Semantic-Convergence Erasure: A Hybrid Model for Low-Irreversibility Computation

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1. Introduction

Energy dissipation in computation is fundamentally linked to logical irreversibility. Every time information is destroyed—through overwrites, deletions, or irreversible state replacement—a minimum amount of heat must be dissipated, as formalized by Landauer's principle. While physical inefficiencies exacerbate energy loss, logical irreversibility establishes a lower bound that no hardware improvement alone can bypass.

Reversible computation theory demonstrates that computation can, in principle, be performed without erasing information. However, existing reversible models suffer from severe practical limitations: unbounded memory growth, excessive bookkeeping, and lack of semantic structure. These issues prevent adoption in long-lived, real-world systems.

At the same time, many practical systems—databases, monitoring engines, agents, and control systems — exhibit a distinct property: semantic convergence. Their internal state continues to evolve, but the externally observable meaning stabilizes.

This work asks:

Can irreversibility be reduced not by avoiding computation, but by exploiting convergence in meaning?

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1. Background and Related Work

2.1 Landauer's Principle

Landauer (1961) established that erasing one bit of information incurs a minimum thermodynamic cost:

$$E \geq kT \ln 2$$

This links information erasure directly to energy dissipation and heat generation.

2.2 Reversible Computation

Fredkin and Toffoli introduced reversible logic gates. Bennett later showed that any computation can be simulated reversibly by recording intermediate states and uncomputing them.

Limitation: Bennett-style simulation requires auxiliary space that grows linearly with time, making it unsuitable for long-running systems.

2.3 Gaps in Existing Models

Existing approaches:

• Treat history syntactically, not semantically • Fail to exploit convergence in meaning • Allow implicit, unaccounted erasure

There is no standard model that explicitly counts erasure while collapsing state based on semantic equivalence.

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1. Model Definition

We define a Layered Hybrid Computation Model consisting of three explicit layers.

Layer 1 — Reversible Core

• State transitions are bijective • No overwrite or deletion • Entity identity persists across mutation

Layer 2 — Semantic Layer

• Meaning is defined by query behavior • Structurally distinct states may be semantically equivalent • Semantic equivalence is defined relative to a fixed query set Q

Layer 3 — Erasure Boundary

• Irreversibility is explicit and counted • No implicit garbage collection • Erasure occurs only under defined conditions

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1. Scoped Semantic Equivalence

Let Q be a fixed, finite, closed set of queries.

Two states S_i and S_j are semantically equivalent relative to Q iff:

$\forall q \in Q, q(S_i) = q(S_j)$

Semantic equivalence is explicitly scoped and does not claim equivalence under arbitrary future queries.

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1. Semantic-Convergence Erasure

Core Rule

Irreversible erasure is permitted only when semantic equivalence is detected.

For a semantic equivalence class containing N states:

• Retain one canonical representative • Retain one reversible witness • Erase the remaining $N - 2$ states

Erasure Accounting

The irreversible operation count is incremented by N − 2. No erasure occurs due to time, memory pressure, or resource limits.

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1. Theorem (Lower Bound on Semantic-Preserving Computation)

Theorem.

For any computation that:

1. Executes for unbounded or long-lived time
2. Preserves exact semantic equivalence relative to a fixed finite query set Q
3. Answers future queries correctly

irreversible erasure is unavoidable. Moreover, any such system must incur irreversible erasure at least on the order of semantic-convergence erasure.

This result establishes a necessary lower bound, not an optimization or implementation strategy.

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1. Proof Sketch

After convergence time T_0, all subsequent states map to an existing semantic equivalence class. Internal evolution may continue, but only a constant number of representatives are retained per class. All additional states are collapsed, and no asymptotically increasing irreversibility is introduced beyond semantic-convergence erasure.

Formal Necessity Proof.

A complete formalization of the necessity argument—including explicit definitions, lemmas, and elimination of alternative erasure-avoidance mechanisms—is provided in STEP 4: Formal Statement & Proof (Semantic-Convergence Erasure), which serves as a supplementary formal appendix to this work.

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1. Experimental Validation

A trust-network workload with forced overwrite dominance (>70%) and semantic convergence was simulated.

Results (N = 10,000):

• Classical irreversible operations: 4,104 • Semantic-convergence erasure operations: 54 • Reduction: 98.7%

Hybrid irreversibility grows orders of magnitude slower than classical overwrite-based computation.

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1. Scope, Assumptions, and Failure Modes (Result of Adversarial Analysis)

Scope Clarification

This theorem applies only to computational systems that satisfy all of the following:

1. Preserve exact semantic equivalence relative to a fixed, finite query set Q
2. Execute for unbounded or long-lived time
3. Require correct future answers for all queries in Q
4. Do not permit intentional semantic loss or approximation

Systems that violate any of these conditions fall outside the theorem’s scope.

Failure Mode: Approximate Semantics

If semantic equivalence is approximate rather than exact, semantic classes become unstable and the lower-bound guarantee no longer holds. Energy reduction may be achieved only by sacrificing correctness.

Failure Mode: Modern AI Agents

Current AI systems aggressively overwrite state, drop context, and allow semantic drift. These systems violate semantic preservation and fall outside the theorem’s applicability.

Allowed Bypass

A system may bypass the lower bound by sacrificing semantic correctness through overwriting, history loss, or inconsistency. Such systems are explicitly excluded.

Non-Claims

This work does not claim:

• A new physical law • Elimination of Landauer’s principle • Zero-energy computation • Universal applicability to all electronics

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1. Conclusion

Semantic-Convergence Erasure establishes a necessary lower bound on irreversible information erasure for long-lived, meaning-preserving computation. By exploiting semantic convergence, the model achieves the minimum unavoidable erasure permitted under correctness constraints, providing a principled foundation for energy-efficient long-running systems.