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DEMONS: MAXWELL'S DEMON, SZILARD'S ENGINE AND LANDAUER'S ERASURE–DISSIPATION

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This talk addressed the following questions in the public debate at HoTPI: (*i*) energy dissipation limits of switches, memories and control; (*ii*) whether reversible computers are possible, or does their concept violate thermodynamics; (*iii*) Szilard's engine, Maxwell's demon and Landauer's principle: corrections to their exposition in the literature; (*iv*) whether Landauer's erasure–dissipation principle is valid, if the same energy dissipation holds for writing information, or if it is invalid; and (*v*) whether (non-secure) erasure of memories, or the writing of the same amount of information, dissipates most heat.

Keywords: Energy requirement of control.

In the subject of energy requirement for information processing (including erasure), and the related field of thermal demons (engines with single thermal bath utilizing measurement information), there is a large body of papers which miss some of the key aspects. Here we briefly comment on several of these issues.

1. Energy requirement for changing a single bit value

Brillouin [1], Alicki [2] and Kish [3–5] have arrived at similar results which show, in independent ways, that the lower limit of energy requirement for changing a bit value in a binary device is given as

$$E_{\min} \approx kT \ln\left(\frac{1}{\varepsilon}\right) , \tag{1}$$

where k is Boltzmann's constant, T is temperature and ε is error probability of bit operation. Strictly speaking, Eq. 1 is valid only for observation times up to the correlation time of the stochastic thermal excitation (thermal noise) in the system. For longer observation time windows t_w, Eq. (1) was generalized [4,5] to read

$$E_{\min} \approx kT \ln\left(\frac{1}{\varepsilon}\frac{t_w}{\tau}\right) , \tag{2}$$

where τ is time and the $\varepsilon \to 0$ limit is assumed.

Figure 1 shows a double-well potential model of bit states and two-stage switches. A bit error is generated as the thermal noise reaches beyond the energy barrier. When the bit state is changed during information processing, the particle must be pushed over the barrier into the other well. The invested energy cannot be saved, because any attempt to do so will result in more energy dissipation than the original one as a consequence of the need of extra switches and control steps and/or timing [4,5].

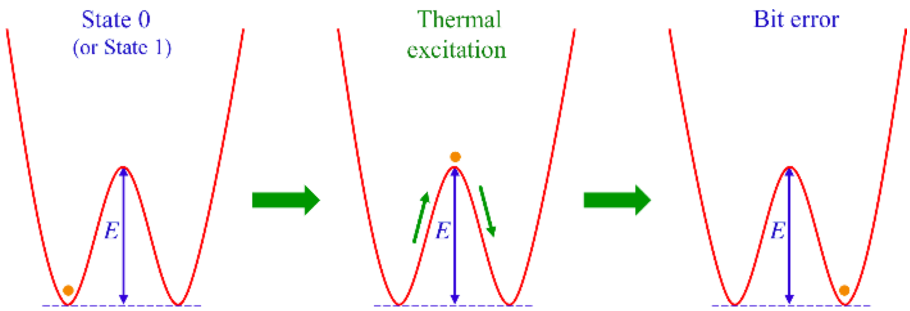

Figure 1. Double-well potential model of bit states and two-stage switches. A bit error is generated when the thermal noise reaches beyond the energy barrier.

2. Brillouin's negentropy-of-information principle *versus* Landauer's principle

Brillouin's negentropy principle of information [6], published in 1953, claims that in order to *change* a bit of information one has to dissipate an energy of at least

$$E_{\min} \approx kT \ln(2) . \tag{3}$$

This result agrees with Eq. (1) for $\varepsilon = 0.5$, *i.e.*, when the binary system has zero bits of information. Thus Eq. (3) is always valid, whereas Eqs. (1) and (2) pose more strict/physical lower limits.

Landauer's principle [7], which was developed in steps after 1961, claims that an energy of at least

$$E_{\min} \approx kT \ln(2) \tag{4}$$

must be dissipated in the memory in order to *erase* a bit of information. While this result looks formally identical to Brillouin's assertion above, Landauer's result is incorrect when the bit state does not change during erasure.

We note that there is an extensive and valuable literature—for example by Porod, Ferry, Norton and their coworkers [8–13]—showing that Landauer's principle is unphysical, and we refer the reader to these works after a study of the present short note.

3. Is a recent "experimental proof" of Landauer's principle valid?

Recent experiments by Bérut *et al*. [7] to prove Landauer's Theorem use advanced tools and are interesting, but the conceptual basis for this proof, and for its interpretation, show characteristic features of poor science. Here are a few examples:

(*i*) *What was the potential well?* An optical field of focused laser light (an optical tweezer) was used in a fluid. This is a highly non-equilibrium situation, and a *strongly driven system in steady state*. Rigorously speaking, this system does not even have a temperature! And an equivalent temperature can be anything, even attaining "negative" values (as for population-inversion in lasers).

(*ii*) *Is relocating the particle between the two wells indeed a single-bit erasure?* Why it is not the *writing* of single-bit information? Nothing would then change in the experiments and their results!

(*iii*) The studied system is a single-bit memory with friction force (loss) *during a change of the state*, it is not damping of excess energy after the bit change is completed as in friction-free potential wells. What happens if one reduces the friction coefficient (viscosity) and forces the particle over the same path and with the same speed? No such test was done; neither was the distance between the two wells varied. One can easily imagine that friction losses would become even smaller than Landauer's energy limit.

(*iv*) The *energy dissipation of keeping up and modifying the potential barrier* during the process, which is of the order of 10^{20} kT, was neglected. It could be noted that Landauer committed a similar error in his famous analysis [7]. This neglected energy—*i.e.*, the modification of potential barriers, or control of gate potentials for MOSFETs—is the dominant fundamental energy dissipation in today's computers [14].

4. Missed control energy in classical and quantum demons

Surprisingly, Landauer's Theorem has been put into seemingly inherent connection with thermodynamic demons such as Maxwell demons, Szilard engines and Quantum demons. We are unable to cite all of the vast literature on this topic, instead we refer to a few examples [15–17] that point clearly to the source of this error.

Equations 1 and 2 make it obvious that whenever a single switching or decision operation takes place during the engine cycle, then energy exceeding $kT\ln(2)$ is dissipated during *each* of these operations. This is extremely important, because the energy the demon is supposed to produce is exactly this one (Szilard engine), or at least has a similar value (Maxwell demon). Scrutinizing one of the cited papers by Bennett [16], all or almost all operations of a single demon cycle involve such single-bit operations, which means that the control steps in themselves generate many times greater heat than the one given by the $kT\ln(2)$ limit. Words such as "insert", "observe", "if", "go to", "attach", (letting to) "expand", "remove", "transform", *etc*, signify such a minimum single-bit control operation in the mentioned paper [16]. Specific operations are exemplified below from [16], where L/R means left/right and M1 … L3 are designations used by Bennett [16] (we added Italic typeface):

M1. *Insert* partition [L]
M2. *Observe* the particle's chamber [L] or [R]
M3. *If* memory bit = R, *go to* R1 [R]
M4. *If* memory bit = L, *go to* L1 [L]
R1. *Attach* pulleys so right chamber can expand [R]
R2. *Expand*, doing isothermal work W [R]
R3. *Remove* pulleys [R]
R4. *Transform* known memory bit from R to L [L]
R5. *Go to* M1 [L] L1. *Attach* pulleys so left chamber can expand [L]
L2. *Expand*, doing isothermal work W [L]
L3. *Remove* pulleys [L] L4. Go to M1 [L]

Even Szilard missed the crucial aspect of control energy in his famous paper [18], because he used a two-stage lever to control a gear. The control of this gear consumes all of the energy the Szilard engine was supposed to produce. *Thus the Szilard-engine-puzzle about the Second Law and intelligent being is non-existent from the beginning.* In hindsight, Szilard's error might be considered fortunate because it led to an expansion of the research field. In the case of Szilard's engine, it is possible to fix the mentioned flaw [5], but the question as to the role of an intelligent being remains obsolete.

Finally, we note that Renner [17] and others claim that control energies can be saved by using a large number of parallel demons mechanically coupled to each other. This belief is incorrect since demons are fundamentally random so that they require independent control units and related energy dissipation. Conservation of control energy can be done in periodic engines, where this effect can be executed both in space (parallel-coupled engines) and time (resonators with high Q-factor) [19], but it is not possible for demons.

5. Lower limit of energy requirement for erasing a large memory

Finally, we address the problem of non-secure bit erasure in computers. Do computers execute erasure when they discard information? The answer is “no” since, in practice, they do not reset the memory bits but just change the address of the boundary of the free part of memory as illustrated in Figure 2. The number of bits in the address scales as $\log_2 N$, where N is the size of the whole memory, and hence (in accordance with Eq. 2) the energy dissipation is of the order of

$$E_{\mathrm{er}} = kT \ln\left(\frac{1}{\varepsilon}\frac{t_w}{\tau}\right)\log_2 N \quad . \tag{5}$$

At fixed error rate and observation time window, the energy dissipation of erasure scales as

$$E_{\mathrm{er}} \propto \log_2 N \quad , \tag{6}$$

which is a much more optimal situation than for the Landuer limit of $kT\ln(2)$ energy dissipation per bit. Thus real memories typically work in the “sub-Landauer” regime during erasure, which again indicates that Landauer’s principle is invalid.

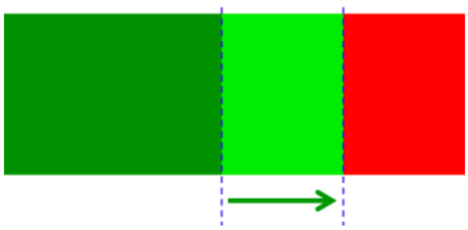

Figure 2. Simplified one-dimensional illustration of discarding information in an idealized computer memory. Green signifies space free for writing, and Red denotes occupied space. The address of the boundary of the free memory is moved along the arrow to discard information and increase the free-memory part.

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