary)**.** *An accounting boundary $\mathcal{A}$ is the set of physical degrees of freedom included in the thermodynamic and information ledger for an operation:*

$$\mathcal{A} = \{q_i : i \in I\}. \tag{11}$$

It may include a visible register, side records, feedback-controller memory, error-correction syndromes, work reservoirs, clocking systems, external logs, and thermal reservoirs, depending on the audit.

The same physical process can look reversible, irreversible, sub-bound, or externalized depending on which degrees of freedom are included. P1 therefore treats erasure as boundary-relative.

Let X be the pre-update record, Y the visible post-update record, $G_{\mathcal{A}}$ side information retained inside $\mathcal{A}$, and $G_{\bar{\mathcal{A}}}$ side information transferred outside $\mathcal{A}$.

Definition 5 (Erasure relative to an accounting boundary)**.** *The preimage information erased relative to $\mathcal{A}$ is*

$$\mathcal{L}_{\mathcal{A}} = H(X \mid Y, G_{\mathcal{A}}). \tag{12}$$

If $G_{\mathcal{A}}$ contains enough side information to reconstruct X, then $\mathcal{L}_{\mathcal{A}} = 0$ even if $H(X \mid Y) > 0$.

Proposition 2 (Side-record relocation)**.** *If an implementation embeds a many-to-one visible map into an injective enlarged map*

$$X \longmapsto (Y, G_{\mathcal{A}}) \tag{13}$$

with $H(X \mid Y, G_{\mathcal{A}}) = 0$, then no erasure has occurred relative to $\mathcal{A}$. The cost has been relocated to memory fill, carrier maintenance, synchronization, externalization, or later garbage cleanup.

Proof. By definition, erasure relative to $\mathcal{A}$ is $H(X \mid Y, G_{\mathcal{A}})$. If the enlarged record is injective, the conditional entropy is zero. The preimage information remains present in $\mathcal{A}$, so the operation avoids immediate Landauer erasure relative to that boundary. However, the retained side record occupies physical memory and must be carried, protected, synchronized, or eventually erased. □

This is the P1 interface to reversible computation. Reversible computation does not make the ledger disappear; it enlarges the accounting boundary and delays payment [12]. Reversible logic delays erasure by retaining preimage information in side registers, at the cost of memory-fill pressure, refresh overhead, and eventual cleanup.

Proposition 3 (Accounting-boundary monotonicity)**.** *If $\mathcal{A} \subseteq \mathcal{A}'$, then $\mathcal{L}_{\mathcal{A}'} \leq \mathcal{L}_{\mathcal{A}}$, where $\mathcal{L}_{\mathcal{A}} = H(X \mid Y, G_{\mathcal{A}})$. Enlarging the accounting boundary to include additional side records, controller memory, or reservoir correlations cannot increase the erased preimage information; it can only reduce or leave it unchanged.*

Proof. Adding degrees of freedom to $G_{\mathcal{A}}$ cannot increase the conditional entropy $H(X \mid Y, G_{\mathcal{A}})$ because conditioning on additional variables never increases entropy. Hence $\mathcal{L}_{\mathcal{A}'} \leq \mathcal{L}_{\mathcal{A}}$. □

Sub-bound erasure illusion. The monotonicity proposition gives a formal handle on a central P1 theme. If an experimental or computational system appears to erase information without heat, it may be using a narrower accounting boundary that excludes side records, feedback memories, or reservoir correlations. The apparent sub-Landauer or sub-bound erasure is real relative to that boundary but does not violate full-boundary accounting when the boundary is widened.

ERASURE MAPS AND DISSIPATIVE PROJECTION

Definition 6 (Erasure map)**.** *Let X be a pre-update physical record space and Y a post-update visible record space. A deterministic update $f : X \to Y$ is an erasure map relative to a prior distribution P_X and an accounting boundary $\mathcal{A}$ if f is many-to-one on a set of nonzero probability and the missing preimage is not retained in $G_{\mathcal{A}}$.*

Definition 7 (Preimage loss)**.** *For a visible deterministic map $Y = f(X)$, the visible preimage loss is*

$$\mathcal{L}_f = H(X \mid Y). \tag{14}$$

For deterministic f,

$$\mathcal{L}_f = H(X) - H(Y). \tag{15}$$

The erasure relevant to boundary $\mathcal{A}$ is $\mathcal{L}_{\mathcal{A}} = H(X \mid Y, G_{\mathcal{A}})$. We call $\mathcal{L}_{\mathcal{A}}$ the residual irreversibility *of the operation relative to the accounting boundary $\mathcal{A}$. It is the part of the preimage that remains unrecoverable after all side records included in the ledger have been conditioned on.*

Theorem 1 (Non-injective updates lose inverse information). *If $f : X \to Y$ is non-injective on a set of positive probability and the output does not include side information selecting the preimage, then $H(X \mid Y) > 0$ for some admissible priors. The output alone cannot reconstruct every input.*

Proof. Since f is non-injective, there exists $y \in Y$ with distinct preimages x_1, x_2 such that $f(x_1) = f(x_2) = y$. Choose a prior assigning positive probability to both x_1 and x_2. Conditioning on $Y = y$ leaves at least two possible inputs with positive probability. Hence $H(X \mid Y = y) > 0$, and therefore $H(X \mid Y) > 0$. □

Definition 8 (Logical projection). *A logical projection is an abstract or descriptive many-to-one map $\pi : X \to Z$. It can be used in a mathematical model without specifying any physical implementation.*

Definition 9 (Dissipative projection). *A dissipative projection $\Pi^{\mathcal{A}}_{\mathrm{diss}}$ is a physical implementation of a many-to-one map inside accounting boundary $\mathcal{A}$ that discards preimage information by reset, overwrite, many-to-one compression, or garbage collection. It is an implementation claim, not a property of the abstract map alone.*

Thus,

$$\text{logical projection} \neq \text{dissipative projection}. \tag{16}$$

A finite projection in T3 or a non-injective update in O2 becomes thermodynamic only when it is physically implemented in this stronger sense.

THE LANDAUER ACCOUNTING BRIDGE

Assumption 1 (Landauer accounting bridge). *If a physical implementation within accounting boundary $\mathcal{A}$ reliably realizes a logically irreversible map with erased preimage information $\mathcal{L}_{\mathcal{A}}$ bits while coupled to a thermal environment at temperature $T > 0$, then the minimal heat dumped to the environment under ideal quasistatic accounting satisfies*

$$Q^{\mathcal{A}}_{\min} \geq k_{\mathrm{B}} T \ln 2\, \mathcal{L}_{\mathcal{A}}. \tag{17}$$

Finite-time, finite-bath, feedback, correlated, strong-coupling, quantum, or nonideal implementations require generalized accounting and may dissipate more than this ideal floor.

Theorem 2 (Boundary-relative erasure heat floor). *For a physical many-to-one implementation satisfying the Landauer accounting bridge, the informational heat obeys Eq. (17). For repeated updates at timescale τ,*

$$\dot{Q}^{\mathcal{A}}_{\mathrm{info}} \geq \frac{k_{\mathrm{B}} T \ln 2}{\tau}\, H(X_t \mid Y_t, G_{\mathcal{A},t}). \tag{18}$$

Proof. $H(X_t \mid Y_t, G_{\mathcal{A},t})$ is the average missing preimage information after all side records inside $\mathcal{A}$ are included. Under the physical bridge, each erased bit contributes at least $k_{\mathrm{B}} T \ln 2$ of heat in the ideal limit. Dividing by the update timescale gives the rate form. □

Remark 1 (Sub-bound appearances). *If an experiment appears to erase below the ideal bound, P1 requires auditing $\mathcal{A}$: side records, feedback memories, measurement correlations, work reservoirs, clocking systems, and thermal reservoirs. A persistent reliable violation after full accounting would demote the physical bridge, not the formal FDS core.*

MAINTENANCE, REFRESH, AND ERASURE LEDGERS

A stable physical record can cost resources even when no erasure occurs. Holding a carrier away from thermal equilibrium, refreshing a leaky memory cell, maintaining an error-correcting code, stabilizing a molecular state, or synchronizing a clock can all carry physical cost. P1 separates the ledger:

$$\dot{Q}_{\mathrm{total}} = \dot{Q}_{\mathrm{phys}} + \dot{Q}_{\mathrm{info}}, \tag{19}$$

where $\dot{Q}_{\mathrm{info}}$ is the logically irreversible preimage-erasure floor and $\dot{Q}_{\mathrm{phys}}$ includes non-erasure physical overhead.

A useful decomposition is

$$\begin{aligned}\dot{Q}_{\mathrm{phys}} = \dot{Q}_{\mathrm{hold}} + \dot{Q}_{\mathrm{refresh}} + \dot{Q}_{\mathrm{read}} + \dot{Q}_{\mathrm{ctrl}} + \dot{Q}_{\mathrm{sync}} \\ + \dot{Q}_{\mathrm{ec}} + \dot{Q}_{\mathrm{clock}} + \dot{Q}_{\mathrm{isolate}} + \dot{Q}_{\mathrm{transport}} + \cdots.\end{aligned} \tag{20}$$

The exact terms are device- and domain-specific. The point is not to replace engineering power models with one formula. It is to avoid conflating all cost with Landauer erasure.

Definition 10 (Refresh cost). *Refresh cost is the physical power required to preserve an existing distinction against leakage, drift, diffusion, thermal switching, decoherence, demagnetization, chemical turnover, or other destabilizing processes. For an event-based refresh model one may write*

$$\dot{Q}_{\mathrm{refresh}} = \eta_{\mathrm{ref}}^{-1} E_{\mathrm{refresh}} f_{\mathrm{refresh}}, \qquad E_{\mathrm{refresh}} = \alpha E_b, \tag{21}$$

where E_b is an effective stability barrier, α is an implementation-dependent repair fraction, and $\eta_{\mathrm{ref}} \in (0, 1]$ is a refresh-efficiency factor. This is not a universal law for memory maintenance; it is a dimensional accounting proxy for systems whose retention is maintained by discrete refresh or repair events.

Definition 11 (Housekeeping dissipation). *Housekeeping dissipation is the ongoing physical cost of maintaining a record-bearing boundary, including holding, refresh,* *synchronization, error correction, isolation, clocking, and irreversible reuse.*

Proposition 4 (Bounded-memory reuse pressure)**.** *A system with finite memory undergoing sustained updates must eventually choose among increased memory, externalization, reversible side-record accumulation, irreversible cleanup, lossy compression, task relaxation, or failure.*

Proof. If every update is logged reversibly, memory demand grows with the number of retained preimage distinctions. With bounded memory, this growth cannot continue indefinitely. If memory does not increase and side records are not externalized, the system must compress, erase, reset, relax the task, or fail to retain the preimage. If it performs irreversible cleanup, the erased information enters the Landauer accounting term. □

This proposition is the direct setup for FDS-P2. P1 defines the ledger. P2 studies the dynamics of bounded-memory reversible computation under that ledger.

INTERFACE WITH REGISTER TIME

FDS-O2 treats usable temporal order as finite-record update. P1 supplies the physical turnover account. If a finite register maintains clock ticks of $b_{\rm tick}$ bits at resolution Δt, the update throughput satisfies

$$\dot{I}_{\rm update} \gtrsim \frac{b_{\rm tick}}{\Delta t}. \tag{22}$$

If $b_{\rm erase}$ bits are irreversibly reused per tick, then the Landauer-style lower bound scales as

$$P_{\rm erase} \geq k_B T \ln 2 \, \frac{b_{\rm erase}}{\Delta t}. \tag{23}$$

This is not a claim of exponential cost. The lower bound is at least linear in irreversible turnover rate. Real systems may incur superlinear engineering costs when sharper timing requires stronger isolation, refresh, error correction, synchronization, or clocking.

Thus sharper register time requires more physical updating:

$$\Delta t \downarrow \quad \Rightarrow \quad \dot{I}_{\rm update} \uparrow, \quad \dot{Q}_{\rm refresh} + \dot{Q}_{\rm erase} + \dot{Q}_{\rm clock} \uparrow \tag{24}$$

under the relevant implementation assumptions.

NUMERICAL MODELS AND SIMULATIONS

The simulations are deterministic synthetic demonstrations. They are not fits to physical memory devices, detector data, quantum experiments, AI benchmarks, or biological records. They provide reproducible model diagrams for the P1 accounting layer. All figures and CSV outputs are generated by `code/generate_results.py`.

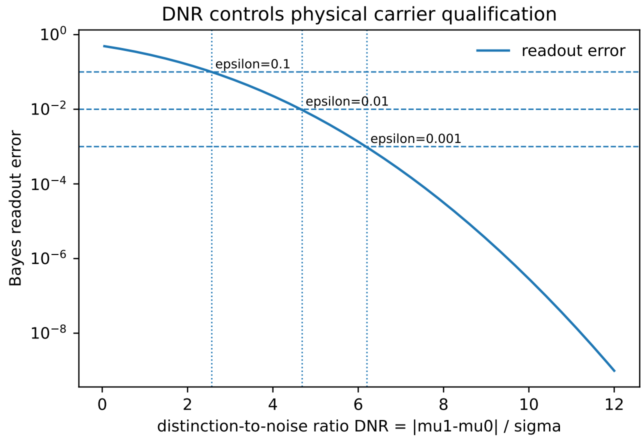

FIG. 1. DNR controls physical carrier qualification. For two equal-variance Gaussian carrier states, readout error falls as $\text{DNR} = |\mu_1 - \mu_0|/\sigma$ increases. A formal distinction becomes task-available only when the physical carrier clears the task tolerance.

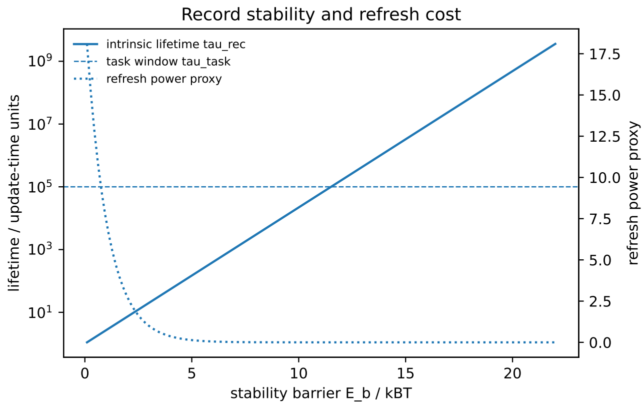

FIG. 2. Record stability and refresh cost. A barrier model gives an Arrhenius-like intrinsic lifetime. When intrinsic lifetime is shorter than the task window, the distinction requires refresh, error correction, or externalization to remain task-available.

Carrier qualification

Figures 1 and 2 illustrate the carrier criterion. DNR controls readout reliability. Barrier height and temperature control retention in the toy model. Both are physical properties of carriers, not properties of the formal partition alone.

Accounting boundaries and dissipative projection

Figures 3 and 4 show why boundary choice matters. A many-to-one visible map can be reversible relative to an enlarged boundary if side records retain the preimage. It becomes dissipative projection when the physical imple-

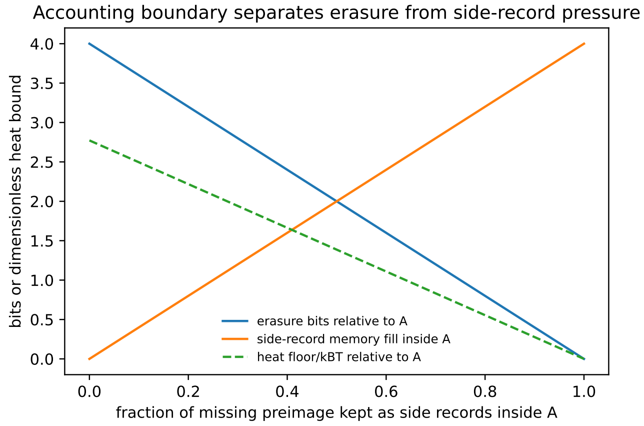

FIG. 3. Accounting boundary separates erasure from side-record pressure. If missing preimage information is retained inside $\mathcal{A}$ as side records, immediate erasure relative to $\mathcal{A}$ falls but memory-fill pressure grows. If no side records are retained, the visible many-to-one map incurs erasure relative to $\mathcal{A}$.

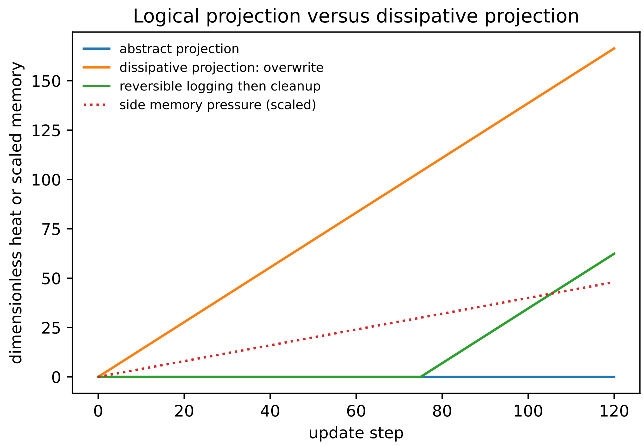

FIG. 4. Logical projection versus dissipative projection. An abstract projection has no thermodynamic ledger by itself. Physical overwrite accumulates erasure cost immediately. Reversible logging delays erasure by increasing side memory and later cleanup burden.

mentation irreversibly discards that preimage within the accounting boundary.

Refresh, full-boundary accounting, and time resolution

Figure 5 separates maintenance from erasure. Figure 6 visualizes the accounting-boundary audit. Figure 7 connects P1 to O2 by showing how finer register time forces higher physical turnover.

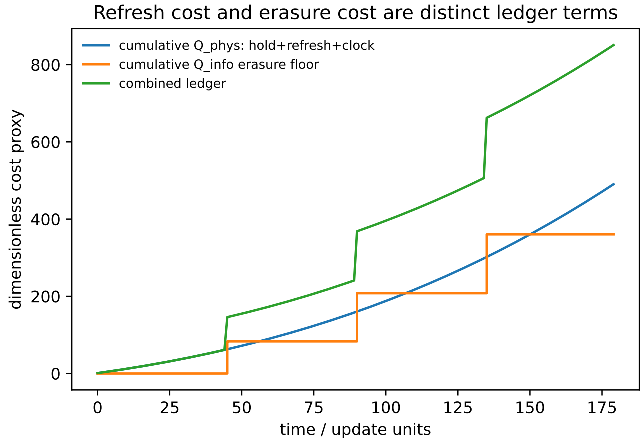

FIG. 5. Refresh cost and erasure cost are distinct ledger terms. Maintaining stable records can require ongoing holding, refresh, and clocking cost even when no erasure occurs. Batched cleanup adds a separate erasure floor.

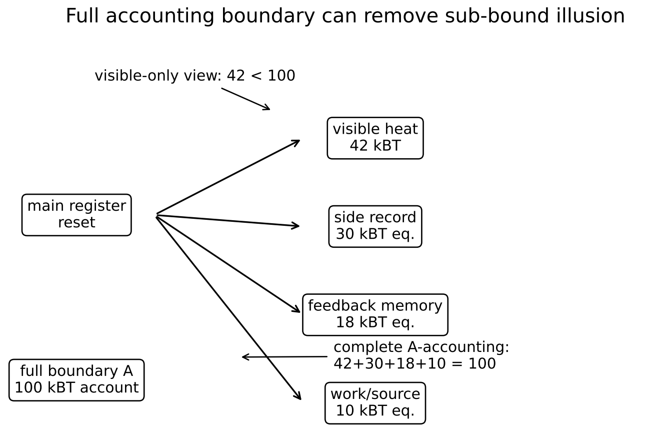

FIG. 6. Full accounting boundary can remove sub-bound illusion. Counting only visible heat can make an operation appear below the full erasure account. Including side records, feedback memory, work sources, and reservoirs restores the complete boundary ledger. Values are illustrative accounting units.

EXPERIMENTAL PROTOCOLS

Protocol 1 (DNR and carrier readout test)**.** *Prepare two or more physical carrier states with tunable separation and noise. Measure the confusion matrix* $P(\hat{d} \mid d)$ *as a function of margin, temperature, drift, or measurement bandwidth. P1 predicts that task-available distinctions require readout error below the task tolerance.*

Protocol 2 (Retention and refresh test)**.** *Prepare a record and vary barrier height, temperature, isolation, or refresh rate. Measure* $\tau_{\mathrm{rec}}(\varepsilon)$ *and compare it to* τ_{task}*. P1 predicts loss of task availability when* $\tau_{\mathrm{rec}} < \tau_{\mathrm{task}}$ *unless refresh, error correction, or external records compensate.*

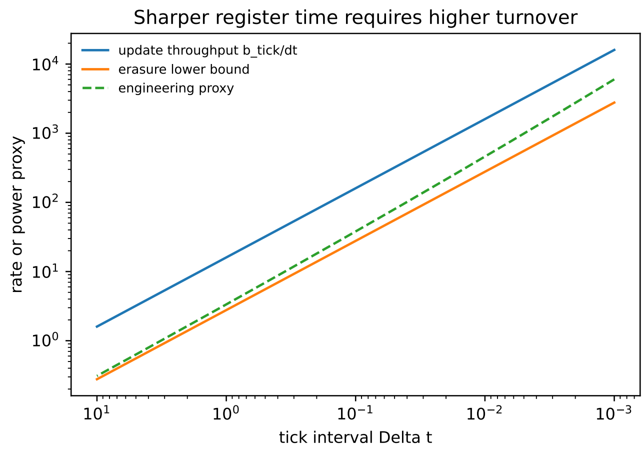

FIG. 7. Sharper register time requires higher turnover. Decreasing tick interval increases update throughput. If irreversible reuse occurs per tick, the lower-bound erasure power scales at least with turnover rate; nonideal engineering overhead may grow faster.

Protocol 3 (Accounting-boundary audit)**.** *Implement a visible many-to-one map and progressively include side registers, feedback memories, reservoirs, and work sources in* $\mathcal{A}$*. P1 predicts that erasure relative to* $\mathcal{A}$ *is* $H(X \mid Y, G_{\mathcal{A}})$*, not simply* $H(X \mid Y)$*.*

Protocol 4 (Projection versus implementation test)**.** *Compare three implementations of the same coarse map: abstract offline description, reversible logging of preimage information, and irreversible overwrite. P1 predicts no heat statement for the abstract map, growing memory for reversible logging, and erasure accounting for overwrite or cleanup.*

Protocol 5 (Refresh-erasure separation)**.** *Operate a memory system with fixed record set and no reset, then with periodic reset under the same holding conditions. Estimate holding/refresh/clocking cost separately from erasure-event heat. P1 predicts that these ledgers are conceptually and often experimentally separable.*

Protocol 6 (Register-time turnover test)**.** *Increase clock or update resolution while measuring refresh, clocking, error-correction, and erase/reset power. P1 predicts that the erasure lower bound grows at least with irreversible turnover rate, while engineering overhead may grow superlinearly depending on implementation.*

LIMITATIONS AND FALSIFICATION

First, P1 is not a universal theory of thermodynamics. It is a bridge between physical records and logically irreversible information loss. Second, it does not claim that every distinction has a thermodynamic cost. Formal distinctions can remain formal. Physical distinctions can be maintained reversibly or with costs dominated by engineering overhead rather than erasure. Third, it does not claim that every measurement is erasure. Fourth, it does not resolve debates over the exact scope of Landauer's principle in every finite-time, finite-bath, quantum, correlated, feedback, or strong-coupling setting. Fifth, the simulations are synthetic demonstrations.

The strong version of FDS-P1 would be weakened or rejected by any of the following:

1. a task-available physical distinction used by a finite system without carrier state, readout contrast, retention interval, causal trace, or external record;
2. controlled readout experiments in which state overlap, noise, drift, or DNR have no effect on reliability;
3. a many-to-one physical reset whose visible output alone reconstructs every input without side information;
4. reliable logically irreversible erasure below generalized Landauer accounting after all reservoirs, correlations, feedback records, work sources, side records, and boundary choices are included;
5. bounded-memory reversible systems that sustain unbounded updates without memory growth, externalization, cleanup, compression, or failure;
6. experiments showing that holding, refresh, clocking, and reset costs cannot be separated under any implementation;
7. systems maintaining arbitrarily fine register-time resolution without increased update throughput, refresh, clocking, or erasure burden.

CONCLUSION

FDS-P1 supplies the first rung of the Physical Bridge Ladder. It takes a concept that is formal in the FDS core–distinction–and specifies the physical conditions under which it becomes a usable record. The result is not a new derivation of Landauer's principle. It is an accounting framework for finite distinction systems: a physical distinction must be carried, readable, stable, and bounded; side records must be included or excluded explicitly; a many-to-one erasure map loses preimage information relative to an accounting boundary; and a physical irreversible implementation of that loss enters the thermodynamic ledger.

The most compact statement is this: formal distinctions separate possibilities, but physical distinctions must be carried by finite records. Mathematical projection is not heat. Dissipative projection is a physical implementation with an accounting boundary. When finite records are irreversibly reused, the erased preimage enters the heat account; when they are preserved reversibly, the cost reappears as memory fill, refresh, synchronization, externalization, or later cleanup. This is the bridge needed before one can discuss bounded-memory reversible computation, housekeeping dissipation, finite-memory entropy production, or topological obstruction to forgetting.

Generalized Carrier Distinguishability Metrics

The main text uses distinction-to-noise ratio (DNR) as the primary distinguishability metric for physical carriers. DNR is intuitive, experimentally accessible, and easy to visualize. However, the carrier criterion generalizes to any pre-registered distinguishability margin. A physical carrier qualifies for a task when a pre-registered error measure falls below the task tolerance, or equivalently when a pre-registered distinguishability margin exceeds the required threshold.

Each metric has domain-specific advantages. Total variation and Helstrom bound are prior-free operational error probabilities. Chernoff information gives the optimal error exponent for repeated or sequential discrimination. Fisher information connects distinguishability to parameter-estimation precision and Cramér–Rao bounds. In quantum carriers with equal priors, the Helstrom bound gives $P_e^* = \frac{1}{2}\big(1 - \frac{1}{2}\|\rho_1 - \rho_2\|_1\big)$. More generally, $P_e^* = \frac{1}{2}\big(1 - \|\pi_0\rho_0 - \pi_1\rho_1\|_1\big)$ for arbitrary priors.

For a given task with tolerance ϵ, the carrier qualifies if

$$P_e^*(\text{readout} \mid \text{carrier states}) \le \epsilon, \tag{25}$$

where P_e^* is the minimum achievable classification error under the relevant physical readout constraints. DNR is the Gaussian binary special case of this criterion. The choice of metric is pre-registered as part of the experimental protocol.

Notation Summary

Simulation Parameters

The simulations are deterministic and use fixed synthetic parameters in `code/generate_results.py`. Figure 1 uses the Gaussian readout error $P_e = \Phi(-\text{DNR}/2)$. Figure 2 uses the Arrhenius lifetime proxy $\tau_{\text{rec}} = \tau_0 \exp(E_b/k_B T)$ and an event-based refresh power proxy. Figure 3 maps 256 inputs to 16 visible classes and varies the fraction of missing preimage information retained inside $\mathcal{A}$. Figure 4 compares abstract projection, physical overwrite, reversible logging, and delayed cleanup. Figure 5 separates holding, refresh, clocking, and erasure events. Figure 6 is an illustrative full-boundary accounting diagram. Figure 7 uses $b_{\text{tick}}/\Delta t$ and $b_{\text{erase}}/\Delta t$ proxies for register-time turnover. No proprietary, device, biological, quantum, or human-subject data are used.

Reproducibility Checklist

1. Code availability: all simulation code is included in the replication package.
2. Deterministic execution: the random seed is fixed where randomness is used.
3. Figure reproduction: run `python code/generate_results.py`; the script regenerates all figures and CSV outputs.
4. Data status: all numerical outputs are synthetic demonstrations generated from the stated model.
5. Platform independence: the code uses standard Python scientific libraries.

Code Availability

The simulation code used to generate Figs. 1–7 is included in the accompanying replication package under `code/generate_results.py`. Running the script regenerates all figures (PDF and PNG) and CSV tables in a single pass.

AI Assistance Disclosure

AI-assisted tools were used for language polishing, structural feedback, LaTeX drafting support, and code-debugging assistance. The author reviewed and edited all content and remains responsible for all claims, references, simulations, and conclusions. No AI system is listed as an author.

[1] Y. Wu, “Active Finite Distinction Systems: A Formal Core for Boundary Maintenance under Finite Capacity,” Zenodo (2026), doi:10.5281/zenodo.20158923.

[2] Y. Wu, “Finite Distinguishability Budgets and Maintenance Bounds for Physical Observers,” Zenodo (2026), doi:10.5281/zenodo.20234249.

[3] Y. Wu, “Observer as a Finite Distinction Register: Measurement Capacity, Dynamic Bottlenecks, and Budget-Crossing Signatures,” Zenodo (2026), doi:10.5281/zenodo.20248792.

[4] Y. Wu, “Time as Irreversible Distinction Update: Finite Records, Causal Ordering, and Register-Time Collapse,” Zenodo (2026), doi:10.5281/zenodo.20249369.

[5] Y. Wu, “Capacity Overflow, Effective Stochasticity, and Phase-B Invariants: Critical Deficit, Markov Closure,

TABLE II. Generalized distinguishability metrics for the carrier criterion. In the Gaussian binary case DNR is sufficient; for non-Gaussian, structured, or quantum carriers the table gives candidate alternatives. Some entries, such as KL divergence and Fisher information, are local or model-dependent margins rather than direct single-shot error probabilities.

Metric	**Definition**	**Typical threshold form**
DNR	$(m_1 - m_2)/\sqrt{\sigma_1^2 + \sigma_2^2}$	$\mathrm{DNR} \geq \mathrm{DNR}_{\min}$
Total variation distance d_{TV}	$\frac{1}{2}\sum_x \lvert p_1(x) - p_2(x)\rvert$	$P_e^* = \frac{1}{2}(1 - d_{\mathrm{TV}})$, so $d_{\mathrm{TV}} \geq 1 - 2\epsilon$
Kullback–Leibler divergence D_{KL}	$\sum_x p_1(x) \log \frac{p_1(x)}{p_2(x)}$	$D_{\mathrm{KL}} \geq d_{\min}$
Chernoff information C_*	$-\log \min_{s\in[0,1]} \sum_x p_1(x)^s p_2(x)^{1-s}$	$C_* \geq c_{\min}$
Fisher information $\mathcal{I}(\theta)$	$\mathbb{E}[(\partial_\theta \log p_\theta)^2]$	$\mathcal{I}(\theta) \geq \mathcal{I}_{\min}$
Helstrom bound P_e^*	$P_e^* = \frac{1}{2}\big(1 - \frac{1}{2}\lVert\rho_1 - \rho_2\rVert_1\big)$ for equal priors	$P_e^* \leq \epsilon$

TABLE III. FDS-P1 notation summary.

Symbol	Meaning
$\mathcal{D}$	formal distinction or partition
d	distinction value or label
s_d	physical carrier state realizing distinction value d
R	readout procedure
ε	tolerated readout or retention error
DNR	distinction-to-noise ratio, e.g. $\lvert\mu_1 - \mu_0\rvert/\sigma$
τ_{rec}	record stability window
τ_{task}	task window requiring the record
$\mathcal{A}$	accounting boundary: included physical degrees of freedom
$G_{\mathcal{A}}$	side record or garbage information retained inside $\mathcal{A}$
X	pre-update physical record space
Y	visible post-update record space
$f : X \to Y$	deterministic update or visible erasure map
$\mathcal{L}_f$	visible preimage loss $H(X\|Y)$
$\mathcal{L}_{\mathcal{A}}$	boundary-relative erasure $H(X\|Y, G_{\mathcal{A}})$
$\Pi_{\mathrm{diss}}^{\mathcal{A}}$	dissipative projection implemented inside $\mathcal{A}$
$\dot{Q}_{\mathrm{info}}$	informational heat-rate floor from logically irreversible erasure
$\dot{Q}_{\mathrm{refresh}}$	refresh power required to maintain existing records
$\dot{Q}_{\mathrm{phys}}$	non-erasure physical power: holding, readout, clocking, isolation, transport, error correction, etc.
$\dot{Q}_{\mathrm{total}}$	total accounting rate $\dot{Q}_{\mathrm{phys}} + \dot{Q}_{\mathrm{info}}$

and Invariant Selection under Finite Projection," Zenodo (2026), doi:10.5281/zenodo.20250367.

[6] C. E. Shannon, "A mathematical theory of communication," Bell System Technical Journal **27**, 379–423 and 623–656 (1948).

[7] C. E. Shannon, "Coding theorems for a discrete source with a fidelity criterion," IRE National Convention Record **7**, 142–163 (1959).

[8] T. Berger, *Rate Distortion Theory: A Mathematical Basis for Data Compression*. Prentice-Hall (1971).

[9] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, 2nd ed. Wiley (2006).

[10] R. Landauer, "Irreversibility and heat generation in the computing process," IBM Journal of Research and Development **5**, 183–191 (1961).

[11] C. H. Bennett, "The thermodynamics of computation–a review," International Journal of Theoretical Physics **21**, 905–940 (1982).

[12] C. H. Bennett, "Logical reversibility of computation," IBM Journal of Research and Development **17**, 525–532 (1973).

[13] S. Toyabe, T. Sagawa, M. Ueda, E. Muneyuki, and M. Sano, "Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality," Nature Physics **6**, 988–992 (2010).

[14] A. Bérut, A. Arakelyan, A. Petrosyan, S. Ciliberto, R. Dillenschneider, and E. Lutz, "Experimental verification of Landauer's principle linking information and thermodynamics," Nature **483**, 187–189 (2012).

[15] T. Sagawa, "Thermodynamics of information processing in small systems," Progress of Theoretical Physics **127**, 1–56 (2012).

[16] J. M. R. Parrondo, J. M. Horowitz, and T. Sagawa, "Thermodynamics of information," Reviews of Modern Physics **87**, 45–67 (2015).

[17] Y. Jun, M. Gavrilov, and J. Bechhoefer, "High-precision test of Landauer's principle in a feedback trap," Physical Review Letters **113**, 190601 (2014).

[18] D. H. Wolpert, "The stochastic thermodynamics of computation," Journal of Physics A: Mathematical and Theoretical **52**, 193001 (2019).

[19] P. Chattopadhyay, A. Misra, T. Pandit, and G. Paul, "Landauer principle and thermodynamics of computation," Reports on Progress in Physics **88**, 086001 (2025).

[20] S. Aimet, M. Tajik, G. Tournaire, P. Schüttelkopf, J. Sabino, S. Sotiriadis, G. Guarnieri, J. Schmiedmayer, and

J. Eisert, “Experimentally probing Landauer’s principle in the quantum many-body regime,” Nature Physics **21**, 1326–1331 (2025).

[21] J. Li, S. Kim, Y. Lee, and W. D. Lu, “Thermodynamic origin of nonvolatility in resistive memory,” Matter **7**, 3970–3993 (2024).