

Abstract

- We introduce a Maxwell demon which generates many-body-entanglement robustly against bit-flip noises, which allows us to obtain quantum advantage.
- Adopting the protocol of the voter model used for opinion dynamics approaching consensus, the demon randomly selects a qubit pair and performs a quantum feed back control, in continuous repetitions.
- We derive a lower bound of the entropy production rate by demon's operation, which is determined by a competition between the quantum-classical mutual information acquired by the demon and the absolute irreversibility of the feedback control.
- Our finding of the lower bound corresponds to a reformulation of the second law of thermodynamics under a class of Maxwell demon which generates many-body entanglement in a working substance.
- This suggests that a general condition for the operation of a successful entangling demon, one for which many-body entanglement stabilization and work extraction are possible, is that the information gain is larger than the absolute irreversibility.

Introduction

- A modern view of a Maxwell demon is a feedback control in which the dynamics of a system uses outputs of a measurement as inputs in a smart manner.
- The field of thermodynamics of information has clarified the fundamental bounds on entropy reduction and work extraction in terms of quantities such as the quantum-classical mutual information and absolute irreversibility.
- However, the thermodynamics of continuous quantum feedback remains a largely unexplored issue.
- Recently, variants of the original Maxwell demon which operate continuously in time have been demonstrated, showing an enhancement of the work extraction beyond the conventional feedback control with a limitation given by modified second-law-like inequalities.
- Stepping further along this direction, we propose a new type of Maxwell demon, namely a continuous quantum feedback control, that is capable of generating many-body entanglement in the working substance and study the quantum dynamics and second law of thermodynamics.
- This provides insights of dynamics in the quantum steady-state engineering studied in quantum information and optics, in the language of thermodynamics of information.

Setup

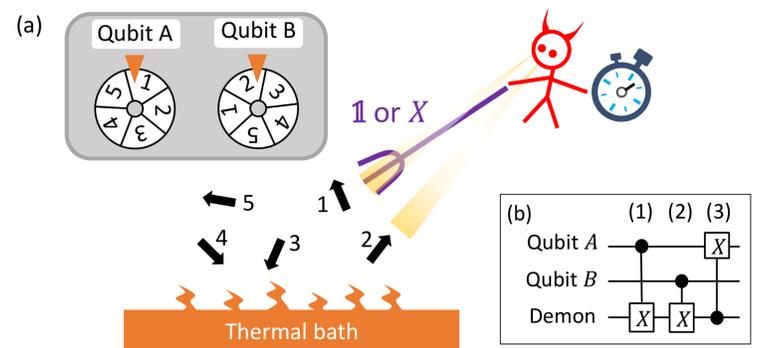


Fig. 1. Entangling maxwell demon adopting a protocol of the voter model (a) The demon selects a random pair of qubit A and B among many, and induces a copy process in which qubit A copies the state of qubit B in certain basis, continuously repeating the selection and copy process with a rate Γ_{copy} . A thermal bath induces bit-flip with a rate Γ_{flip} . (b) Quantum circuit realizing the copy process.

Entanglement generation

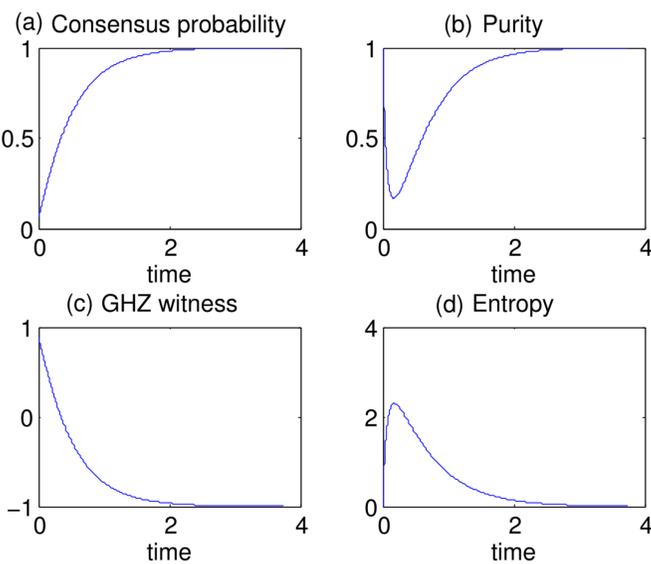


Fig. 2. Entanglement generation by the consensus dynamics in the absence of bit-flip noise. The quantum feedback controls induce consensus among the qubits (a), while enhancing GHZ entanglement (c). They reduce [or increase] von Neumann entropy of the qubits depending on time (d), accompanying the enhancement [or reduction] of coherence (b). Here, 5 qubits are considered, and the initial state is symmetric superposition $\sum_{s_1, \dots, s_N=0,1} |s_1 \dots s_N\rangle$. The time is measured in $\Gamma_{\text{copy}}^{-1}$.

Entanglement protection

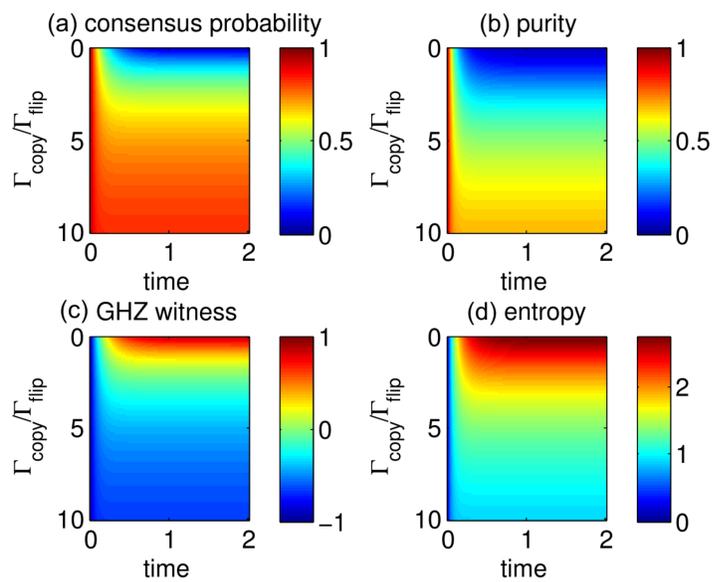


Fig. 3. Entanglement stabilization against bit-flip noise. Here, the initial state is 5-qubit GHZ state, $|00000\rangle + |11111\rangle$. When $\Gamma_{\text{copy}} > \Gamma_{\text{flip}}$, the consensus (a), entanglement (c), coherence (b), and entropy (d) is protected against the thermal fluctuations. The time is measured in $\Gamma_{\text{flip}}^{-1}$.

- Combining the two properties of entanglement generation and protection, the GHZ state can be generated even in the presence of bit-flip noises.

Entropy production by demon

- We find that the entropy production by the copy processes, \dot{S}_{copy} , are lower bounded as

$$\dot{S}_{\text{copy}} \geq N_{\text{copy}} \Gamma_{\text{copy}} (-\overline{I_{\text{QC}}} + \overline{\lambda_{\text{fb}}})$$

N_{copy} : number of possible copy pairs.

$\overline{I_{\text{QC}}}$: quantum-classical mutual information for quantum system and classical measurement outcomes

$\overline{\lambda_{\text{fb}}}$: absolute irreversibility.

- Determined by how much the feedback-operated states are different for distinct selections.

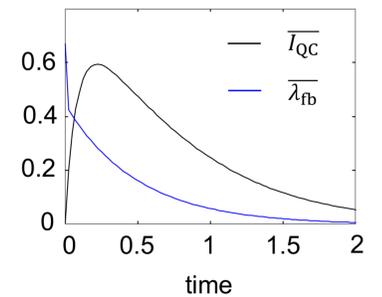


Fig. 4. Competition of $\overline{I_{\text{QC}}}$ and $\overline{\lambda_{\text{fb}}}$, responsible for the entropy in Fig. 2(d).

Conclusion

- Inspired by the voter model and realized by stochastic and continuous quantum feedback controls, we have introduced a quantum coherent consensus dynamics and we have shown that it is able to generate GHZ-entanglement robustly against bit-flip noises.
- We have also formulated the second law of thermodynamics under this new class of entangling Maxwell demon and obtained that the lower bound of the entropy production rate is determined by a competition between the quantum-classical information and the absolute irreversibility of the feedback control.
- Our finding will be helpful for stabilizing a many-body entangled state and for the exploration of the quantum information engine whose working substance is in a many-body entangled state.

Reference: Sungguen Ryu, Rosa López and Raúl Toral, New J. Phys. **24** 033028 (2022)