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Study explains how Maxwell's demon uses mutual information to extract work

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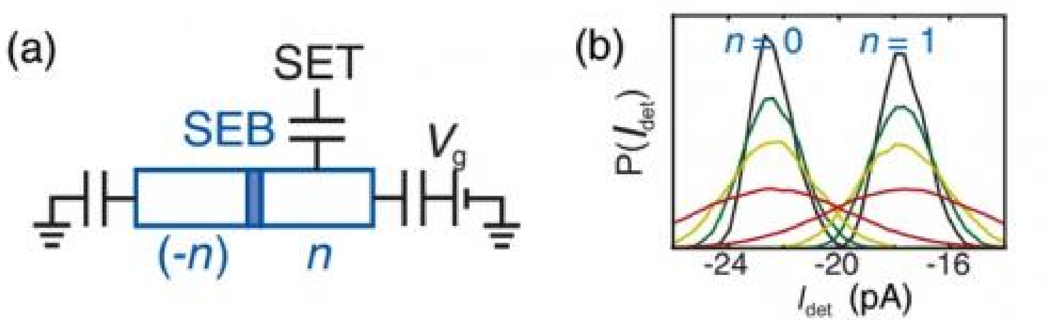

Electron tunneling occurs between the two islands on either side of a single-electron box (SEB, light blue). A nearby single-electron transistor, like Maxwell's demon, measures the state of the system and controls the system through feedback. Credit: J. V. Koski, et al. ©2014 American Physical Society

(Phys.org) —Maxwell's demon, the hypothetical doorman that controls how particles travel between two chambers in an attempt to decrease entropy, is at its heart a feedback-controlled system. The demon makes measurements on the microscopic state of the system, stores the measurement outcomes in its memory, and uses the information as a kind of "thermodynamic fuel" to extract work from the system.

This relation between information and thermodynamics embodied by Maxwell's demon is a topic of long-standing interest in the field of statistical physics. Recent research on fluctuation theorems, which describe the probability distribution of entropy production, have brought renewed attention to this concept.

Working in this area, a team of researchers, J. V. Koski, et al., have experimentally demonstrated the first evidence of the connection between mutual information in a feedback-controlled device (such as the demon) and fluctuation theorems. In an experiment involving tunneling electrons, the researchers show how the mutual information created by a measurement can be used to implement feedback control that enables the extraction of useful work.

The purpose of their experiment was to determine the probability distribution of the measurement efficiency, which is defined as the difference between the true state and the measurement outcome. This measurement efficiency provides the upper limit to how much work can be extracted from the system for the given information. When measurement efficiency is perfect, then feedback control is also perfect and all of the mutual information is extracted as work.

The experiment itself consists of a single-electron box that connects two metallic "islands," each a few micrometers long, in which electron transport between the two is permitted by tunneling. The box is cooled to a temperature near absolute zero (100 mK). A gate controls the electron tunneling between the islands, and a nearby single-electron transistor, like Maxwell's demon, measures the state of the system and controls the system through feedback.

When investigating how the measurement error affects the amount of work that can be extracted, the researchers found that the measurement error probability distribution follows a fluctuation theorem called the generalized Jarzynski equality. Through this equality, the study shows for the first time the connection between thermodynamics and mutual information. As expected, the results reveal that the efficiency of the feedback and the amount of extracted work increase as measurement efficiency increases. These results provide a better understanding of the nature of thermodynamics.

"In driven systems the fluctuations and dissipation are governed by non-equilibrium fluctuation relations," coauthor Jukka P. Pekola, Professor at Aalto University in Aalto, Finland, told Phys.org. "They typically govern deterministically driven dynamics, i.e., situations where information and feedback play no role. In the present work we have experimentally demonstrated how feedback, based on information collected from a measurement, modifies such fluctuation relations, and how one can, in the case of nearly perfect measurement, approach the limit of extracting heat and work from the thermal bath."

In the future, the scientists plan to build on this result by applying it to various uses.

"Our goal is to devise an experiment where the feedback is fast enough to demonstrate real cooling of the bath in the form of decreasing the actual temperature of the electron gas directly coupled to the system of interest," Pekola said. "Another more general goal is to investigate thermodynamics in pure (superconducting) quantum systems."

More information: J. V. Koski, et al. "Experimental Observation of the Role of Mutual Information in the Nonequilibrium Dynamics of a Maxwell Demon." *PRL* 113, 030601 (2014). DOI: 10.1103/PhysRevLett.113.030601