Maxwell's Uncertain Demon: Achieving Nonclassical and Enhanced Refrigeration when Causality Blurs

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Extended Abstract

Motivation. Maxwell's demon revealed that information is a physical resource that can play a role in physical systems such as in thermodynamical processes. Particularly, knowledge or information gained about a system can be leveraged to achieve information processing and thermodynamical tasks beyond what is possible without this information. However, recent developments in quantum information science introduce a twist: while classical processes unfold in a fixed causal order, quantum processes can exhibit indefinite causal order, where the causal ordering of events are in a state of quantum uncertainty. Indefinite causal order alters how the system interacts with the environment, allowing non-Markovian information in the environment to flow between different paths of quantum superposition [1]. This raises an important question: can Maxwell's demon exploit information gained in such information landscapes where events have indefinite causality and information can flow between paths of quantum superposition, to achieve nonclassical thermodynamical tasks? This question can grant insights into the dynamics of information in complex quantum processes, opening the doors to design quantum devices that can leverage such novel information processing for enhanced refrigeration or computing tasks.

Approach and Methodology. Our approach requires the combination of the two distinct phenomena of Maxwell's demon and indefinite causal order into a single quantum process, and to demonstrate the process' ability to grant an enhancement to thermodynamic tasks. Particularly, we demonstrate this as an enhancement to the coefficient of performance (COP) of a quantum refrigeration cycle. We start with a known quantum process called the quantum switch Φ^{sw}, that interacts a working quantum system with two cold baths, A and B, in a superposition of the two different orderings of $B \circ A$ and $A \circ B$, achieving the simplest case of indefinite causal order [3]. Next, to implement a Maxwell's demon, we take the Maxwellian information ratchet-tape system which grants a natural representation of Maxwell's demon, where the Maxwell's demon memory can be represented as a finite 1-dimensional tape of qubits with periodic boundary conditions [4]. We then augment the quantum switch $\Phi^{\text{sw}} \rightarrow \tilde{\Phi}^{\text{sw}}$ (Fig. 1) such that in each interaction with the heat bath, a record of heat extraction is stored in the Maxwell's demon memory. A refrigeration cycle utilizing this augmented quantum switch $\tilde{\Phi}^{\text{sw}}$ can then be constructed to extract heat from the cold baths, and the COP of refrigeration is then computed to demonstrate an enhancement due to the presence of the Maxwell's demon memory.

Results. Interestingly, the augmented quantum switch $\tilde{\Phi}^{\text{sw}}$ is able to extract heat from the cold baths even when the working system starts at a temperature that is hotter than the baths, achieving nonclassical refrigeration not possible in conventional refrigeration cycles. Furthermore, the COP of refrigeration can be enhanced, depending on the amount of entropy the Maxwell's demon memory can hold. This is shown as a derived relation between the amount of heat extracted and the amount of von Neumann entropy that the Maxwell's demon memory can hold, and demonstrated by a numerical computation of the COP with a Maxwell's demon memory of three qubits [2]. These results demonstrate that nonclassical and enhanced refrigeration can indeed be achieved using a Maxwell's demon that operates in quantum processes with indefinite causal order.

Conclusions and Outlook. By examining Maxwell's demon under indefinite causality, we uncover the interplay between causality, information, and thermodynamics in complex quantum systems, demonstrating how Maxwell's demon can still operate in the information landscapes of nonclassical causal structures to grant thermodynamic advantages. However, there are still additional open questions that require further study, such as how information flow and are utilized by the Maxwell's demon exactly to grant such advantages.

References

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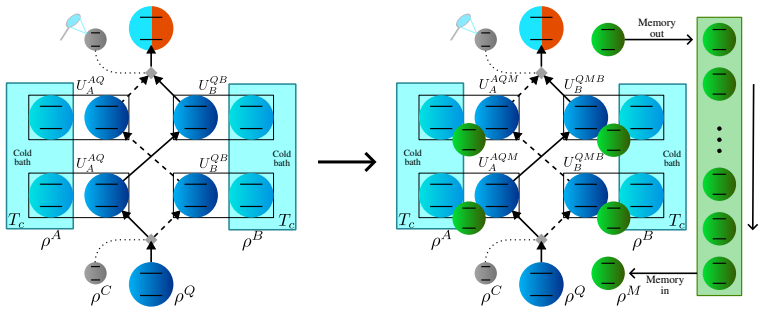

Figure 1: **The quantum switch and its augmentation.** Left: The quantum switch Φ^{sw} where the working system ρ^Q interacts with bath qubits ρ^A and ρ^B in a superposition of two alternate paths. Right: Its augmentation $\tilde{\Phi}^{\text{sw}}$ to include Maxwellian memory qubits ρ^M in its operation.