Information into Energy with an Electronic Szilard Engine

Jonne V. Koski[1] and Jukka P. Pekola[1]

[1]Low Temperature Laboratory, Department of Applied Physics, Aalto University School of Science
P.O. Box 13500, 00076 Aalto, Finland

Email: jonne.koski@aalto.fi

April 29th, 2015 (STH31, HP96). It became apparent that information has an important role in thermodynamics by the famous thought experiment, Maxwell demon [1], an intelligent being who forms a temperature difference by separating fast and slow moving molecules. Information was further quantified by the works of Szilard [2] and Landauer [3, 4], giving a fundamental correspondence between one bit of information and energy as $k_BT\ln(2)$, where k_B is the Boltzmann constant, and T is temperature. The thought experiment known as Szilard engine is a single molecule in a box. The box is initially divided into two equal halves by a wall, and after determining whether the molecule is on the left or right half of the box, it is allowed to expand adiabatically to its full volume by sliding the divider to the opposite wall. The molecule contributes $k_BT\ln(2)$ of energy to the wall, directly extracting heat from thermal bath. This would violate the second law of thermodynamics if it were not for the one bit of information - whether the molecule is or is not on the left section of the box - that needs to be recorded. Landauer principle states that at least an equal amount of heat needs to be dissipated to erase this information, restoring the second law.

While the concept of Maxwell demon has existed for more than 150 years, the possibility for experimental realizations [5, 6, 7] has emerged only quite recently with the help of nanotechnology. A recent experiment [8] demonstrates extraction of $k_BT\ln(2)$ heat for one bit of information with a device known as single electron box (SEB). The SEB (Figure 1 top left) has two small micrometer-scale metallic islands, of which one is superconducting, coupled by a tunnel junction. Although the total charge of the SEB remains constant, the charge distribution of the two islands varies as electrons tunnel through the junction. For this to occur, the electron must provide the energy to overcome the change of electrostatic potential, $E_C(n-n_g)^2$, where $E_C = e^2/(2C)$ is the charging energy for a single electron charge on the capacitance C between the two islands, and n is the number of electrons on, say, left island. A gate voltage V_g induces a charge $en_g = C_gV_g$, effectively controlling the charge distribution on the islands. Finally, a single electron transistor is coupled to the SEB. The current through the transistor depends on n, providing means to continuously monitor the SEB.

The SEB is cooled down to a low temperature, in our case $T = 100$ mK, such that $k_BT \ll E_C$. By operating in the $n_g = 0...1$ range, n is limited to either $n = 0$ or $n = 1$. The applied protocol (Figure 1 bottom left) has a close resemblance to the original Szilard engine. Initially, the gate voltage is set to $n_g = 0.5$, where an excess electron has an equal probability to reside in the left (n = 1) or right (n = 0) electrode. A measurement with the transistor establishes the position of the electron, after which the gate voltage is abruptly changed to lock the charge distribution: if $n = 0$ was measured, n_g is also driven towards 0, and with $n = 1$, n_g is driven towards 1. This is followed by an adiabatic drive back to degeneracy. While driving back, a fast moving 'hot' electron with energy above the fermi level can escape the trapping potential by tunneling to the other SEB island, losing a part of its energy in the process. Such an event is soon followed by another electron tunneling from that island back to the trap. However,

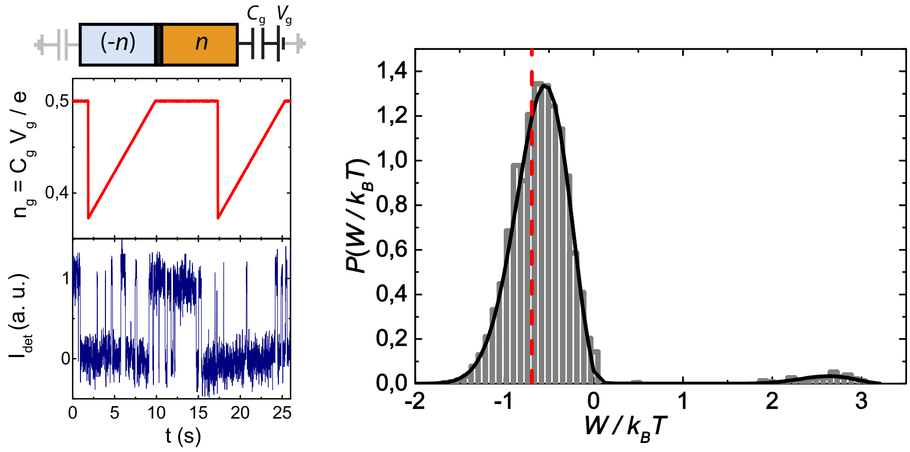

Fig. 1. (top left) Sketch of the SEB. The electron count n is controlled by the gate voltage V_g. (bottom left) Example measured trace of two successive Szilard engine processes. (right) The measured distribution of work W per cycle in the SEB Szilard engine [8]. The histogram is split into two parts, the main peak at negative values of W, corresponding to successful feedback, and a smaller peak at positive W corresponding to errors in the measurement and feedback. The average of W in successful cycles is close to $-k_BT\ln(2)$, indicated by the vertical dashed line.

as the gate has been continuously driven closer to $n_g = 0.5$, lowering the energy difference between states $n = 0$ and $n = 1$, the electron gains less energy than the previous electron had to contribute. Energy has thus been extracted from the thermal bath.

In practice, the slow drive is not fully adiabatic, such that due to the stochastic nature of tunneling, some realizations extract less than $k_BT\ln(2)$ heat. The extracted heat forms a distribution (Figure 1 right), which is measured by repeating the process multiple times. The average dissipated heat was 75% of the fundamental upper limit $k_BT\ln(2)$. The current realization of the Szilard engine is far from practical also in terms of its output power: the operation cycle is very slow, lasting several seconds, which means that the demonstrated SEB serves only as a proof of the principle of a Maxwell demon. As a future prospect, a realization with fast local feedback e.g. by two coupled quantum dots as proposed in [9] looks feasible. This could lead to efficient cooling of the circuit.

References

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