Autonomous Maxwell's demon in a cavity QED system

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Maxwell's Demon

Statistical character of the second law
To the left: molecules faster than a threshold
To the right: molecules slower than a threshold

Sufficient control would “violate” the second law

Modern standpoint:
Information acquisition = Measurement
Feedback control = Conditional evolution

J. C. Maxwell, Theory of Heat 4th edition, London: Longmans, Green, and Co. (1875).
Experimental Implementations

On-Chip Maxwell’s Demon as an Information-Powered Refrigerator
J. V. Koski, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola
Experimental Rectification of Entropy Production by Maxwell’s Demon in a Quantum System
Patrice A. Camati, John P. S. Peterson, Tiago B. Batalhão, Kaonan Micadei, Alexandre M. Souza, Roberto S. Sarthour, Ivan S. Oliveira, and Roberto M. Serra

Photonic Maxwell’s Demon
Mihai D. Vidrighin, Oscar Dahlsten, Marco Barbieri, M. S. Kim, Vlatko Vedral, and Ian A. Walmsley

Observing a quantum Maxwell demon at work
Nathanaël Cottet, Sébastien Jezouin, Landry Bretheau, Philippe Campagne-Ibarcq, Quentin Ficheux, Janet Anders, Alexia Auffèves, Remi Azout, Pierre Rouchon, and Benjamin Huard

Information-to-work conversion by Maxwell’s demon in a superconducting circuit quantum electrodynamical system
Y. Masuyama, K. Funo, Y. Murashita, A. Noguchi, S. Kono, Y. Tabuchi, R. Yamazaki, M. Ueda, & Y. Nakamura

Information Gain and Loss for a Quantum Maxwell’s Demon
M. Naghilio, J. J. Alonso, A. Romito, E. Lutz, and K. W. Murch
Cavity QED setup (2020)

Average photon number
\[ \overline{n_{th}} = 0.63 \pm 0.04 \]

Thermal field temperature
\[ T_C = 2.6 \pm 0.1 \text{ K} \]

Resonance frequency
\[ f_C = 51 \text{ GHz} \]

Rabi frequency
\[ \Omega_0 = 2\pi \times 77 \text{ kHz} \]

Atomic relaxation time
\[ \Gamma_a^{-1} \approx 30 \text{ ms} \]

Total travel time
\[ \tau \approx 100 \mu\text{s} \]
Protocol without demon

The qubit and the cavity exchange energy through the interaction map

\[ H^{QC}(t) = -\frac{\hbar \omega}{2} \sigma_z + \hbar \omega a^\dagger a + V(t) \]

Interaction map \( U^{QC} \)

- \( |1, n\rangle \rightarrow |0, n + 1\rangle \)
- \( |0, n + 1\rangle \rightarrow |1, n\rangle \)
- \( |0, 0\rangle \rightarrow |0, 0\rangle \)

Single-energy quanta exchange
Features without demon

Entropy production (average)

\[ \langle \Sigma \rangle = \beta_Q Q_Q + \beta_C Q_C \]

\[ \Delta \beta = \beta_C - \beta_Q \]

Energy conservation

\[ Q_C = -Q_Q \]

Second law

\[ \langle \Sigma \rangle = \Delta \beta Q_C \geq 0 \]

The hotter system always give off heat to the colder one
Exchange of energy controlled by a Maxwell's demon

Protocol with the demon

No demon

The feedback step is build so that heat from the cavity to the qubit is blocked
Exchange of energy controlled by a Maxwell's demon

Autonomous implementation

No demon

The measurement + feedback are performed dynamically (autonomous performance)
Relation between them

\[ p(k) \] is the probability of measuring the outcome k

\[ \rho_1^{QC} = \sum_k p(k) \rho_1^{QC, (k)} \]

\[ \rho_2^{QC} = \sum_k p(k) \rho_2^{QC, (k)} \]
The Rydberg atom energy levels are related to the qubit + demon levels through the logic map.
Setup (revisited)

In light of the logic map both circuits can be implemented by turning the source SD on and off.

Demon on-off

(Controlled) gate
From the conservation of entropy in the global system we can show that

\[
\Delta \beta Q_C = D \left( \rho_2^{QC} \parallel \zeta_{\beta Q}^Q \otimes \zeta_{\beta C}^C \right) + \Delta I^{QC:D}
\]

Relative entropy \hspace{2cm} Mutual information change during the feedback step
Heat transference

Without the demon, the heat flows in the “expected” direction.

With the demon, the heat flows in the “inverse” direction.

\[ \Delta \beta Q_C = D \left( \rho^Q_{2} \| \tilde{\zeta}_Q^Q \otimes \tilde{\zeta}_C^C \right) + \Delta \mathcal{T}^Q_{C:D} \]
Entropic quantities

Generalized second law

Entropy conservation

K. Micadei, et al. Nat. Commn. 10, 2456 (2019)
Wrapping up

- By employing a logic map we experimentally implemented an autonomous Maxwell's demon in a cavity QED setup.
- From the fact that our tripartite system (qubit + demon + cavity) is closed we obtained a thermodynamic relation between the qubit-cavity heat exchanged and the mutual information between the demon and the qubit-cavity system.
- The presence of the demon allows the inversion of heat flow at the expense of consuming the correlations created by the demon during the readout.
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- Mihai D. Vidrighin, Oscar Dahlsten, Marco Barbieri, M. S. Kim, Vlatko Vedral, and Ian A. Walmsley, Photonic Maxwell’s Demon, PRL 116, 050401 (2016).

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Thank you!