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LECTURE 2

Information Thermodynamics: Classical and Quantum Perspective

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Abstract

The paradox of Maxwell's demon was resolved through Landauer's principle, which incorporates information into thermodynamics. To illustrate the resulting framework of information thermodynamics, we introduce the information ratchet as a canonical model. This ratchet is known to exhibit the thermodynamic functionality of either an engine or an eraser through its interaction with a memory tape and a heat reservoir. When the memory capacity of the tape is finite, however, we show that these functionalities cannot be sustained because the system eventually equilibrates. Nevertheless, cumulative work can be extracted or expended through successive tape scans during the transient regime, and we prove that the ratchet obeys the Information Processing Second Law (IPSL) throughout its operation. Interestingly, we find that a finite-tape ratchet can exploit correlations encoded in the ratchet-tape memory to accumulate more work by exhibiting a longer relaxation timescale to reach the steady state.

We next generalize the model by breaking the symmetry of detailed-balance of the thermal transitions, which gives rise to a housekeeping heat. In this setting, we observe theoretically the mathematical condition under which the information ratchet can function as a heat engine, using the Kullback–Leibler divergence as a measure of statistical distance. Using a Markov transition process that violates detailed balance, we further show that the ratchet's ability to extract heat is diminished by the presence of housekeeping heat.

Finally, we place the information ratchet as the working body in a quantum thermodynamic system to cool a heat reservoir via indefinite causal order. In this setting, the ratchet's finite tape of qubits serves as a quantum resource that absorbs the entropic cost of refrigeration. We find that this approach enhances the coefficient of performance of quantum refrigeration beyond that achieved by the state-of-the-art Density Matrix Exponentiation method in certain temperature ranges. Remarkably, this improvement persists even in the unconventional regime where the working body is hotter than the cold bath, as well as in prethermalization regimes, where further performance gains can be realized.