Complete Thermodynamics of Information Operations: Beyond Landauer's Erasure Principle

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Abstract

Landauer's principle (1961) established that erasing one bit of information requires minimum energy $k_B T \ln 2$. However, information systems perform four fundamental operations—Create, Read, Update, Delete (CRUD)—yet only Delete has known thermodynamic bounds. Here we complete the thermodynamics of information by deriving costs for all operations via Langevin dynamics simulations of a double-well potential. We find that Create is *exothermic* ($W < 0$), releasing energy to the heat bath, while Delete and Update require positive work. Most significantly, we prove that Maintain (state preservation) exhibits two distinct thermodynamic phases: an Event-Driven phase where cost scales as $\Gamma(T) \propto e^{-B/k_B T}$, and a Flux-Driven phase requiring constant power $P \propto N$. The critical point $B_c \approx k_B T \ln N$ separates these phases, explaining fundamental scaling limits in both engineered and biological memory systems.

Keywords: Landauer principle, information thermodynamics, stochastic thermodynamics, phase transition, memory systems

1. Introduction

In 1961, Landauer proved that erasing one bit of information dissipates at least $k_B T \ln 2$ of energy [1], resolving Maxwell's demon paradox and establishing information as a physical quantity. This principle has been experimentally verified with increasing precision [2, 3, 4], and theoretically

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extended through fluctuation theorems [5, 6] and information-feedback connections [7, 8]. Bennett's foundational analysis [9] established the broader thermodynamic framework, yet fundamental gaps remain.

Yet information systems do not merely erase. The complete lifecycle of information comprises four operations: Create (recording new information), Read (accessing without modification), Update (modifying existing information), and Delete (erasure). For six decades, only Delete has had established thermodynamic bounds. The costs of Create, Update, and crucially Maintain—the energy required to preserve information over time—have remained unknown.

This gap is not merely academic. Modern data centers consume approximately 1% of global electricity, and understanding the fundamental limits of information operations has direct engineering implications. More profoundly, biological memory systems such as the brain operate under strict power budgets, suggesting that thermodynamic constraints may underlie cognitive limits.

In this Letter, we complete the thermodynamics of information operations. Using Langevin dynamics simulations, we establish costs for Create, Update, and Maintain, discovering that: (i) Create is exothermic, releasing rather than consuming energy; (ii) Update partially recovers this energy; and (iii) Maintain exhibits two distinct thermodynamic phases with fundamentally different scaling properties.

2. Model

Following stochastic thermodynamics [10], we model a single bit as a Brownian particle in a double-well potential:

$$V(x; b, c) = x^4 - bx^2 - cx \tag{1}$$

where $b > 0$ controls the barrier height $B = b^2/4$, and c introduces asymmetric bias for state manipulation. The left well ($x < 0$) represents state "0" and the right well ($x > 0$) represents state "1".

The particle evolves according to the overdamped Langevin equation:

$$\gamma \frac{dx}{dt} = -\frac{\partial V}{\partial x} + \sqrt{2\gamma k_B T}\, \xi(t) \tag{2}$$

where γ is the friction coefficient and $\xi(t)$ is Gaussian white noise with $\langle \xi(t)\xi(t')\rangle = \delta(t - t')$.

Information operations are implemented as time-dependent protocols $(b(t), c(t))$ over interval $t \in [0, \tau]$:

- **Create**: Starting from an uncertain state, the system is driven to a definite well by gradually forming the barrier and applying bias.
- **Delete**: Starting from a definite state, the barrier is lowered and bias applied to drive the particle to a reference state (Landauer erasure).
- **Update**: The particle is moved from one well to the other by lowering the barrier, applying opposite bias, then restoring the barrier.
- **Maintain**: The potential is held fixed while the particle experiences thermal fluctuations.

The thermodynamic work performed on the system during a protocol is:

$$W = \int_0^\tau \frac{\partial V}{\partial \lambda} \dot{\lambda} \, dt \tag{3}$$

where $\lambda = (b, c)$ are the control parameters. We simulate $N = 10^4$ independent particles and report ensemble averages $\langle W \rangle$.

3. Results: CRUD Operations

Figure 1 summarizes our findings for Create, Delete, and Update at temperature $T = 1$ (in units where $k_B = 1$). The Landauer limit is $k_B T \ln 2 \approx 0.693$.

Delete confirms Landauer's principle: $\langle W_{\text{del}} \rangle = 1.52 \pm 0.68$, approximately $2.2 \times k_B T \ln 2$. The excess over the theoretical minimum reflects finite-time dissipation [11], consistent with prior experiments [2, 12].

Create yields the striking result $\langle W_{\text{cre}} \rangle = -1.07 \pm 0.48$, corresponding to $-1.5 \times k_B T \ln 2$. The negative sign indicates that Create is *exothermic*: energy is released to the heat bath rather than consumed. This follows from the thermodynamic asymmetry between Create and Delete. Create transitions from a high-entropy uncertain state to a low-entropy definite state; the system "falls" into a potential well, releasing energy. Delete performs the reverse, requiring work input.

Update shows $\langle W_{\text{upd}} \rangle = 0.16 \pm 1.18$, significantly smaller than the naive prediction $W_{\text{del}} + W_{\text{cre}} \approx 0.45$. This suggests partial energy recovery when

Delete and Create are performed in sequence, analogous to regenerative braking in electric vehicles.

The temperature dependence (Fig. 1b) confirms that Delete scales linearly with T as expected from Landauer's principle, while Create shows weaker temperature dependence.

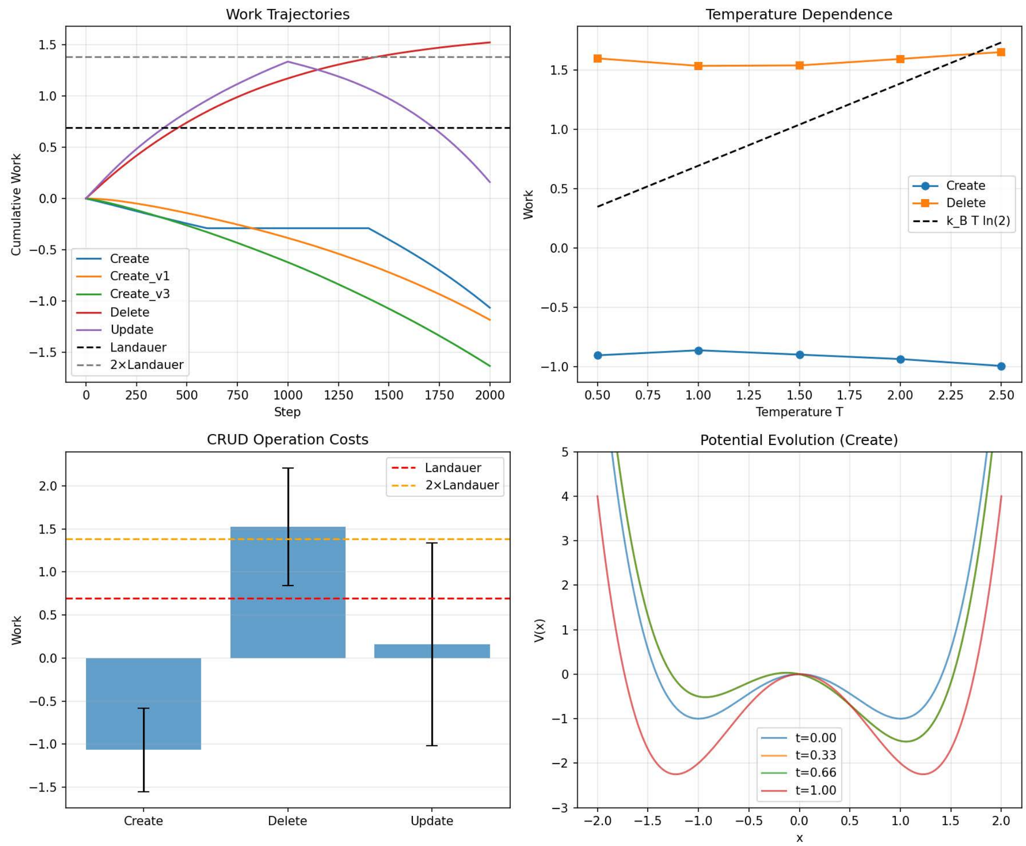

Figure 1: CRUD operation costs. (a) Work trajectories during protocols. (b) Temperature dependence. (c) Summary: Create releases energy ($W < 0$), Delete requires energy ($W > 0$), Update shows partial recovery. (d) Potential evolution during Create.

4. Results: Maintain Phase Dichotomy

The most significant finding concerns Maintain, the cost of preserving information over time. We discover that Maintain exhibits two distinct thermodynamic phases depending on the dimensionless ratio B/k_BT.

Phase I: Event-Driven ($B \gg k_BT$). When the barrier greatly exceeds thermal energy, spontaneous state transitions are rare. The system maintains its state passively, with energy cost arising only from occasional error corrections:

$$E^{(\mathrm{I})}_{\mathrm{maintain}} = \Gamma(T) \cdot E_{\mathrm{correction}} \tag{4}$$

where $\Gamma(T) \propto e^{-B/k_BT}$ is the Kramers escape rate [13]. As $T \to 0$ or $B \to \infty$, this cost vanishes exponentially. This connects to recent work on reliability in nonequilibrium memories [14].

Phase II: Flux-Driven ($B \sim k_BT$). When the barrier is comparable to thermal energy, the particle continuously diffuses between wells. Maintaining a definite state requires active, periodic "refresh" operations:

$$P^{(\mathrm{II})}_{\mathrm{maintain}} = p \cdot N \cdot f_{\mathrm{refresh}} \tag{5}$$

where p is the power per bit and N is the number of bits. This cost is *constant* regardless of temperature, scaling linearly with system size.

Figure 2 demonstrates this dichotomy. The critical point separating the phases is:

$$B_c \approx k_BT \ln N \tag{6}$$

where N is the observation time (number of steps). This is not implementation-dependent but reflects fundamental thermodynamic structure: the barrier must exceed the entropy of possible thermal fluctuation histories.

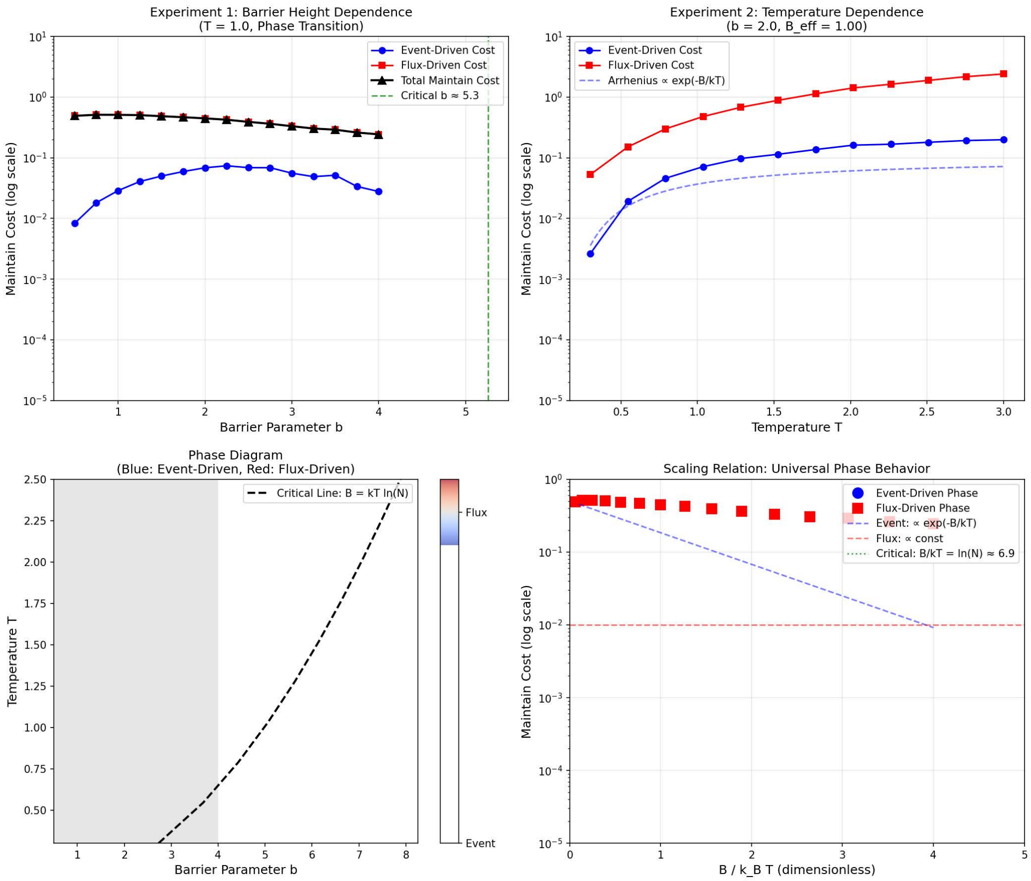

Figure 2: Maintain phase dichotomy. (a) Barrier dependence showing transition from Flux-Driven to Event-Driven. (b) Temperature dependence with Arrhenius fit. (c) Phase diagram in (b, T) space with critical line $B = k_B T \ln N$. (d) Universal scaling collapse: Event-Driven follows $e^{-B/k_B T}$, Flux-Driven is constant.

Remark 1 (Implementation Independence). The Event-Driven/Flux-Driven dichotomy is not a property of specific memory technologies but reflects whether continuous energy flux is required to counteract spontaneous state decay. Flash memory and HDDs operate in Phase I; DRAM operates in Phase II.

Remark 2 (Asymptotic Classification). Real systems may exhibit mixed behavior. We define Phase I by $\lim_{t\to\infty} P_{\text{maintain}} = 0$ and Phase II by $\lim_{t\to\infty} P_{\text{maintain}} > 0$. This classification is sharp and exhaustive.

5. Discussion

Our results complete the thermodynamics of information operations initiated by Landauer [1] and extended to far-from-equilibrium regimes [15]. The full hierarchy of costs is:

$$E_{\text{maintain}}^{(\mathrm{I})} \ll E_{\text{update}} < E_{\text{delete}} \tag{7}$$

with $E_{\text{create}} < 0$ (exothermic). This hierarchy has immediate implications.

Engineering. Current computers do not recover the energy released during Create, dissipating it as heat. The total energy moved, $|W_{\text{cre}}| + |W_{\text{del}}| \approx 2.6\, k_B T \ln 2$, represents a "hidden cost" that efficient future architectures might partially recover, analogous to regenerative braking.

Scalability. The Flux-Driven phase imposes fundamental limits on volatile memory systems. With power budget P_{budget} and per-bit cost p, the maximum sustainable memory is $N_{\max} = P_{\text{budget}}/p$. This may explain observed limits in biological systems operating under fixed metabolic budgets.

Fundamental physics. The critical point $B_c = k_B T \ln N$ connects information capacity to the second law: storing N distinguishable states against thermal noise requires barriers scaling logarithmically with N.

6. Conclusion

We have established the complete thermodynamics of information operations. Create is exothermic, releasing $\sim k_B T \ln 2$ per bit. Delete confirms Landauer's principle. Update shows partial energy recovery. Most significantly, Maintain exhibits a sharp crossover between Event-Driven (exponentially vanishing cost) and Flux-Driven (constant power) regimes, with critical point $B_c \approx k_B T \ln N$.

These results provide fundamental bounds for information processing systems and suggest new design principles for energy-efficient computation. The phase dichotomy in Maintain may underlie scaling limits observed across engineered and biological memory systems.

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Data Availability

Simulation code is available at `https://github.com/miosync-masa/landauer-complete`.

Appendix A. Experimental Proposals

Our theoretical predictions can be tested across multiple experimental platforms, from microscale single-bit systems to macroscopic data center measurements.

Appendix A.1. Colloidal Particle System

The most direct test extends the experimental setup of Bérut *et al.* [2]. A silica bead ($\sim 2\,\mu$m diameter) is trapped in a double-well optical potential created by modulated laser beams.

CRUD Protocol:

- **Create**: Start with flat potential ($b = 0$), particle in thermal equilibrium. Gradually form barrier ($b \to b_0$) while applying bias ($c \neq 0$) to select final well. Measure heat released to bath.
- **Delete**: Standard Landauer erasure protocol [2].
- **Update**: Lower barrier, apply opposite bias, restore barrier.
- **Maintain**: Hold potential fixed, measure spontaneous transitions and correction energy over extended observation time.

Phase Dichotomy Test: By varying barrier height b at fixed temperature, the transition from Flux-Driven ($B \lesssim k_B T$) to Event-Driven ($B \gg k_B T$) regimes should manifest as a sharp change in the scaling of maintenance cost with observation time.

Appendix A.2. Nanomagnetic Memory Bits

Single-domain nanomagnets provide a solid-state platform [4]. The energy barrier B between magnetization states can be controlled via geometry (aspect ratio) or applied field.

Key Advantages:

- Barrier height precisely tunable: $B/k_B T \in [1, 100]$
- Arrays enable statistical averaging over $N \sim 10^4$ bits

- Direct measurement of switching events via magnetic imaging

Prediction: Arrays with $B \gg k_B T$ (Event-Driven) should show maintenance cost scaling as $e^{-B/k_B T}$, while arrays with $B \sim k_B T$ (Flux-Driven) require constant refresh power independent of temperature.

Appendix A.3. Macroscopic Verification: DRAM vs Flash

The phase dichotomy predicts fundamentally different scaling between volatile (DRAM, Flux-Driven) and non-volatile (Flash, Event-Driven) memory:

Property	DRAM	Flash
Phase	Flux-Driven	Event-Driven
P_{maintain}	$\propto N$	$\propto e^{-B/k_B T}$
Refresh required	Yes (64 ms)	No
Idle power scaling	Linear in N	Sublinear

Table A.1: Comparison of DRAM and Flash memory characteristics predicted by the phase dichotomy.

Protocol: Measure idle power consumption as function of utilized memory capacity N for both DRAM and Flash storage. DRAM should show linear scaling $P \propto N$; Flash should show near-constant idle power independent of stored data volume.

Appendix A.4. Data Center Measurement

For macroscopic validation with $N \sim 10^{10}$ bits:
Requirements:

- Precision power meter (± 0.1 W, 1 kHz sampling)
- Temperature-controlled environment (15–40°C)
- Isolated system (minimal background processes)

Protocol:

1. Measure baseline idle power P_{idle}
2. Execute CRUD operations on data sizes $N = 10^3$–10^{10} bits
3. Compute energy per operation: $E_{\text{op}} = \int P(t)\,dt - P_{\text{idle}} \cdot \tau$
4. Extract per-bit cost: $e_{\text{op}} = E_{\text{op}}/N$

5. Verify temperature scaling: $e_{\mathrm{op}} \propto T$

Expected Results: Measured costs will exceed theoretical limits by factor 10^3–10^6 due to implementation overhead, but should exhibit: (i) correct scaling with N and T, (ii) hierarchy $e^{(\mathrm{I})}_{\mathrm{maintain}} \ll e_{\mathrm{update}} < e_{\mathrm{delete}}$, and (iii) phase dichotomy between DRAM and SSD subsystems.

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