

Maxwell's Demon and Thermodynamic Constraints on the Brain: The Second Law of Thermodynamics

Susumu Ito, Takayuki Matsuto and Katsuhiko Hata*

Research Centre for Mathematical Medicine, Tokyo, Japan

***Corresponding Author:** Katsuhiko Hata, Department of Neuroscience, Research Centre for Mathematical Medicine, Tokyo, Japan

Received: October 16, 2025; **Published:** October 30, 2025

Abstract

The Second Law of Thermodynamics dictates that closed systems move toward maximum entropy. In the real world, it seems to be defied by highly organized living organisms at first glance. The Maxwell's Demon thought experiment, which appears to generate free energy by using information to selectively sort molecules, highlights a critical link between thermodynamics and information processing. The paradox's resolution-that the necessary erasure of information increases the total entropy of the Demon and its memory-establishes a fundamental thermodynamic cost for information processing, formalized by Landauer's Principle.

The animal nervous system and, by extension, the brain, acts as a sophisticated "local information engine". Its core operation-the collection of information via sensory organs and subsequent action via effectors to maintain internal homeostasis-is fundamentally analogous to the Demon's function. Modern theoretical neuroscience principles, such as Friston's Free Energy Principle (FEP) and Tononi's Integrated Information Theory (IIT), implicitly support this thermodynamic view by positing that the brain actively resists entropic decay by minimizing surprisal or maintaining a non-equilibrium, integrated causal structure. The Thermodynamic Uncertainty Relation (TUR) provides a more stringent constraint, defining a mandatory cost-precision trade-off: the metabolic energy (entropy generation) required for the brain to achieve a specific level of precision (low noise) in its information processing, like neuronal spike generation. A key remaining open question is if the thermodynamic imperative of information erasure in the brain-processes of forgetting may represent the biological equivalent of the Demon's necessary memory reset to avoid a prohibitive energetic cost of perpetually storing data.

Keywords: *Maxwell's Demon; Second Law of Thermodynamics; Landauer's Principle; Free Energy Principle (FEP); Integrated Information Theory (IIT); Thermodynamic Uncertainty Relation (TUR); Information Erasure*

Introduction: The Second Law and Maxwell's Demon

The Second Law of Thermodynamics states that in a closed system, processes are irreversible, and heat moves naturally from higher to lower temperatures, driving the system towards thermodynamic equilibrium (maximum entropy). James Clerk Maxwell proposed a famous thought experiment in which he involved a hypothetical intelligent being-later termed Maxwell's Demon by William Thomson (Lord Kelvin)-that seemed capable of violating this law [1-3]. The Demon controls an aperture between two adiabatically separated chambers of gas at uniform temperature, selectively allowing only faster-than-average molecules to pass one way and slower ones the

other. By doing so, the Demon would increase the temperature difference between the chambers, thereby decreasing the total entropy (or gaining free energy, in other words) of the system without external work.

The link between information, entropy, and life

The significance of Maxwell's Demon lies in its implication of a strong correlation between the manipulation of information and changes in thermodynamic entropy. The paradox was ultimately resolved by concluding that the total entropy of the system (including the Demon's memory) must increase. The increase in entropy arises not from the measurement or door manipulation, but from the necessary erasure or resetting of the information recorded by the Demon.

This resolution, formalized by Landauer's Principle [7], establishes a fundamental thermodynamic cost for any logically irreversible information processing, such as erasure, as shown below:

$$E \geq k_b T \ln 2$$

Here, E is the energy needed for erasing 1 bit information, k_b is the Boltzmann constant and T is the absolute temperature. $\ln 2$ is the conversion factor between the natural unit of information in thermodynamics, the nat, and the bit commonly used in information theory. Expressing the amount of information in nats, and letting E_{nat} denote the minimum energy required to process 1 nat, the inequality simply becomes $E_{\text{nat}} \geq k_b T$.

Living organisms, as highly organized, low-entropy systems, appear to resist the Second Law, but do so as open systems that maintain a quasi-steady state known as homeostasis [4,5]. Erwin Schrödinger characterized this process as organisms constantly consuming free energy (or "negative entropy") and releasing heat (entropy) into the environment to sustain their internal order [6]. The active maintenance of this non-equilibrium steady state requires a constant intake of free energy and a mechanism for dissipating the waste heat associated with generating and processing information.

The nervous system as an information engine

Evolutionary strategies to acquire free energy differ dramatically: plants adopt a passive approach using solar radiation, while animals developed an active strategy. This strategy relies on sensory organs to gather information (e.g. for predation or defence) and effectors to initiate action based on that information [7]. The evolution of the nervous system to process the information flow between sensing and acting resulted in the emergence of highly developed brains [8].

The minimal function of Maxwell's Demon was the collection of information and the subsequent external action based upon it. It was fundamentally analogous to the core operation of the animal nervous system. In this view, the brain functions as a sophisticated "local information engine" that actively samples the environment (non-equilibrium state) and exploits the resulting information to maintain its own highly ordered state against entropic decay [9].

Thermodynamic principles in modern neuroscience

The constraint of the Second Law on information processing is a major theme in modern theoretical neuroscience [10]:

- **Friston's free energy principle (FEP):** FEP posits that biological systems resist the natural increase in entropy by minimizing an upper bound on surprisal (negative log-probability of sensory data) known as variational free energy. Minimizing this quantity mathematically ensures that the system maintains a non-equilibrium steady state (homeostasis) and effectively models the brain as an inference engine that continuously updates its internal model of the world [11].

- **Tononi's integrated information theory (IIT):** IIT attempts to quantify the level of consciousness (Φ) by measuring the amount of integrated information generated by a system. The existence of a highly integrated, irreducible causal structure (a complex with $\Phi > 0$) inherently requires maintaining a physical structure that is far from thermodynamic equilibrium. Thus, it implicitly demanding continuous free energy consumption and entropy dissipation [12,13].

The thermodynamic uncertainty relation (TUR) and brain efficiency

The thermodynamic uncertainty relation (TUR), a concept developed in information thermodynamics, provides a more stringent physical constraint on the efficiency and function of the brain as an information engine.

- **Overview of TUR:** TUR is an inequality that states that a mandatory lower bound exists between the average value of a thermodynamic current (e.g. heat flow or work) and its fluctuation (variance), determined by the system's entropy production [14]. This relation quantitatively expresses a fundamental trade-off: to increase the precision (reduce the fluctuation) of a thermodynamic output, a greater cost in terms of entropy production must be paid.
- **Connection to information thermodynamics:** While Maxwell's Demon attempts to extract work from thermal fluctuations using information, TUR strictly dictates the minimum entropy production (cost) required for any engine to achieve a certain precision. The modern framework of the information engine, which includes information-based feedback, is established through the formulation of fluctuation theorems [15].
- **Application to the brain:** As a non-equilibrium system that processes information and learns, TUR is an important tool for understanding the brain [16,17]. Applying this principle yields a theoretical lower bound on the minimum metabolic energy (entropy generation) the brain must consume to achieve a specific level of precision (low noise) in information processing, offering a framework to understand the cost-precision trade-off in phenomena like neuronal spike generation.

The thermodynamic open question: Information erasure in the brain

If the brain is an information engine, the thermodynamic imperative of information erasure remains a key unsolved question. The concept of the brain at a point devoid of external experiential information—the tabula rasa—must be considered in light of the continuous entropy cost of perpetually storing data. The brain must have a mechanism for actively discarding “old” or unnecessary information to avoid this prohibitive energetic cost. Understanding the biological and thermodynamic basis of processes like synaptic pruning, forgetting, or the active restructuring that occurs during sleep may hold the key to resolving the brain's equivalent of the Demon's necessary memory reset [18].

Conclusion

The principles developed from resolving the Maxwell's Demon paradox provide a crucial framework for understanding the thermodynamic constraints on the brain. The brain must be viewed as an information engine operating far from equilibrium, continuously consuming free energy to combat the relentless increase of entropy and sustain its highly ordered state. The powerful principles of information thermodynamics, particularly the Thermodynamic Uncertainty Relation (TUR), now offer a quantitative link between the energetic cost (metabolic energy) and the functional quality (precision/low noise) of neural computations. Ultimately, the outstanding thermodynamic open question for neuroscience is the physical and biological mechanism for information erasure. Understanding how the brain actively discards data through processes of forgetting will be essential to find a solution to the energetic requirements of perpetually storing information, offering the final piece to the brain's equivalent of the Demon's memory reset.

Acknowledgment

This commentary was inspired by the insights of the late Dr. Takayuki Murakoshi, to whom we wish to express our gratitude [19].

Conflict of Interest (COI)

No conflict of interest to be declared.

Bibliography

1. Maxwell JC. "Theory of heat. Ch.12". London: Longmans, Green and Co. (1871).
2. Thomson W. "The kinetic theory of the dissipation of energy". *Nature* 9 (1874): 441-444.
3. Thomson W. "The sorting demon of Maxwell". *Proceedings of the Royal Society* 9 (1879): 113-114.
4. Bernard C. "Leçons sur les phénomènes de la vie communs aux animaux et aux végétaux". Bris: Bailliere (1878-79).
5. Cannon WB. "Organization for physiological homeostasis". *Physiological Reviews* 9.3 (1929): 399-431.
6. Schrödinger E. "What is life? the physical aspect of the living cell". Cambridge University Press (1944).
7. Barlow HB. "Possible principles underlying the transformation of sensory messages". *Sensory Communication* 1.01 (1961): 217-233.
8. Ito S. "The necessity of brain function in animals". *EC Neurology* 15.3 (2023): 15-17.
9. Shimazaki H. "Neurons as an information-theoretic engine". arXiv preprint arXiv:1512.07855 (2015).
10. Collell G and Jordi F. "Brain activity and cognition: a connection from thermodynamics and information theory". *Frontiers in Psychology* 6 (2015): 818.
11. Friston K. "The free-energy principle: a unified brain theory?". *Nature Reviews Neuroscience* 11.2 (2010): 127-138.
12. Albantakis L., et al. "Integrated information theory (IIT) 4.0: Formulating the properties of phenomenal existence in physical terms". *PLoS Computational Biology* 19.10 (2023): e1011465.
13. Perez Velazquez JL., et al. "Unifying biophysical consciousness theories with MaxCon: maximizing configurations of brain connectivity". *Frontiers in Systems Neuroscience* 18 (2024): 1426986.
14. Seifert U. "From fluctuation theorems to the second law and beyond". *Reports on Progress in Physics* 82 (2019): 076001.
15. Sagawa T and Ueda M. "Fluctuation theorem for information exchange". *Physical Review Letters* 109 (2012): 180602.
16. Schiessl HG., et al. "The thermodynamic uncertainty relation in biological systems". *Nature Communications* 9 (2018): 218.
17. Marzen SR. "Thermodynamic costs of information processing in cellular sensing and signaling". *Physical Review Research* 2 (2020): 013280.
18. Tononi G and Cirelli C. "Sleep and the price of plasticity: from synaptic and cellular homeostasis to memory consolidation and integration". *Neuron* 81.1 (2014): 12-34.
19. Ito S., et al. "A message of condolence: neuroscientist Dr Murakoshi has passed away". *EC Neurology* 16 (2024): 01-03.

Volume 17 Issue 11 November 2025

©All rights reserved by Rozin Katsuhiko Hata., et al.

Citation: Katsuhiko Hata., et al. "Maxwell's Demon and Thermodynamic Constraints on the Brain: The Second Law of Thermodynamics". *EC Neurology* 17.11 (2025): 01-04.