C. R. Physique 17 (2016) 1130–1138

Contents lists available at ScienceDirect

Comptes Rendus Physique

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Thermoelectric mesoscopic phenomena / Phénomènes thermoélectriques mésoscopiques

Maxwell's demons realized in electronic circuits

Démons de Maxwell réalisés avec des circuits électroniques

Jonne V. Koski [a,b], Jukka P. Pekola [a,*]

[a] *Low Temperature Laboratory, Department of Applied Physics, Aalto University School of Science, P.O. Box 13500, 00076 Aalto, Finland*
[b] *Solid State Physics Laboratory, ETH Zurich, CH-8093 Zurich, Switzerland*

ARTICLE INFO

Article history:
Available online 21 August 2016

Keywords:
Maxwell's demon
Information

Mots-clés :
Démon de Maxwell
Information

ABSTRACT

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.

RÉSUMÉ

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 refrigérateur 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

* Corresponding author.
E-mail address: jukka.pekola@aalto.fi (J.P. Pekola).

http://dx.doi.org/10.1016/j.crhy.2016.08.011

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 $S = -k_\mathrm{B} \sum P_n \ln(P_n)$ 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 $\Delta S_\mathrm{env} = Q/T$, 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, $k_\mathrm{B}T = pV$, the amount of work performed by the demon is $W = -\int_{V/2}^{V} p\,\mathrm{d}V = -k_\mathrm{B}T\ln(2)$, and energy conservation demands $W = Q$. In other words, the demon extracted $k_\mathrm{B}T\ln(2)$ 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 $k_\mathrm{B}\ln(2)$ 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 $k_\mathrm{B}T\ln(2)$ 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 $k_\mathrm{B}T\ln(2)$ 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.

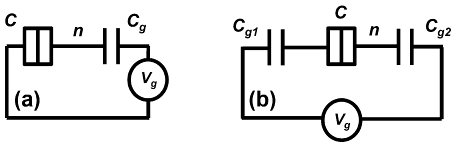

Fig. 1. A single-electron box (SEB). The tunnel junction is indicated by the split rectangle, and it has capacitance C and conductance R_T^{-1}. In (a), the gate capacitor is denoted by C_g, biased at voltage V_g. The net number of electrons tunneled through the junction is given by n. In (b), we show a split SEB that has been used in the actual experiments. Apart from rescaled parameters, it is equivalent to the basic SEB in (a).

Our focus here is on single-electron circuits. To set the stage, let us consider a basic example, the single-electron box (SEB) [15,16], see Fig. 1a, that has furthermore served as one archeotypal experimental realization of stochastic thermodynamics over recent years. An SEB is a small capacitor, with total capacitance C_Σ, on which a discrete number n of electrons can dwell. The energy (Hamiltonian H) of this capacitor is tunable by the external control parameter, a gate voltage V_g, which polarizes the charge in the SEB via the gate capacitance C_g, such that $H(n, n_g) = E_C(n - n_g)^2$. Here $E_C = e^2/(2C_\Sigma)$ is the elementary charging energy for one electron with charge e and $n_g = C_g V_g/e$ is the normalized gate voltage. For this particular basic configuration of SEB, $C_\Sigma = C + C_g$, where C is the capacitance of the tunnel junction, admitting single electrons in and out of the island. What is important here is that the charges are transported stochastically; the tunneling rate is given by the chemical potential difference $\Delta\mu$ (corresponding to the voltage V in the general discussion above) and the temperature $T = 1/(k_B\beta)$ of the bath. In particular, for a common situation where the electrodes in the SEB can be considered as electronic Fermi seas, i.e. with normal metal leads, the rate in (+) or out (−) of the box is given by $\Gamma_\pm = (e^2 R_T)^{-1}\Delta\mu_\pm/(1 - \mathrm{e}^{-\beta\Delta\mu_\pm})$. Here R_T is the inverse tunnel junction conductance, which has a constant value determined by the parameters characteristic for a particular SEB determined by the fabrication details. For the SEB considered here, $\Delta\mu_\pm = H(n, n_g) - H(n \pm 1, n_g) = -E_C[1 \pm 2(n - n_g)]$, which does not depend on the nature of the lead electrodes, but is purely the charging energy of the capacitor(s). This is at the same time the heat ΔQ dissipated to the bath consisting of the rest of the electrons coupled with the phonon reservoir.

Typically, at low enough temperatures, i.e. for $\beta E_C \gg 1$, the tunneling rates above dictate that the charge state n can have at most two values. Without loss of generality, we may choose $n = 0, 1$ in the range $n_g = 0...1$. In this case, $\Delta Q = \pm E_C(1 - 2n_g)$. This means that the heat dissipated to the bath can be monitored by bookkeeping the external control parameter n_g and the corresponding transitions of n using a single-electron detector. Usually one is interested in the work done on the system, W, besides the heat $Q = \sum_i \Delta Q_i$, where the sum is over all the jumps during the measurement. Since according to the first law of thermodynamics $W = U + Q$, one still needs to determine the change in the internal energy, U, which is equal to change in $H(n, n_g)$ in the process. The quantities U and Q are thus accessible via charge detection, and this allows one to investigate stochastic thermodynamics in a circuit with high precision. For instance, one can choose a protocol of driving n_g repeatedly, and measure the mentioned quantities in each realization of the experiment. Then one obtains a test of common fluctuation relations [4,5], e.g., the Jarzynski equality $\langle \mathrm{e}^{-\beta W}\rangle = 1$, where the average is taken over the realizations. This relation was verified in the experiment of Saira et al. [17] within about 3% accuracy of the mentioned average, by applying hundreds of thousands of repetitions of the gate protocol. An advantage of the single-electron circuits is, indeed, the possibility of repeating the experiment very many times under identical conditions. Besides metallic single-electron circuits, another option for these studies is to use semiconducting quantum dots monitored by quantum point-contact single-electron detectors [18,19].

The SEB employed in the experiments below has a slightly different architecture from the basic one, see Fig. 1b. One typically employs such a split box design to make the system less susceptible to external noise. The set-up then consists of a tunnel junction, which has two islands, one on each side of the junction, which are furthermore connected to the biasing source via capacitances from each island. Thus the experimental SEB is kind of a symmetric version of that in Fig. 1a, with the same Hamiltonian and operation principle but with different effective capacitances.

3. Basic principles of circuit-based Maxwell's demons

Based on the capability of detecting and manipulating single electrons, the concept of an experimentally feasible Maxwell's demon is quite obvious. It comprises of observing the system by the charge detector, and utilizing this information for conditional feedback applied on gate voltage(s), based on the outcome of the said measurement of the system. One of the early proposals of the electronic Maxwell demon [20] follows closely the idea of the experiment of Toyabe et al. on a microsphere in an alternating electric field [8]. We present this idea here since it illustrates the principle of gaining energy with the help of thermal fluctuations in a simple way. The experimental realization of it in a circuit is still to come. The idea of [20] is to "lift" electrons up to higher potential with the help of thermal fluctuations and a measurement-feedback protocol. This way one can in principle store energy in a battery or a capacitor. The circuit (Fig. 2) consists of a voltage-biased array of "single-electron boxes", i.e. a tunnel junction array of minimum three junctions, where each dot in between the contacts is monitored by a single-electron charge detector. Each jump of the charge up in the array corresponds to energy extracted from the bath: the tunneling rates introduced earlier allow for such unfavorable processes at finite temperature. When such a transition occurs, energy is extracted to the charging degrees of freedom from the bath,

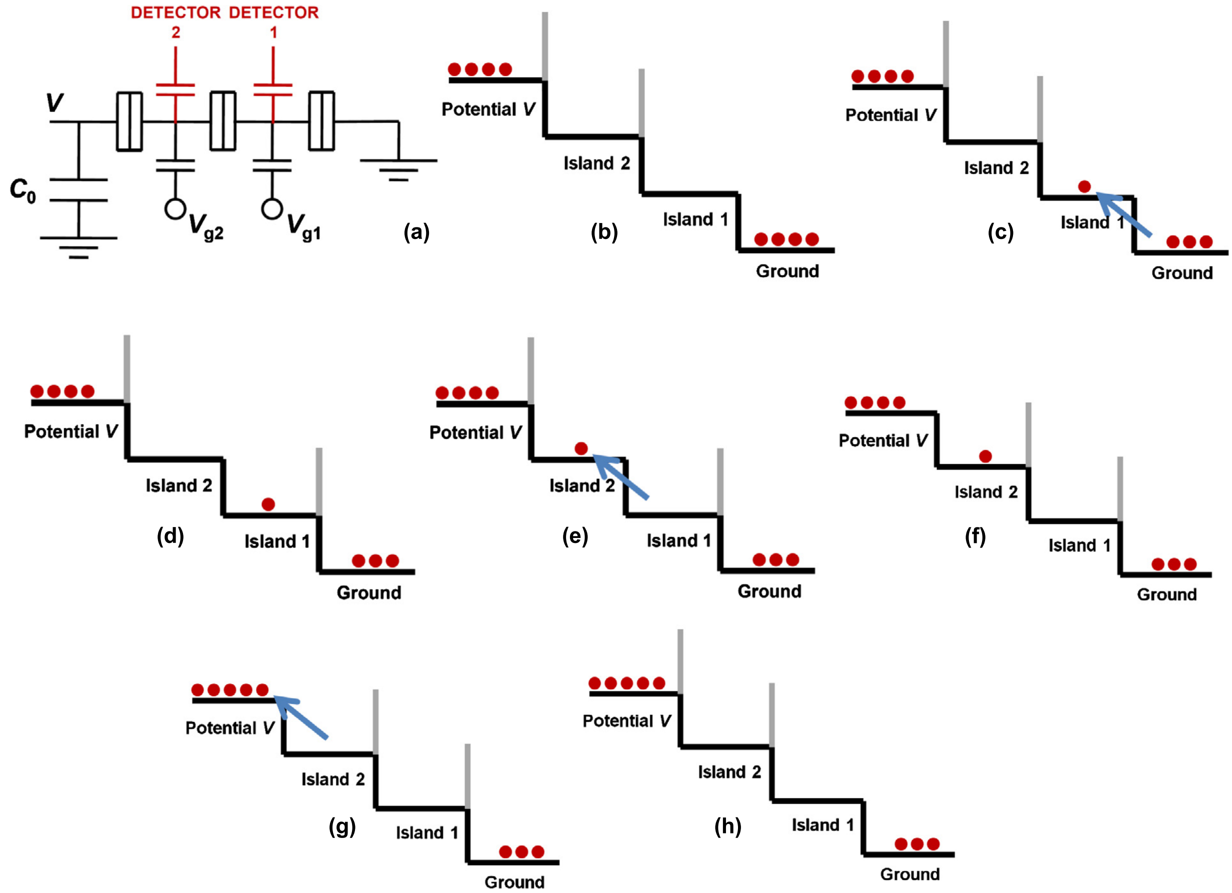

Fig. 2. Maxwell's demon based on a three-junction array of small tunnel junctions [20]. (a) The circuit diagram. Charges on the islands 1 and 2 of a biased (voltage V) array are monitored by the corresponding charge detectors, and feedback is based on the tunneling events observed. The demon is able to move charges up in the potential from right to left. (b)–(h) illustrate a cycle of collecting charge at potential V based on feedback. In this cycle, an amount of energy eV is stored in the capacitor at a potential V. Each blue arrow indicates a thermally activated tunneling event against bias, and the vertical gray lines depict a barrier to prevent tunneling downwards.

i.e. the extra electron moves to a higher energy. As soon as this process takes place, the charge detector observes it and the control gates are turned to a new position to prevent the charge from tunneling back to the lower potential. It is possible to make this process cyclic as demonstrated in [20], and to convey electrons one by one from the low potential end of the array to the high one with the help of the information of the measurement and feedback.

The principle of the two experimentally realized Maxwell's demons, the Szilard Engine and the autonomous Maxwell's demon, will be introduced along with the description of the experiment in the next Sections.

4. Realization of the Szilard engine in a single-electron box

The original gedanken experiment presented by Szilard consists of a single particle in a box. The work extracted for one bit of information in the setup can be derived by the ideal gas law. Yet, as discussed by Szilard, the relevant quantity is the change of entropy. Practically any system, where the microscopic degree of freedom can be measured and controlled externally at the accuracy of a single bit, is feasible. This also means that an SEB cooled down to meet $\beta E_C \gg 1$ can be operated as a Szilard's engine by measuring n with a single-electron charge detector, namely a single-electron transistor (SET) which is essentially an SEB connected to two leads at different potentials and whose charge transport depends on the nearby potential, and performing feedback by modulating V_g, see Fig. 3. In the present experiment, the SEB consists of two metallic islands connected by a tunnel junction, a device which effectively operates identically to a single island connected to a single lead, as sketched in Fig. 1.

The operation cycle begins with $\Delta\mu_+ = 0$ for $n = 0$ (and therefore $\Delta\mu_- = 0$ for $n = 1$), such that thermal equilibrium corresponds to equal 1/2 probabilities for $n = 0$ and $n = 1$, that is, for an excess electron to reside either on the left or the right island. This is analogous to the Szilard's engine setup, where the particle is initially in either the left or the right half of the box. Next follows the determination of the charge state of the SEB. This is achieved by measuring the current of a

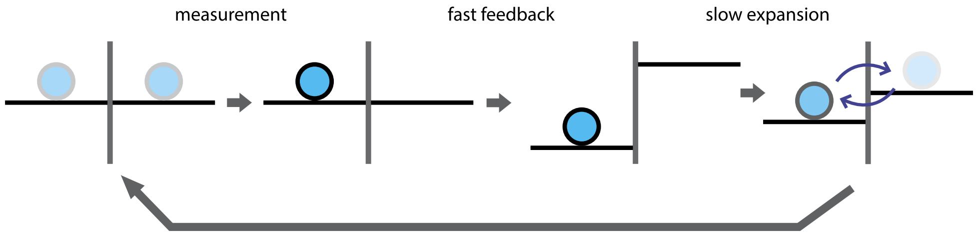

Fig. 3. The principle of the Szilard engine operation realized by an SEB. The back-and-forth tunneling events during the slow expansion is the source of $k_B T \ln(2)$ extracted work.

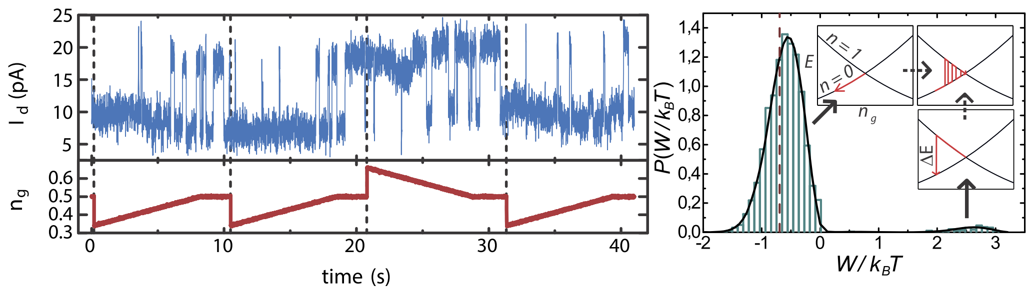

Fig. 4. Four experimental traces on an SEB following the Szilard engine protocol (left panel), showing the detector signal that identifies n in blue, and the control parameter n_g in red. The measurement of the state n is performed on the points indicated by vertical dashed lines. Determining the applied work in 2944 such traces gives a distribution (right panel), which averages to 75% of the fundamental limit $k_B T \ln(2)$, indicated with a red dashed vertical arrow. The contribution on positive W originates from errors in the measurement and feedback process, which results in heat dissipation. Figure adapted from [21].

nearby capacitively coupled SET. The measurement changes the entropy of the system by $\Delta S = -k_B \sum P_n \ln P_n = -k_B \ln(2)$. After the measurement, the SEB is immediately feedback-controlled with V_g such that $\Delta\mu_+ \ll -k_B T$ if $n = 0$ was measured, and $\Delta\mu_- \ll -k_B T$ if $n = 1$. The electron is thereby trapped to its island. These steps are analogous to the wall insertion and measurement in the original thought experiment.

The final step to complete the cycle is to drive $\Delta\mu$, the energy difference between states $n = 0$ and $n = 1$, back to zero. However, this step is performed slowly, such that thermal excitations allow electrons to tunnel back and forth between the SEB islands – see the left panel in Fig. 4. It is the fluctuations that are the origin of extracting energy from the heat bath; indeed, should no excitations occur such that the system would constantly remain in the original state, exactly the same amount of work would be spent on the final step as was gained from the immediate feedback. Conversely, when thermal excitations take place and the system is at the excited state, the drive $\Delta\mu \to 0$ again extracts electrostatic energy. As the charge states are degenerate with equal energy at the end of the cycle, it is also apparent that the amount of work extracted equals that of heat removed from the environment. In the special limit of infinitely slow drive, such that the system continuously maintains its thermal equilibrium, work equal to $k_B T \ln(2)$ is extracted from the heat bath. At optimized settings, the device was able to extract 75% of the maximum $k_B T \ln(2)$ energy from the heat bath [21], see the right panel in Fig. 4.

In a practical experiment, it is not possible to measure the system state with full certainty, as illustrated in Fig. 5a–b). There will exist a finite probability that the measurement outcome m deviates from the actual state n. The quality of the measurement is characterized by mutual information, $I(n,m) = \ln(P_{n,m}) - \ln(P_m) - \ln(P_n) = \ln(P_{n|m}) - \ln(P_n)$, where $P_{m,n}$ is the joint probability distribution of m and n, and $P_{n|m}$ is the conditional probability of measuring n when it is actually m. If the measurements were perfect, i.e. $n = m$ for every measurement implying $P_{n|m} = \delta_{n,m}$, the mutual information would reach its maximum, $I(n,m) = -\ln(P_n)$. It can be shown [22] that the amount of mutual information limits the amount of work that can be extracted per measurement, as $-\langle W \rangle \le k_B T \langle I \rangle$, where $\langle \ldots \rangle$ denotes the expectation value.

It has been shown [23] that in the presence of a measurement error, the optimal $\Delta\mu$ is determined by the error probability ϵ. Incorrect feedback results in dissipation of additional heat equal to $\Delta\mu$ due to relaxation before the next quasi-static ramp. In the SEB setup, ϵ is controlled by the choice of cut-off frequency $f_{\mathrm{cut-off}}$ for filtering the SET signal [24]. When $f_{\mathrm{cut-off}}$ is high, the signal-to-noise ratio is low, giving rise to a possibility of a measurement error. Collecting the statistics of ~ 1000 repetitions for a given $f_{\mathrm{cut-off}}$, the ϵ – and thus the mutual information $I(n,m)$ – is determined in post-analysis as a fraction of the measurement errors. This approach also allowed us to test the Sagawa–Ueda equality with mutual information [7], see Fig. 5.

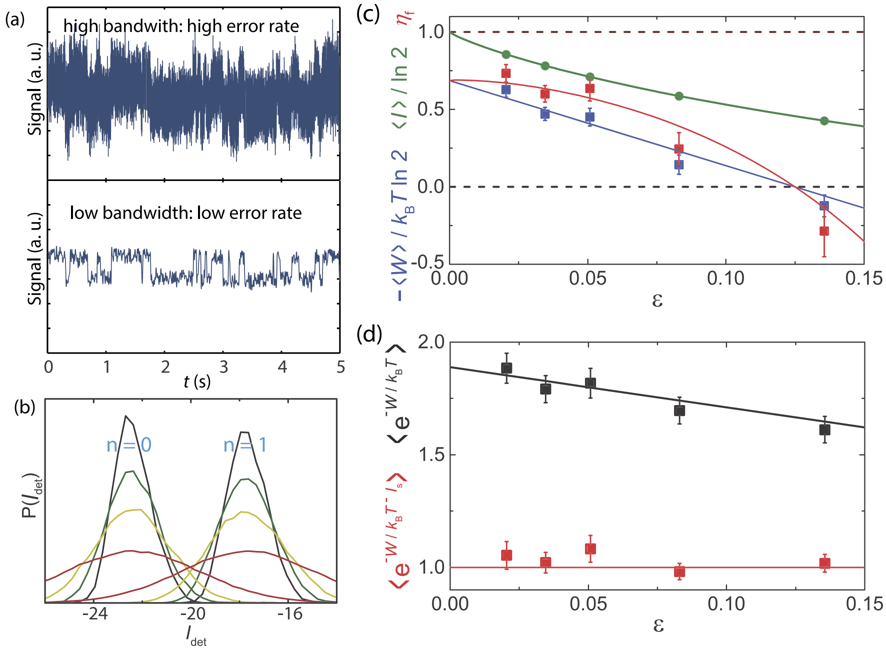

Fig. 5. Mutual information in feedback processes. Panel (a) shows the same signal under different $f_{\mathrm{cut-off}}$ for the low-pass filter. For high $f_{\mathrm{cut-off}}$, the $n = 0$ signal partially overlaps with that for $n = 1$ as in panel (b), leading to a chance for a measurement error with probability ϵ. Panel (c) shows the measured (symbols) and simulated (solid lines) average mutual information (green), applied work (blue), and their ratio (red) as a function of ϵ. Moreover, the setup allows one to test the Sagawa–Ueda equality, shown in panel (d). Figure adapted from [24].

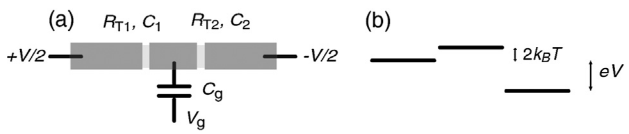

Fig. 6. A single-electron refrigerator. A biased (voltage V) single-electron transistor (panel (a)) is gate-positioned (panel (b)) such that the electrons tunneling from the left to the island need to extract an amount of energy $\sim k_B T$ from the bath, whereas those tunneling from the island to the right lead release an amount of energy $\sim eV$ to the bath. Figure adapted from [25].

5. Single-electron refrigerator

Before presenting the autonomous Maxwell's demon (AMD), we first introduce a recently demonstrated device, a single-electron refrigerator [25,26]. Its working principle is closely related to that of the AMD, but without information-based feedback.

In tunnel junctions, the particle (electron) current is in general associated with the energy current [27]. The experiments demonstrate that tunnel currents in contact with electrodes having unequal density of states (DOS), in particular when one of the conductors has a gap in its DOS, can produce electronic refrigeration of the un-gapped or the lower gap conductor. Basic examples of this phenomenon are tunnel junctions between a normal conductor and a superconductor (NIS junctions) [27], or a degenerate semiconductor reservoir coupled with another one via a quantum dot [28]. Recently, a similar effect was discussed in a system with equal DOS on the two sides of a tunnel barrier, but in the presence of large Coulomb energy on one electrode [25]. The idea is that the electrons need to extract energy from the bath upon tunneling against local bias. This is illustrated in Fig. 6. Electrons are transported from left to right with the help of bias voltage V. In doing so, they need to overcome the Coulomb barrier in the first step while tunneling through the left junction. This extracts energy from both the left electrode and the island. The first event is immediately followed by the energetically favorable tunneling through the second junction, which then dissipates a large amount of energy, $\sim eV$, to the island and the right electrode. The optimized positions of the levels are such that the left barrier is of the height $\sim k_B T \ll eV$. The left electrode cools down in this process, and in practise it is possible to engineer the structure such that the left and right ends of the island are thermally isolated from each other, and the left side of the island cools down as well.

This effect was experimentally demonstrated in recent experiments by Feshchenko et al. [26], where in a carefully designed SET structure, combining normal metals and superconductors for optimized thermal isolation, a temperature drop of up to 15% could be achieved at bath temperatures around 100 mK. The predicted and measured cooling improves dramatically towards lower temperatures.

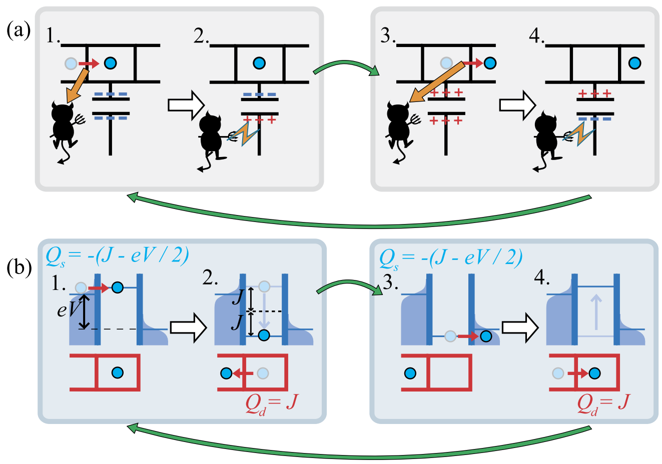

Fig. 7. The operation principle of the autonomous Maxwell's demon. Figure adapted from [29].

6. Realization of an autonomous demon in coupled single-electron circuits

The single-electron refrigeration paves the way for the realization of an autonomous Maxwell's demon based on single-electron phenomena. The energy barrier induced by Coulomb interaction induces a single-sided cooling effect on the SET; however, in total the heat Q (and therefore entropy Q/T) generated in the device is positive. The cooling effect can be introduced to both junctions on the SET by feedback control, illustrated in Fig. 7a, provided that it can be accurately determined whether an electron is on the island ($n = 1$) or not ($n = 0$). For $n = 1$, the potential of the island is set such that the electron experiences an energy cost when it tunnels to the drain electrode, and for $n = 0$, it is set to yield an energy cost for the electrons that would tunnel from the source electrode.

It turns out that such a process can be realized autonomously by coupling two normal metallic SETs capacitively to each other, as depicted in Fig. 7b. One of the devices takes the role of the demon, measuring and feedback-controlling the other. Just like a single-electron refrigerator, the feedback-controlled SET – the system – is voltage biased. This increases the rate at which electrons tunnel against Coulomb repulsion, giving rise to increased cooling power. The tunnel junctions of the demon are designed to have a low resistance. This enables it to immediately react to the tunneling events in the system; when an electron enters the island from a source electrode, an electron tunnels out of the demon island as a response, exploiting the mutual Coulomb repulsion between the two electrons. Similarly, when an electron enters to the drain electrode from the system island, an electron tunnels back to the demon island, attracted by the overall positive charge. The cycle via such interaction between the two devices realizes the scheme described in the previous paragraph.

With thermometry as well as thermal insulation by superconducting leads, it is possible to measure the operation of the device as a change in the local temperature of the system as well as the demon, see Fig. 8. In the experimental realization presented in [29], two-sided cooling of ~ 1 mK was measured in the system at the operation temperature of about 50 mK. The demon was simultaneously measured to experience a temperature rise of a few mK. The directly measurable amount of cooling is possible because the rate of thermally excited electron tunneling events is of the order of a few MHz, which is high compared to the electron–phonon relaxation rate (~ 10 kHz) [30], but low compared to the electron–electron interaction rate (~ 1 GHz) [31], the latter being responsible for local electron equilibrium in each electrode. In comparison, the demon produces the feedback by the tunneling event in it within about 1 ns ($= (1\text{ GHz})^{-1}$).

7. Discussion of information and feedback in a Maxwell's demon

The experiment described in Section 6 shows that cooling can be achieved even without particles acting as energy carriers. The setup also allows us to investigate the nature of information in an autonomous Maxwell's demon. The configuration has two degrees of freedom, n for the number of electrons in the system island, and N for the demon island. The information content of such a state is $-\ln(P_{n,N})$, and the mutual information is $I = \ln(P_{n,N}) - \ln(P_n) - \ln(P_N)$. Each tunneling event changes mutual information: if n changes to $n \pm 1$, mutual information changes by $\Delta I = \ln(P_{n\pm1,N}) - \ln(P_{n,N})$ as $P_n, P_N = 1/2$ remain constant. Similarly, N changing to $N \pm 1$ results in $\Delta I = \ln(P_{n,N\pm1}) - \ln(P_{n,N})$.

Consider the steps taken in the cycle. The transitions in the system generally bring the configuration to an energetically unfavorable – and therefore to a more unlikely – state. Correspondingly, $\Delta I < 0$, implying that the transitions tend to break the correlation between the system and the demon, and instead produces information content. The demon in contrast brings the setup back to the energetically favorable state, and thus those events have $\Delta I > 0$. The overall information content decreases, as the demon has now measured the system. In other words, there is an information flow between the two SETs, directed from the system to the demon.

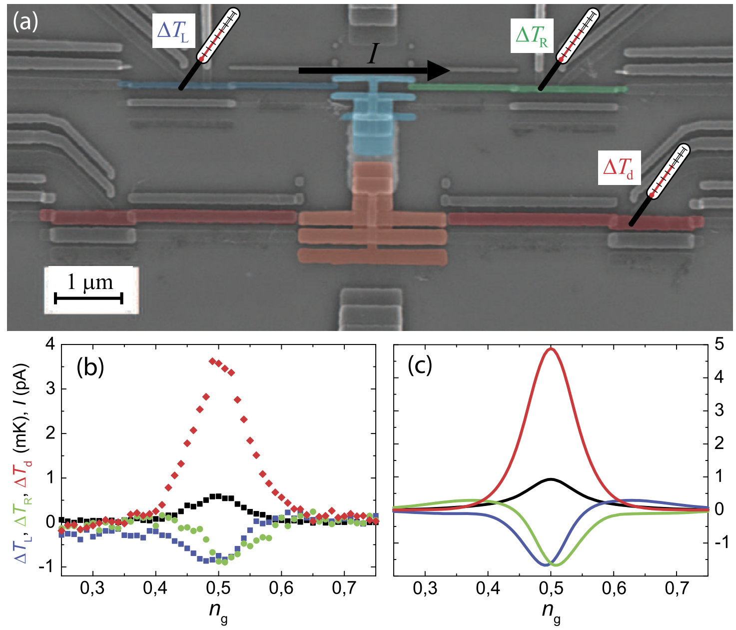

Fig. 8. (a) A scanning electron micrograph of the autonomous Maxwell's demon. The parts are false colored to identify the left system lead (dark blue), the system island (light blue), and the right system lead (green), as well as the demon leads (red) and the demon island (orange). Panels (b) and (c) show the measured (b) and numerically estimated (c) temperature in the autonomous Maxwell's demon (AMD) as a function of control parameter n_g. At the optimal operation point $n_g = 0.5$, the system cooling down is signaled by a decrease in the temperatures of both the leads, T_L and T_R, of the system, while the demon heats up, indicated by an increase in T_d. Figure adapted from [29].

As discussed in [14], this information flow gives rise to the cooling in the system within the bounds of the second law. Indeed, the maximum cooling power is bound by $-\langle \dot{Q} \rangle \leq k_B T \langle \dot{I} \rangle$, where the dot denotes time derivative. Correspondingly, the demon must in turn generate heat by at least an equivalent amount, $\langle \dot{Q} \rangle \geq k_B T \langle \dot{I} \rangle$. It can further be shown that as the demon reaction rate is high, the generated heat coincides with the information produced (the latter becomes an equality). The experiment thus allows us to directly measure the information flow between the two devices based on the heat observed.

8. Perspectives and conclusions

The experiments briefly reviewed here are of "proof-of-principle" type. They demonstrate that logical operations can be performed at a cost which is not far from the fundamental lower bound of $k_B T \ln 2$, which is orders of magnitude below the energy cost per bit operation in present-day computers. Therefore the presented experiments constitute a step towards reversible computing [32,33]. These devices also show a way how to cool critical elements in a circuit with information as a fuel.

The devices presented are based on principles of classical physics. On the level of basic research, it will be interesting to investigate quantum systems with superpositions and entangled states as elements of Maxwell's demons. In particular, a simple qubit circuit, e.g., made of a superconducting circuit, could provide a basis to study a quantum Szilard's engine [34].

Acknowledgements

We thank the Academy of Finland (projects 272218, 284594) and the Nanosciences Foundation, foundation under the aegis of the Joseph Fourier University Foundation and the European Union Seventh Framework Programme INFERNOS (FP7/2007-2013) under Grant Agreement No. 308850 for financial support.

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