Quantum trickster

A Brazilian group controlled the heat generated by atomic nuclei

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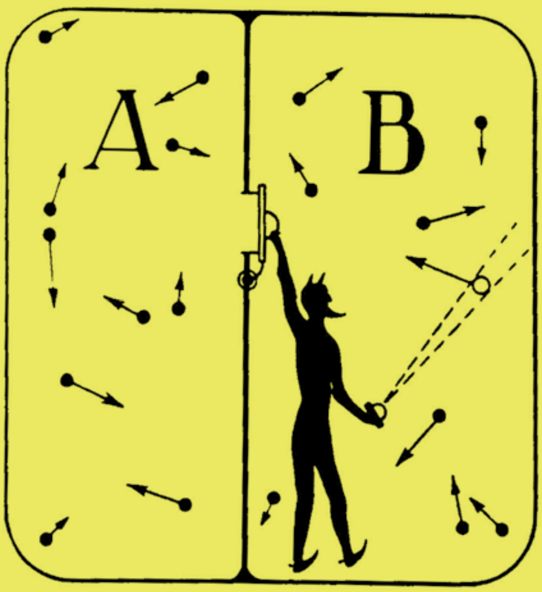
The random generation of heat in the microscopic world is one of the main obstacles to advances in nanotechnology. As nanodevices become smaller and more complex, with parts the size of molecules or even atoms, there is a greater chance that they will generate dangerous quantum fluctuations while operating. These fluctuations are abrupt, unpredictable energy variations that are governed by the probabilistic laws of quantum mechanics and can damage nanomechanisms. A group of Brazilian physicists led by Roberto Serra, a professor at the Federal University of the ABC (UFABC), presented a technique that is able to attenuate the production of these heat fluctuations at the subatomic level in early December 2016 in *Physical Review Letters*.

The microscopic fluctuations in energy and heat affect nanomachines in a way similar to how uncontrolled overheating can damage a conventional macroscopic motor such as a car engine. During the Industrial Revolution in the nineteenth century, one of the motivations behind the development of classical thermodynamics—the area of physics that establishes how energy in the form of heat is converted into mechanical energy and vice-versa—was to understand the operation of pressure valves and refrigerators, devices that made the operation of steam and internal combustion engines safer and more efficient. Anticipating advances in nanotechnology, Serra and his colleagues are part of a community of physicists who have been developing a more general and detailed theory of thermodynamics, called non-equilibrium quantum thermodynamics, that can ensure the efficient operation of molecular- and atomic-scale devices in which quantum effects occur.

To develop a new control technique, Serra and his colleagues were inspired by "Maxwell's demon," a fantastic being invented by Scottish physicist and mathematician James Clerk Maxwell (1831-1879). Maxwell was one of the first to understand that the temperature of a given volume of gas depends on the average speed at which the molecules in it move. The faster the molecules, the hotter the gas. In an 1867 letter to his colleague Peter Tait, Maxwell posited a microscopic, intelligent being that is able to measure and record velocities of all gas molecules. In this mental experiment, the being controlled a valve that separated two identical containers, both containing a gas at the same temperature. Opening and closing the valve quickly, the creature separated the molecules of gas, leaving the slower-than-average ones—which were thus colder—in one container and allowing the faster ones into the other container.



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A 1975 paper by Russian mathematician Alexander Lerner includes a depiction of Maxwell's demon inside a container of gas molecules to be selected

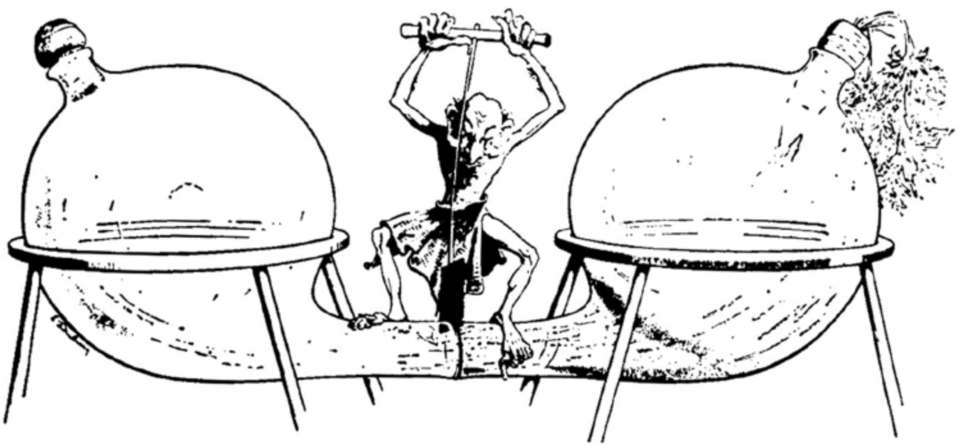
THERMODYNAMIC SIN

In a *Nature* article in 1874, Irish physicist William Thomson, who is better known as Lord Kelvin, called the intelligent being a demon, to emphasize that the creature, by heating gas in one container while cooling gas in the other, committed the sin of violating the second law of thermodynamics.

This law states that an isolated body, or a set of isolated bodies, has a property called entropy, which always tends to increase over time. For a set of particles, entropy corresponds to the possible number of arrangements of all of them in a given situation.

When ordering gas molecules according to their speed, the demon supposedly reduces the number of possible arrangements of the system, which reduces its

In an article published in 1955 in the *American Journal of Physics*, the imaginary figure controls the flow of gas molecules from outside the containers



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entropy. After Thomson's article, physicists still wondered: is the demon a mere fantasy, or does the mental experiment indicate a failure to understand the laws of thermodynamics?

More than a century later, in 1982, American physicist Charles Bennett, then a researcher at IBM, realized that to work effectively, Maxwell's demon would need to record information on the speed of gas molecules on a physical substrate, such as the memory bits of a computer. However, writing and erasing data in memory cannot be done without generating heat, which was something discovered years earlier by Rolf Landauer, another IBM researcher. Furthermore, heat generation always increases entropy.

When assessing the increase and decrease of heat in both stages of this process, one notes that the second law of thermodynamics is never violated: the demon can reduce entropy inside gas containers by selecting molecules, but the heat generated to record the speeds of the molecules in memory increases entropy outside the containers much more. The calculations show that Maxwell's supernatural creature obeys all physics laws and that its function can be performed, in practice, by an automatic mechanism, controlled by computer memory.

Experiment with a chloroform molecule and electromagnetic pulses reproduced the mental experiment proposed in the 19th century

Since then, researchers have created increasingly smaller mechanisms in the laboratory, similar to that imagined by Maxwell. The current project being carried out by Serra and his colleagues is the first to design a completely quantum Maxwell's demon. In a laboratory at the Brazilian Center for Physics Research (CBPF) in Rio de Janeiro, the researchers shot a pulse of electromagnetic waves at a solution of chloroform molecules—each one consisting of a carbon atom, a hydrogen atom, and three chlorine atoms ($CHCl_3$). The pulse was adjusted to cause quantum fluctuations in the energy of the nuclei of carbon atoms of the molecules. At the same time, physicists shot additional electromagnetic waves at the molecules with the goal of adjusting the interaction between the carbon and hydrogen nuclei of each molecule.

The researchers managed to use the hydrogen nucleus as a Maxwell's demon, storing information about the state of the carbon nucleus. Depending on the energy level of the carbon nucleus, the hydrogen nucleus activated and restricted the energy fluctuations of its neighbor. The actions of hydrogen nuclei caused the energy fluctuations of the carbon nuclei to occur in a way that produced the least possible entropy. "We designed this process based on a mathematical equation that we derived, relating information, entropy and energy," says Serra. "The equation is quite general and can be applied to any quantum system, such as electrons and photons, not just to atomic nuclei."

"It is an exciting study," comments Vlatko Vedral, a physicist at Oxford University, England, who participated in an experiment carried out in 2016, in which laser beams were used to produce Maxwell's demon. "They tested a formula that describes the production of entropy in quantum systems under generic conditions. It is still unclear why the entropy of the Universe must always increase, and this approach could help explain the origins of the second law of thermodynamics." ■

Project
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Scientific article

CAMATI, P. A. *et al.* Experimental rectification of entropy production by Maxwell's demon in a quantum system. **Physical Review Letters**. v. 117, 240502. 5 Dec. 2016.

ILLUSTRATIONS 1 FUNDAMENTALS OF CYBERNETICS | A. Y. LERNER | SPRINGER **2** DARLING & HULBURT, *AMERICAN JOURNAL OF PHYSICS*, 23-7, 1955