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Maxwell's demons realized in electronic circuits

Démons de Maxwell réalisés avec des circuits électroniques

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A B S T R A C T

We review recent progress in making the former gedanken experiments of Maxwell's demon [1] into real experiments in a lab. In particular, we focus on realizations based on single-electron tunneling in electronic circuits. We first present how stochastic thermodynamics can be investigated in these circuits. Next we review recent experiments on an electron-based Szilard engine. Finally, we report on experiments on single-electron tunneling-based cooling, overviewing the recent realization of a Coulomb gap refrigerator, as well as an autonomous Maxwell's demon.

R É S U M É

Nous passons en revue des progrès récents qui ont permis de faire des anciennes propositions du démon de Maxwell des expériences réelles de laboratoire. En particulier, nous nous concentrons sur des réalisations basées sur l'effet tunnel à un électron dans des circuits électroniques. Nous montrons d'abord comment la thermodynamique stochastique peut être explorée dans ces circuits. Ensuite, nous passons en revue des expériences récentes sur un moteur de Szilard électronique. Enfin, nous rendons compte d'expériences de refroidissement basées sur l'effet tunnel à un électron, incluant la réalisation d'un réfrigérateur à *gap* de Coulomb, ainsi que celle d'un démon de Maxwell autonome.

1. Introduction to the concept of a Maxwell's demon, motivation

Classical mechanics describes the evolution of a system with a limited number of degrees of freedom in a deterministic manner. Given that the initial configuration is known, the equations of motion give the exact system state at an arbitrary time. The most essential constraint is dictated by the first law of thermodynamics, which states that energy must be conserved. Thermodynamics investigates systems with a macroscopic number of degrees of freedom. In such a case, it would be

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cumbersome to study the dynamics, if not for the fact that the majority of the degrees of freedom often behave collectively, forming a heat bath that interacts with the remaining degrees that form the 'system'. The approach ultimately accepts that the exact state of the heat bath is not known, but it rather follows a probability distribution that is characterized by temperature T. As an immediate consequence, the dynamics of the system are stochastic and – unless all the microscopic degrees of freedom are constantly monitored – will evolve to follow a probability distribution P_n, where n is the system state. The relevant quantity in this picture is entropy $S = -k_B \sum P_n \ln(P_n)$ characterizing the amount of disorder or uncertainty in the system. Here k_B is the Boltzmann constant.

Entropy has a central role in thermodynamic processes. It is bound by the second law of thermodynamics, which states that, on the average, entropy cannot decrease. The entropy of the heat bath is linked to its temperature as $\Delta S_{env} = Q/T$, where Q is energy or 'heat' injected into it. The second law would thus require that when two reservoirs are interacting by, e.g., exchanging particles, the only allowed direction for heat flow is from hot to cold. As energy is conserved, the two reservoirs would eventually equilibrate to have equal values of T. In 1867, J.C. Maxwell presented a thought experiment to challenge the second law. He pictured an intelligent observer that monitors and controls the particle transport between the two reservoirs, allowing only high-energy particles to pass from the hot reservoir to the cold one, and only low-energy particles to pass the other way. Following this simple procedure, one would seemingly violate the second law. It is natural that the apparent controversy which, if correct, would permit machines of perpetual motion has generated significant scientific discussion.

The concept today known as 'Maxwell's demon' [1] was studied by Leo Szilard in 1929 on a thought experiment with a single particle in a box [2]. The box is operated by a Maxwell's demon, who first inserts a wall to split the box in two equal halves. The particle is trapped in either half, and the demon determines the position of the particle by measurement. With this information, the demon can allow the one-molecule gas to expand back to the full volume of the box. By ideal gas law, $k_B T = pV$, the amount of work performed by the demon is $W = -\int_{V/2}^{V} p\,\mathrm{d}V = -k_B T \ln(2)$, and energy conservation demands $W = Q$. In other words, the demon extracted $k_B T \ln(2)$ of energy directly from the heat bath of the box. Szilard concluded that during the expansion, the entropy of the heat bath is converted into that of the system, which increases by $k_B \ln(2)$ as the initial full certainty on the position of the particle converts into equal probability $1/2$ for the particle being on either half of the box.

Szilard presumed that the measurement performed by the demon has to involve production of at least an equivalent amount of entropy. The thought experiment was later on investigated by Rolf Landauer, who in 1961 concluded that it is the act of information erasure that generates at least an equivalent amount of entropy as was decreased by the feedback. Upon measurement, the demon must record one bit of information to its memory. Should this information be erased, which must be done in order to complete the thermodynamic cycle, energy of at least $k_B T \ln(2)$ must be spent on the process. This statement, known as Landauer's erasure principle, has a major significance for logical computing. Any logically irreversible operation, such as AND or OR, has a fundamental minimum energy cost.

Since the beginning of this millennium, scientific interest in Maxwell's demon has reignited as experimental access to the microscopic degrees of freedom has become available. This development has been spurred by the discovery of fluctuation relations [3–7] that describe non-equilibrium processes by equalities. Of particular importance to the Maxwell's demon concept is the Sagawa–Ueda equality [7], which links the information extracted from the microscopic system to applied work and the change of free energy. The theorem was promptly verified by an experiment on a system consisting of a colloidal particle in an alternating, feedback-controlled electric field [8]. Further experimental progress was made on Landauer's principle by demonstrating that when an erasure protocol on a particle in a double-well potential is taken to the adiabatic limit, the energy spent on the process tends to $k_B T \ln(2)$ limit [9]. Other experiments have demonstrated how feedback can be utilized to suppress thermal excitations [10]. Recently, Maxwell's demon operation was demonstrated on an optical system [11].

As the connection between information and thermodynamics has become apparent, further investigation has been devoted on configurations involving both the demon and the feedback-controlled system. Such devices are known as autonomous Maxwell's demons (AMD). AMDs have been proposed to function by using a bit stream as a resource to decrease the entropy in the heat bath while increasing entropy in the memory [12]. Others focus on two coupled systems that exchange information which is immediately erased, resulting in heat generation in the measuring device [13,14].

In this review, we focus on recent experiments on Maxwell's demons based on electric circuits that realize the Szilard engine protocol, and an autonomous Maxwell's demon.

2. Energetics in an electric circuit

Electron transport in circuits offers an arena to investigate stochastic thermodynamics of small systems. Quite generally, if we consider a charge q overcoming a potential difference $\pm V$, there is energy qV dissipated or extracted in this event. Entropy production is then given by $\Delta S = \pm qV/T$ in a constant temperature process. Since current is the rate of charge transport, average power can be very generally associated with the product IV for an average current I at voltage V.

Nowadays, charges in electric circuits can be controlled and detected routinely down to single electrons: with this capability, energetics in circuits can be studied in great details, although indirectly. Yet in most recent experimental works, heat could be measured directly by observing temperature changes: this is a topic of Section 6.

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