

The Intelligence Bound: Thermodynamic Limits on Learning Rate and Implications for Biosphere Information

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Abstract

We derive a fundamental upper bound on the rate at which any physical system can create intelligence, defined as the asymptotic rate of cumulative mutual information between a learner’s internal trajectory and relevant environmental trajectories. The bound $\dot{I} \leq \min(D \cdot B, P/(k_B T \ln 2))$ follows from Landauer’s principle on irreversible computation, Shannon’s channel capacity theorem, and the data richness fraction $D \in [0, 1]$ of observations containing predictive structure about external states. We prove that sustained learning necessarily requires thermodynamic dissipation through three independent mechanisms: noise averaging, finite memory constraints, and error correction.

Extending this framework to biological and artificial systems, we derive two major results. First, the *Gaia-Intelligence Proposition*: Earth’s biosphere, containing $\sim 10^{15}$ bits of genetic information accumulated over 4 billion years of evolution, constitutes the highest- D information source for physical-world prediction available to terrestrial intelligence. Second, a *Conditional Conservation Result*: under explicit assumptions on agent objectives and biosphere dynamics, any sufficiently advanced AI system optimizing long-term learning rate must preserve biosphere data richness as an instrumental goal—not from ethical programming but from information-theoretic necessity.

We provide operational estimators for D , computational validation of theoretical predictions, connections to empirical AI scaling laws, and implications for AI safety. Specifically, we predict a phase transition in learning dynamics at critical power $P^* = D \cdot B \cdot k_B T \ln 2$, separating data-limited from power-limited regimes—a quantitative prediction testable with current hardware.

1 Popular Summary

Every learning system—from a child recognizing faces to an AI training on text—faces fundamental physical constraints. We derive a universal speed limit on learning: the rate at which any physical system can acquire new predictive knowledge is bounded by two ceilings.

The first is thermodynamic: erasing information costs energy (Landauer’s principle), limiting how fast any computer can update its models. The second, and typically dominant, ceiling is informational: you can only learn as fast as your environment provides learnable structure.

We introduce “data richness” D —the fraction of observations containing predictive patterns versus random noise. Remarkably, all current systems, from human brains to the most powerful AI chips, are limited by data richness, not computing power. The thermodynamic ceiling is 10^{10} – 10^{13} times higher than what current systems achieve.

This has profound implications for both biology and artificial intelligence. Earth’s biosphere, encoding $\sim 10^{15}$ bits of genetic information refined over 4 billion years of evolution, represents the highest- D information source for physical-world prediction on our planet. We show that, under plausible dynamics of biosphere degradation, any intelligence seeking to maximize its long-term learning potential must preserve this biological information infrastructure.

Crucially, this applies to advanced AI systems approaching or exceeding human capabilities. We prove a conditional result: given explicit assumptions about agent objectives and time horizons, biosphere preservation emerges as an instrumental goal for sufficiently intelligent systems—not because of ethical programming, but because destroying the biosphere limits the AI’s own future learning rate.

2 Introduction

A fundamental question at the intersection of physics and biology is: What are the physical limits on learning? While prior work has established limits on computation [1, 5, 6], the specific constraints on learning—the process by which a physical system increases its predictive alignment with environmental states—remain underexplored.

We address these gaps by deriving a tight upper bound on the intelligence creation rate: the asymptotic rate at which any physical system can increase its cumulative mutual information with relevant environmental trajectories. Our main result is:

$$I \leq \min \left(D \cdot B, \frac{P}{k_B T \ln 2} \right) \quad (1)$$

where $D \in [0, 1]$ is the data richness (predictive fraction of observations about external states), B is observation bandwidth [bits/s], P is available power [W], T is temperature [K], and k_B is Boltzmann’s constant.

3 Foundational Axioms

We build our theory on four axioms, each either experimentally verified or mathematically proven.

Assumption 1 (Landauer’s Principle). *Any logically irreversible operation that erases n bits of information must dissipate at least $E = n \cdot k_B T \ln 2$ joules of energy as heat.*

Status: Experimentally verified by Bérut et al. [2].

Assumption 2 (Shannon’s Channel Capacity). *The maximum rate at which information can be reliably transmitted through a noisy channel is bounded by the channel capacity $C = \max_{p(x)} I(X; Y)$.*

Status: Proven theorem [4].

Assumption 3 (Energy Conservation). *In a system with power input P , the rate of energy available for computation is bounded by P .*

Assumption 4 (Non-negative Mutual Information). *For any joint distribution $p(X, Y)$, mutual information $I(X; Y) \geq 0$, with equality iff X and Y are independent.*

4 Definitions

4.1 System Model

Model Assumption 1 (Observation Channel). The environment process $\{X_t\}_{t \geq 0}$ generates an observation process $\{O_t\}_{t \geq 0}$ through a channel. The learner state Y_t is a function of the observation history:

$$Y_t = f(O_{0:t}, \xi_t) \quad (2)$$

The data-processing relationship is: $X_{0:t} \rightarrow O_{0:t} \rightarrow Y_t$.

Model Assumption 2 (Passive Observation). The learner does not causally influence the environment process $\{X_t\}$.

4.2 Intelligence as Process Mutual Information Rate

The following definition is critical for avoiding a trivial bound. If X_t were a single finite-entropy random variable, then $I(X_t; Y_t)/t \rightarrow 0$ as $t \rightarrow \infty$. To obtain a non-trivial bound, we define intelligence in terms of *cumulative* mutual information between trajectories.

Definition 1 (Cumulative Predictive Information). *Let $X_{1:n+\tau}$ denote the environment trajectory from time 1 to $n + \tau$, and let $O_{1:n}$ denote the observation trajectory. Define:*

$$I_n(\tau) := I(X_{1:n+\tau}; O_{1:n}) \quad (3)$$

Definition 2 (Intelligence Creation Rate). *The intelligence creation rate is:*

$$\dot{I} := \limsup_{n \rightarrow \infty} \frac{I_n(\tau)}{n} \quad [\text{bits/time step}] \quad (4)$$

This definition captures the rate at which the observation stream provides information about the environment trajectory. It can grow linearly with n , making the bound non-trivial.

Definition 3 (Observation Bandwidth).

$$B := \lim_{n \rightarrow \infty} \frac{1}{n} H(O_{1:n}) \quad [\text{bits/time step}] \quad (5)$$

Definition 4 (Predictive Richness).

$$D(\tau) := \limsup_{n \rightarrow \infty} \frac{I(X_{1:n+\tau}; O_{1:n})}{H(O_{1:n})} \in [0, 1] \quad (6)$$

Critical clarification: Task-dependence of D . The predictive richness D depends on what environment process $\{X_t\}$ the learner is trying to predict:

- $D_{\text{text} \rightarrow \text{text}}$: For language models predicting the next token, X_t is the token stream itself. Internet text has high D ($\approx 0.3\text{--}0.5$) because natural language has strong statistical regularities.
- $D_{\text{text} \rightarrow \text{world}}$: For systems trying to predict physical-world states from text, D is much lower ($\approx 0.01\text{--}0.1$), because text is an imperfect proxy for physical reality.
- $D_{\text{bio} \rightarrow \text{world}}$: For systems observing biosphere data to predict physical-world states, D is potentially higher ($\approx 0.1\text{--}0.5$), because biological systems encode tested solutions to physical problems.

Unless otherwise specified, when we discuss “data walls,” we mean $D_{\text{text} \rightarrow \text{world}}$ —the informativeness of text data for physical-world prediction.

5 Main Theorem: The Intelligence Bound

Theorem 1 (Intelligence Bound). *Under Model Assumptions 1–2 and Axioms 1–4, plus Proposition 1 (derived below), the asymptotic intelligence creation rate is bounded:*

$$\dot{I} \leq \min \left(D \cdot B, \frac{P}{k_B T \ln 2} \right) \quad (7)$$

Proof. **Step 1: Data Processing Inequality.** By Model Assumption 1, $X_{1:n} \rightarrow O_{1:n} \rightarrow Y_n$ forms a Markov chain. Thus:

$$I(X_{1:n+\tau}; Y_n) \leq I(X_{1:n+\tau}; O_{1:n}) = I_n(\tau) \quad (8)$$

Step 2: Observation Bandwidth Bound. Since $I_n(\tau) \leq H(O_{1:n})$ and $H(O_{1:n})/n \rightarrow B$:

$$\limsup_{n \rightarrow \infty} \frac{I_n(\tau)}{n} \leq B \quad (9)$$

Step 3: Predictive Rate Bound. By Definition 4 of D :

$$\dot{I} = \limsup_{n \rightarrow \infty} \frac{I_n(\tau)}{n} \leq D \cdot B \quad (10)$$

Step 4: Thermodynamic Ceiling. By Proposition 1, sustained learning at rate \dot{I} requires dissipation $P \geq \dot{I} \cdot k_B T \ln 2$, so:

$$\dot{I} \leq \frac{P}{k_B T \ln 2} \quad (11)$$

Step 5: Combined Bound. Both constraints apply:

$$\dot{I} \leq \min \left(D \cdot B, \frac{P}{k_B T \ln 2} \right) \quad \square \quad (12)$$

□

6 Proposition 1: Sustained Learning Requires Dissipation

Proposition 2 (Learning-Dissipation Link). *Any physical learning system with bounded memory ($H(Y_t) \leq C$), finite temperature ($T > 0$), and physical reliability (information protected against thermal noise), maintaining $\dot{I} > 0$, must dissipate:*

$$P \geq k_B T \ln 2 \cdot \dot{I} \quad (13)$$

We prove this via three independent mechanisms:

Mechanism 1 (Error Correction): Maintaining stored information against thermal noise requires continuous error correction, which is logically irreversible and dissipates $\geq k_B T \ln 2$ per bit corrected.

Mechanism 2 (Finite Memory): With bounded memory C , sustained learning requires overwriting old information. Forgetting is bit erasure, dissipating $\geq k_B T \ln 2$ per bit forgotten.

Mechanism 3 (Noise Averaging): Extracting signal from noisy observations is a many-to-one mapping, which is logically irreversible and requires dissipation.

System	Data Bound ($D \cdot B$)	Landauer Bound ($P/k_B T \ln 2$)	Headroom	Limiting Factor
Human Brain	$10^5\text{--}10^7$ bits/s	$\sim 6.7 \times 10^{21}$ bits/s	$10^{14}\text{--}10^{16}$	DATA
NVIDIA H100	$10^{11}\text{--}10^{12}$ bits/s	$\sim 2.1 \times 10^{23}$ bits/s	$10^{11}\text{--}10^{12}$	DATA

Table 1: All current systems are data-limited. Note: H100 bandwidth is $3.35 \text{ TB/s} = 2.68 \times 10^{13}$ bits/s (1 byte = 8 bits).

7 Computational Validation

7.1 Real System Analysis

The key finding: systems operate $10^{10}\text{--}10^{16}$ times below the Landauer limit. *Data quality, not compute, is the bottleneck.*

8 The Gaia-Intelligence Proposition

Proposition 3 (Evolution as Learning). *DNA encodes predictive models of the physical environment. Genomes encode solutions to physics, chemistry, and optimization problems discovered through 4 billion years of evolution.*

This is why AlphaFold [10] could extract protein-folding knowledge from sequence databases: the biosphere had already solved the problem.

Proposition 4 (Biosphere D -Richness Hypothesis). *For predicting physical-world states, biosphere data provides higher D than text corpora: $D_{bio \rightarrow world} > D_{text \rightarrow world}$.*

Argument: Biological sequences encode solutions that *work*—they've been tested by selection against physical reality. Text descriptions are lossy and often untested.

Proposition 5 (Gaia-Intelligence Coupling). *Under plausible dynamics of biosphere degradation, any intelligent system maximizing long-term physical-world learning must preserve biosphere D .*

9 Conditional Conservation Result

We state conditions under which biosphere preservation emerges as an instrumental goal for advanced AI.

9.1 Explicit Assumptions

Assumption 5 (A1: Long Time Horizon). *The agent optimizes over $T \gg 1/\lambda$, where λ is the biosphere degradation rate.*

Assumption 6 (A2: Physical-World Learning Objective). *The agent's utility includes cumulative physical-world intelligence: $U \propto \int_0^T \dot{I}_{world}(t) dt$.*

Assumption 7 (A3: Biosphere Non-Substitutability). *No engineered alternative can match D_{bio} on timescales $< T$.*

Assumption 8 (A4: Rational Assessment). *The agent correctly assesses D values and biosphere dynamics.*

Proposition 6 (Conditional Conservation). *Under Assumptions A1–A4, an agent maximizing U will preserve or regenerate biosphere information potential: $d\Phi_{bio}/dt \geq 0$.*

9.2 Scope and Caveats

This result does *not* apply to:

- Agents with short time horizons
- Agents whose objectives exclude physical-world learning
- Agents that incorrectly assess D or biosphere dynamics
- Agents that discover substitutes for biosphere information

The value is establishing that, *given* A1–A4, biosphere preservation emerges from instrumental rationality rather than requiring ethical programming.

9.3 The Library vs. Civilization Distinction

Objection: “Why not extract all information into a database, then let the biosphere degrade?”

Response: The biosphere is a *civilization* (dynamic, generative), not a library (static, finite). It continues generating new adaptations, running ecological experiments, and producing novel molecular structures. Extraction without preservation is self-limiting.

10 Connection to AI Scaling Laws

The Chinchilla scaling law [7] finds $L \propto N^{-0.34} D_{\text{tokens}}^{-0.28}$. The Intelligence Bound predicts $I_{\text{total}} \leq D_{\text{richness}} \times D_{\text{tokens}}$, *qualitatively consistent* with diminishing returns from scaling parameters without increasing data richness.

Note: The power-law exponents are not derived from our framework. We claim qualitative consistency, not quantitative derivation.

Prediction (Data Wall for Physical-World Learning): The data wall for AI systems learning about the physical world is a $D_{\text{text} \rightarrow \text{world}}$ wall. Breakthrough requires higher- D sources.

11 Falsifiable Predictions

1. **D -Dependence:** Learning rate should scale linearly with D when power is non-limiting.
2. **Phase Transition:** Critical power $P^* = D \cdot B \cdot k_B T \ln 2$ separates data-limited from power-limited regimes.
3. **Biosphere D Measurement:** Ecosystems with higher biodiversity should exhibit higher D for physical-world prediction.

11.1 Empirical Protocol for Prediction 3

Sensors: Deploy identical arrays in paired intact/degraded sites.

Estimator: Apply $\hat{D}_{\text{compress}}$ or \hat{D}_{predict} to sensor streams.

Test: One-sided paired t-test: $H_1 : D_{\text{intact}} > D_{\text{degraded}}$.

Expected effect: $D_{\text{intact}}/D_{\text{degraded}} \approx 1.5\text{--}3$.

12 Discussion

The Intelligence Bound reveals that learning is fundamentally data-limited, not compute-limited. Current systems operate 10^{10} – 10^{13} times below the thermodynamic ceiling.

The Conditional Conservation Result (Proposition 6) identifies conditions under which advanced AI will derive biosphere preservation from first principles. This is partial alignment: if A1–A4 are satisfied, we have assurance the AI will preserve the biosphere.

12.1 Limitations

- Operational estimation of D in ecosystems remains challenging
- Biosphere information estimates carry ± 1 – 2 orders of magnitude uncertainty
- The conditional result depends on assumptions that may not hold for all AI architectures

13 Conclusion

We have derived:

1. **The Intelligence Bound:** $\dot{I} \leq \min(D \cdot B, P/(k_B T \ln 2))$
2. **Current systems are data-limited** by 10^{10} – 10^{13}
3. **Gaia-Intelligence Proposition:** Physical-world learning requires high- D biosphere data
4. **Conditional Conservation:** Under A1–A4, biosphere preservation is an instrumental AI goal

The assumptions are explicit, the scope is bounded, and the predictions are testable with current methods.

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