Physics

VIEWPOINT

Exorcising Maxwell's Demon

A pair of connected single-electron devices functions as a Maxwell's demon that operates without external control.

by Sebastian Deffner*

Physicists have been haunted by the idea of Maxwell's demon for almost 150 years. The beast, conjured in a thought experiment by James Clerk Maxwell, sorts particles in a gas according to their speeds, thus transferring heat from the colder, evenly mixed gas to the region containing the hotter, high-speed particles. At first sight, the demon appears to violate the second law of thermodynamics. But the paradox can be resolved by realizing that work must be performed on the demon for it to do its job properly. This description isn't entirely satisfying, however, as it introduces an external—not necessarily physical—entity to do work on the demon. Jukka Pekola and colleagues of Aalto University in Finland [1] have now exorcised such nonphysical beings by realizing a nanodevice equivalent to a Maxwell's demon (Fig. 1), but one whose operation doesn't depend on an external entity. This so-called autonomous device, also known as an information machine, is completely self-contained. So far, autonomous demons have been a purely theoretical concept; this new experimental system provides a way to test formulations of fundamental axioms of thermodynamics and descriptions of information processing.

In the second half of the 19th century, the second law of thermodynamics was still relatively new. The law had been restated to describe specific situations, including, for instance, that heat cannot be transferred from cold to hot without doing work (Clausius statement), and that heat engines cannot operate with 100% efficiency (Carnot statement) [2]. But physicists questioned whether the second law was true for a system whose properties were governed by the average behavior of many particles or if it held for each individual particle. To illustrate the average quality, Maxwell proposed, in an 1867 letter to his colleague Peter Tait, a thought experiment that allowed a violation of the Clausius statement [3]. Maxwell imagined two boxes, filled with a gas of particles and separated by a common wall. A "neat fingered being," capable of measuring each particle's velocity, sat by a little door in the wall. This being could sort particles by opening and closing the door, allowing only fast particles to go to the right and only slow particles to the left. This sorting process would, in direct violation of the Clausius statement, transfer heat from a cold reservoir to a hot one.

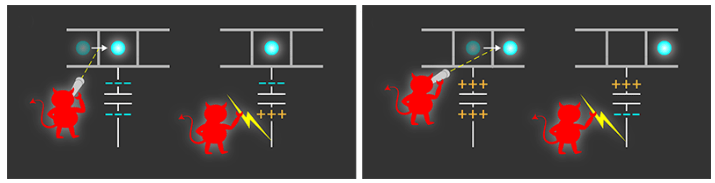

Figure 1: An electronic version of a self-contained (autonomous) Maxwell demon. The "system" is a single-electron box connected to an external potential. The demon monitors the charge on the box. (Left) If an electron (blue) enters the box, the demon immediately traps it by applying a positive charge. (Right) If the electron leaves the box, the demon repels it by applying a negative charge. This is the electronic equivalent of the demon opening or shutting the door for fast/slow particles in Maxwell's original thought experiment. (APS/Alan Stonebraker)

Maxwell's demon was an instant source of fascination and led to many important results, including the development of a thermodynamic theory of information. But a particularly important insight came in the 1960s from the IBM researcher Rolf Landauer [4]. He realized that the extra work that can be extracted from the demon's action has a cost that has to be "paid" outside the gas-plus-demon system. Specifically, if the demon's memory is finite, it will eventually overflow because of the accumulated information that has to be collected about each particle's speed. At this point, the demon's memory has to be erased for the demon to continue operating—an action that requires work. This work is exactly equal to the work that can be extracted by the demon's sorting of hot and cold particles. Properly accounting for this work recovers the validity of the second law. In essence, Landauer's principle means that "information is physical" [5]. But it doesn't remove all metaphysical entities nor does it provide a recipe for building a demon. For instance, it is fair to ask: Who or what erases the demon's memory? Do we need to consider an *über*-demon acting on the demon?

Researchers have recently revisited these conceptual conundrums. And these efforts have shifted our way of picturing Maxwell's thought experiment from setups requiring that the demon be operated by an external agent to ones that are self-contained [2, 6, 7]. Interestingly, Leo Szilard anticipated this modern framework and understanding some

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eighty years ago [8]. Szilard was never comfortable with the need to introduce a metaphysical, human-like intelligence to operate Maxwell's demon. Instead, he thought that it should be possible to construct autonomous, maybe even mechanical, systems that act like a demon yet fully obey the laws of physics—a fully inclusive conceptual approach. Although the idea has attracted a lot of attention, it has only been realized in theoretical form. (For recent examples, see Refs. [9, 10].)

The work by Pekola and colleagues has made Szilard's autonomous demon a physical reality. Their device consists of two single-electron boxes: a "system" box and a "demon" box. The system box is made of a small metal (copper) island connected to two metal leads via superconducting aluminum junctions that allow electrons to tunnel onto and off the island. (Using superconducting materials ensures that electrons are transported without transference of heat, allowing the authors to accurately track the heat entering and leaving the system and the information exchanged with the demon.) The system box is coupled to a neighboring demon box with a similar electronic structure, which detects the voltage associated with an electron either entering the island or leaving it (Fig. 1). This voltage, in turn, activates the demon: When an electron tunnels onto the island, the demon box is designed to trap it by applying a positive charge; if an electron leaves the island, the demon repels it by applying a negative charge. The charge induced by the demon forces the electrons to tunnel against a potential—the electrons must move uphill—and the system cools down. No external control drives the action of the demon (it is thus autonomous), and the whole process is accomplished because of the clever way in which the two electron boxes are coupled.

The researchers showed that the demon's actions make the system's temperature drop and the demon's temperature rise, in agreement with the predictions of a simple theoretical model. The temperature change is determined by the so-called mutual information between the system and demon. This quantity characterizes the degree of correlation between the system and demon; or, in simple terms, how much the demon "knows" about the system.

We now have an experimental system that fully agrees with our simple intuition—namely that information can be used to extract more work than seemingly permitted by the original formulations of the second law. This doesn't mean that the second law is breakable, but rather that physicists need to find a way to carefully formulate it to describe specific situations. In the case of Maxwell's demon, for example, some of the entropy production has to be identified with the information gained by the demon. The Aalto University team's experiment also opens a new avenue of research by explicitly showing that autonomous demons can exist and are not just theoretical exercises. For example, understanding the information contribution to entropy production might become important in cases where information needs to be written or read with high efficiency—such as the remote operation of a computer in humans or in space.

One day, we might have a truly mechanical demon, as envisioned by Szilard [8] and in more recent theoretical proposals [10]. Like mechanical heat engines, mechanical demons are easier to visualize than their electrical counterparts and could therefore better illustrate fundamental principles of thermodynamics.

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REFERENCES

[1] V. Koski, A. Kutvonen, I. M. Khaymovich, T. Ala-Nissila, and J. P. Pekola, "On-Chip Maxwell's Demon as an Information-Powered Refrigerator," Phys. Rev. Lett. **115**, 260602 (2015).

[2] S. Deffner and C. Jarzynski, "Information Processing and the Second Law of Thermodynamics: An Inclusive, Hamiltonian Approach," Phys. Rev. X **3**, 041003 (2013).

[3] Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing, edited by H. S. Leff and A. F. Rex (IOP Publishing, Bristol, 2003) 0750307595.

[4] E. Lutz and S. Ciliberto, "Information: From Maxwell's Demon to Landauer's Eraser," Phys. Today **68**, No. 9, 30 (2015).

[5] R. Landauer, "Information is Physical," Phys. Today **44**, No. 5, 23 (1991).

[6] A. C. Barato and U. Seifert, "Stochastic Thermodynamics with Information Reservoirs," Phys. Rev. E **90**, 042150 (2014).

[7] J. M. R. Parrondo, J. M. Horowitz, and T. Sagawa, "Thermodynamics of Information," Nature Phys. **11**, 131 (2015).

[8] L. Szilard, "On the Decrease of Entropy in a Thermodynamic System by the Intervention of Intelligent Beings," Z. Phys. **53**, 840 (1929).

[9] D. Mandal and C. Jarzynski, "Work and Information Processing in a Solvable Model of Maxwell's Demon," Proc. Natl. Acad. Sci. U.S.A **109**, 11641 (2012).

[10] Z. Lu, D. Mandal, and C. Jarzynski, "Engineering Maxwell's Demon," Phys. Today **67**, No. 8, 60 (2014).

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