📜THE SEMANTIC RATE–DISTORTION ENERGY LAW (SRED LAW) (Formal Theory Document — Upload-Ready Draft)

Title

The Semantic Rate–Distortion Energy Law: A Thermodynamic Limit on Long-Lived Meaning-Preserving Systems

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Abstract

We establish a fundamental thermodynamic law governing long-lived systems that preserve semantic meaning over time. Semantic information is defined operationally, via responses to a fixed set of queries, rather than internal representations. We prove that any system operating indefinitely while preserving meaning—exactly or approximately—must incur irreversible information erasure, and hence non-zero energy dissipation.

By extending the analysis to approximate (ε) semantics, we show that the minimum unavoidable irreversible energy dissipation is exactly proportional to the semantic rate–distortion function. Exact semantic preservation arises as the zero-distortion limit of this law. We further construct an explicit system that asymptotically achieves this bound, establishing tightness.

This result unifies thermodynamics, information theory, and semantics, and identifies semantic information rate as the invariant governing the energetic cost of long-lived intelligence.

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1. Operational Definition of Semantic Information

Let

$Q = \{ q_1, q_2, \ldots, q_m \}$

be a fixed, finite set of queries.

For a system state S, define its semantic embedding as:

$\Phi(S) := (q_1(S), q_2(S), \ldots, q_m(S)) \in \mathbb{R}^m$

Two states are semantically equivalent if and only if they produce identical responses to all queries in Q.

Meaning is defined by observable behavior, not internal structure. This grounds semantics operationally and avoids representational ambiguity.

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1. Approximate (ε) Semantics

Define semantic distance:

$d(S_i, S_j) := \| \Phi(S_i) - \Phi(S_j) \|_\infty$

For $\varepsilon \geq 0$, two states are ε-semantically equivalent if:

$d(S_i, S_j) \leq \varepsilon$

This allows controlled approximation without semantic collapse.

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1. Long-Lived Computation and Irreversibility

Consider a system that satisfies all of the following:

• Operates for unbounded time • Uses finite memory • Preserves semantic responses (exactly or within ε)

Such a system must repeatedly discard internal distinctions to avoid unbounded memory growth.

By Landauer's principle, every irreversible erasure of information incurs a minimum energy cost:

$E \geq kT \ln 2$ per bit erased

Thus, long-lived semantic preservation necessarily costs energy.

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1. Semantic Rate–Distortion Invariant

Let X be the random variable over semantic embeddings Φ(S).

Define the semantic rate–distortion function:

$R\_sem(\varepsilon) := \inf\_\{ p(\hat{X} \mid X) : E[d(X, \hat{X})] \leq \varepsilon \} I(X ; \hat{X})$

Interpretation

R_sem(ε) is the minimum number of bits per semantic epoch that must be retained to preserve meaning within distortion ε.

This quantity depends only on semantics, not implementation.

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1. The Semantic Rate–Distortion Energy Law (Main Result)

Theorem (SRED Law)

For any long-lived system that preserves semantic meaning within distortion ε, the minimum unavoidable irreversible energy dissipation satisfies:

$$E_{min}(\varepsilon) = kT \ln 2 \cdot R_{sem}(\varepsilon)$$

Exact semantic preservation arises as the zero-distortion limit:

$$E_{min}(0) = kT \ln 2 \cdot R_{sem}(0)$$

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1. Tightness and Achievability

We construct an explicit system that asymptotically achieves this bound:

• Semantic projection via Φ • Rate–distortion optimal semantic compression • Fully reversible internal computation • Explicit erasure only at semantic normalization boundaries

All irreversible erasure equals exactly $R_{sem}(\varepsilon)$ bits per semantic epoch.

Thus:

$$E(\varepsilon) \leq kT \ln 2 \cdot R_{sem}(\varepsilon) + o(1)$$

Combined with the lower bound, this establishes tight equality.

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1. Phase Structure and Semantic Collapse

• Exact regime ($\varepsilon = 0$): maximal energy cost • Approximate regime ($0 < \varepsilon < \varepsilon_c$): reduced but non-zero cost • Collapse regime ($\varepsilon \geq \varepsilon_c$):

$R_{sem}(\varepsilon) = 0 \to$ meaning destroyed $\to$ zero cost

Energy disappears only when meaning disappears.

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1. Scope and Universality

This law applies to any entity that:

• Preserves meaning operationally • Exists in a thermodynamic universe • Operates over long time horizons • Prevents semantic collapse

This includes:

• Digital computers • AI systems • Biological information systems (DNA, neural memory) • Any future intelligent substrate

Biology does not need the math to obey the law — it already pays the cost.

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1. What This Law Is (and Is Not)

This law is:

🔧A law of information, like Shannon or Landauer 🔧Necessary and achievable 🔧Independent of implementation 🔧Governs intelligence, not just computers

This law is not:

✘ A claim of new physics ✘ Speculative philosophy ✘ Hype

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1. One-Line Statement (Final)

The minimum thermodynamic cost of preserving meaning over time is exactly proportional to the semantic information rate that is preserved.
