# Thermodynamics of Information: History and Recent Advances

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The relationship between information and thermodynamics dates back to the thought experiment of Maxwell's demon in the nineteenth century. By observing and manipulating individual molecules, the demon appears capable of reducing the entropy of a gas, in apparent violation of the second law of thermodynamics. The developments in the twentieth century, from the Szilard engine to the Landauer bound, revealed that information is the key to resolving this paradox. Information is a physical resource that can be interconverted with work and free energy.

Over the past few decades, advances in nonequilibrium thermodynamics, particularly fluctuation theorems, together with classical and quantum information theory, have led to a general theoretical framework for the thermodynamics of information [1]. Within this framework, information-theoretic quantities, such as Shannon entropy and mutual information, and thermodynamic quantities, such as work, heat, and entropy production, are treated on an equal footing. For example, under feedback control based on measurement outcomes, the mutual information acquired through measurement sets the upper bound on the additional work that can be extracted by the demon. In 2010, information-to-energy conversion was experimentally demonstrated using a colloidal particle [2]. Since then, experimental research has expanded to a wide variety of classical and quantum systems, including biomolecules, single-electron devices, NMR, and superconducting qubits.

After reviewing this history and the basic concepts, I will present our two recent studies. The first concerns the thermodynamics of continuous/iterative quantum measurements and feedback control. In quantum systems, measurement backaction cannot be neglected, and classical information flow is insufficient to quantify thermodynamic resources. We introduced quantum-classical-transfer (QC-transfer) entropy to quantify quantum information flow and generalized the second law and the fluctuation theorem under continuous/iterative quantum measurement and feedback [3]. Furthermore, we experimentally verified these relations using the electronic spin of a silicon-vacancy (SiV) center in a diamond nanocavity [4].

The second study concerns the relationship between finite-time information

processing and optimal transport theory. The Landauer bound gives the minimum work required to erase one bit of information and is attained by an infinitely slow quasi-static operation. For practical information processing, however, it is essential to achieve both low energy cost and high processing speed. Optimal transport theory, a field of pure and applied mathematics, offers important theoretical insight into this problem, and its connection to thermodynamics has recently been revealed. In particular, for overdamped Langevin systems, a geometric quantity called the Wasserstein distance provides an achievable lower bound on the unavoidable dissipation in a finite-time process. Using a colloidal particle controlled by optical tweezers, we experimentally realized thermodynamically optimal transport and optimal finite-time information erasure [5]. This experiment verified that the excess dissipation beyond the Landauer bound is characterized by the Wasserstein distance, and saturated the trade-off among processing speed, dissipation, and erasure accuracy.

Through these topics, I will illustrate how the fundamental question posed by Maxwell's demon has evolved into an active field of modern research on the thermodynamic limits of information processing.

## References


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