"Everything should be made as simple as possible, but not simpler." **Albert Einstein**

Demons: Maxwell demon; Szilard engine; and Landauer's erasure-dissipation

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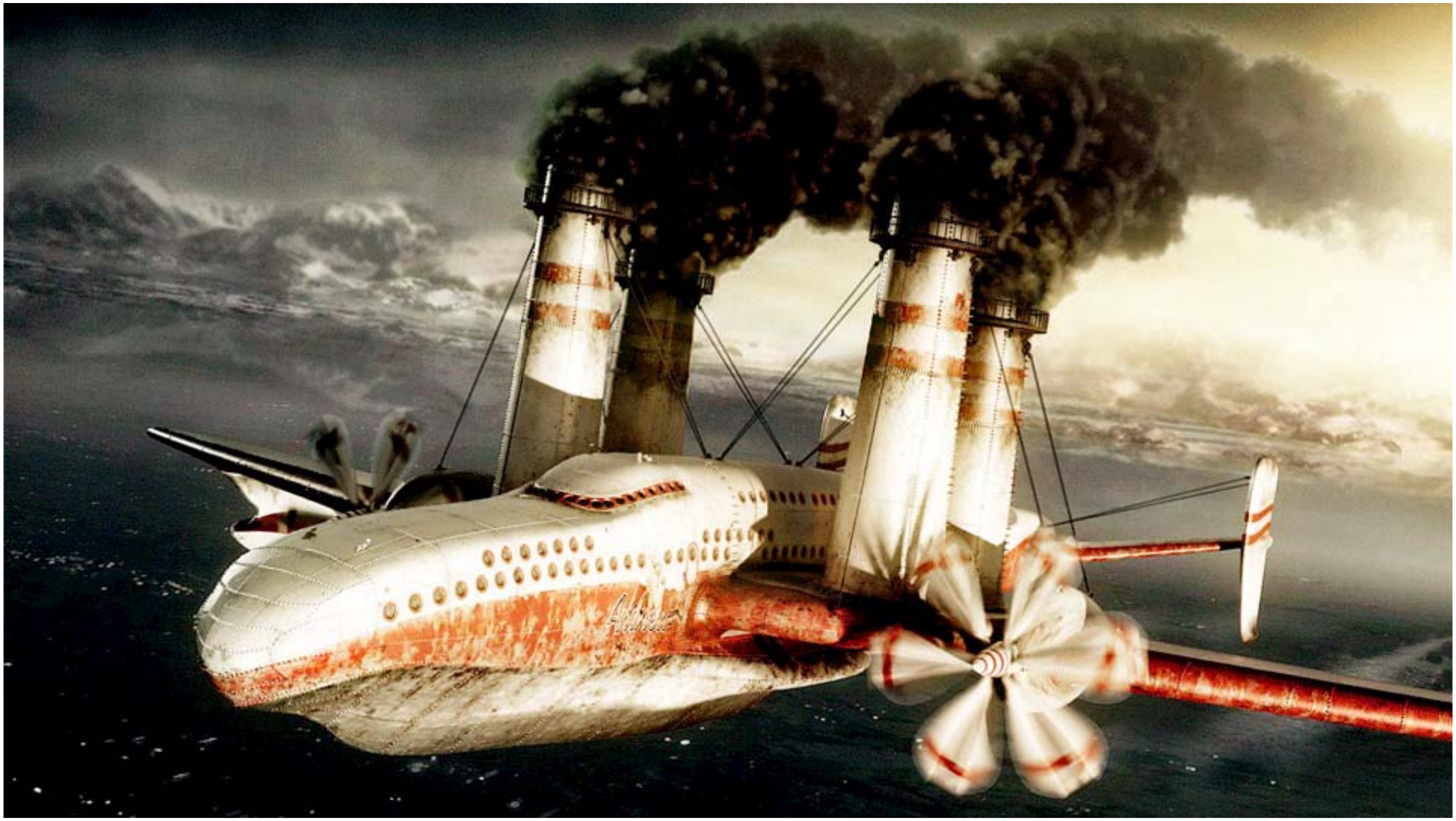
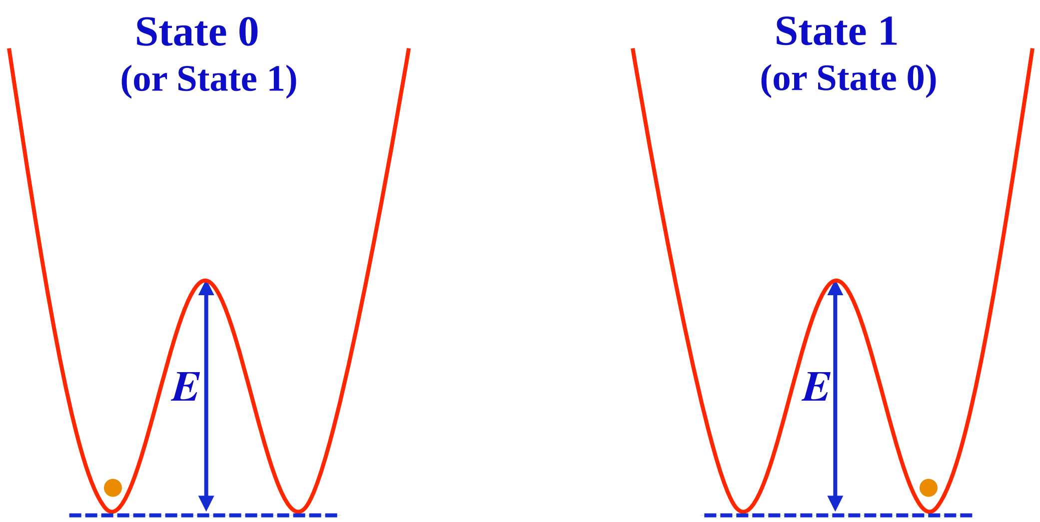


In accordance with the related debate at HoTPI, we address the following questions:

- Energy dissipation limits of switches, memories and control.
- Are reversible computers possible or their concept violates thermodynamics?
- Szilard Engine, Maxwell demon, Landauer principle: typical mistakes in the literature.
- Is Landauer's erasure-dissipation principle valid; or the same is true for writing the information; or it is simply invalid?
- Does (non-secure) erasure of memories or the writing of the same amount of information dissipate more heat?

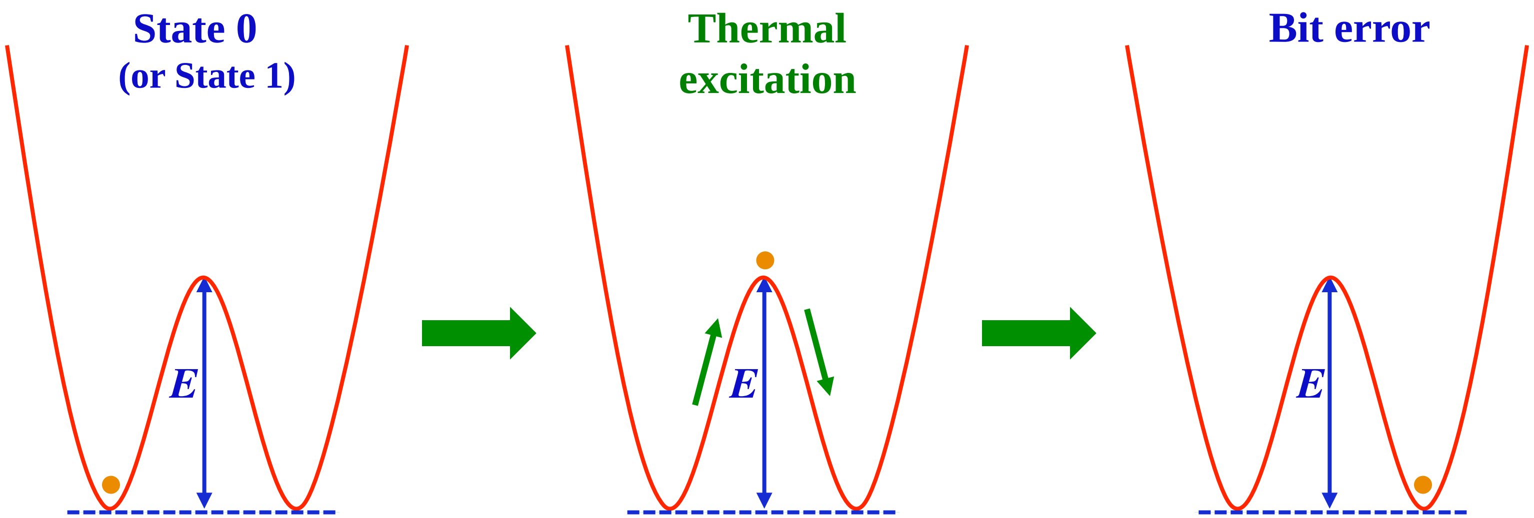
Energy dissipation limits of switches, memories and binary (yes/no) control.

Energy diagram of switches and symmetric non-volatile memories. (Notes about flash memory come later)



How about errors?

Errors (the thermally activated ones) are threshold-crossing phenomena:



Rice formula for sharply band-limited (at f_c) thermal noise yields for the threshold crossing frequency:

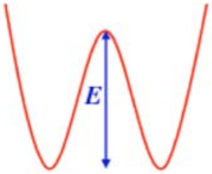
$$\nu(U_{th}) = f_c \frac{2}{\sqrt{3}} \exp\left(-\frac{E}{kT}\right)$$

Note: for Lorentzian noise spectra (softly band-limited), *first-passage time* analysis yields the same kind of result.

Kish LB, Granqvist C-G (2012) Electrical Maxwell Demon and Szilard Engine Utilizing Johnson Noise, Measurement, Logic and Control. PLoS ONE 7(10): e46800

Energy barrier of two-state switches and memories with fixed error rate. Minimum energy dissipation of a control step. Zero error rate requires infinite energy.

Within the *correlation time* of thermal excitation:



E **potential barrier in switches and memories**

$$\boxed{E_{\min} \approx kT \ln\left(\frac{2}{\sqrt{3}}\frac{1}{\varepsilon}\right) \approx kT \ln\left(\frac{1}{\varepsilon}\right)}$$

for each switch/memory operation!

L.B. Kish, "Moore's Law and the Energy Requirement of Computing versus Performance", *IEE Proc. - Circ. Dev. Syst.* 151 (2004) 190-194.

In a different way, the same result for the classical limit: R. Alicki, "Stability versus reversibility in information processing", HoTPI 2013

For longer operation times $\boldsymbol{t_o}$ than the *correlation time* τ :

$$\boxed{E_{\min} \approx kT \ln\left(\frac{1}{\varepsilon}\frac{t_o}{\tau}\right)}$$

(independent errors add up in small error limit)

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L.B. Kish, C.G. Granqvist, "Energy requirement of control", EPL 98 (2012) 68001

Binary (yes/no) control step is a two-state switching process.
Minimum energy dissipation of a control step. Zero error rate requires infinite energy dissipation.

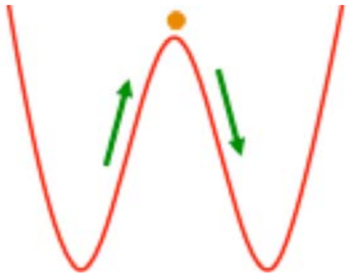
For error probability $\boxed{\varepsilon < 0.5}$, that is for a functioning system, the energy dissipation is greater than the famous result for the Szilard engine:

$$E_{\min} > kT \ln 2$$

Switching operation
Bit value change in a memory
Binary control step

⇒ $\boxed{E_{\min} \approx kT \ln\left(\frac{1}{\varepsilon}\right)}$ for each operation

The system totally stops working at $\boxed{\varepsilon = 0.5}$



After a state-changing operation, the system must be damped and all the invested energy dissipates, it is lost <u>irreversibly.</u> Any effort to gain this energy back results in more energy dissipation than simple damping because it requires a multiple-step control!

Surprise for the Landauer principle debate. *If this is real then no debate except the name* (Brillouin):

Changing picture??? ~~*erasure*~~ *change*

http://en.wikipedia.org/wiki/Landauer's_principle on Nov. 2, 2013 says:

"*Landauer's principle asserts that there is a minimum possible amount of energy required to* ***change*** *one bit of information, known as the Landauer limit*" [that is $kT\ln(2)$]

This is true, but it is not Landauer but Brillouin, etc, much earlier !

Brillouin's *negentropy principle* **(1950's)**: Creating/realizing a single bit of information (switching a switch, etc.) at T temperature requires at least $\boldsymbol{kT\ln(2)}$ energy dissipation.

Brillouin L., Science and Information Theory, (Academic Press, New York) 1962.
Brillouin L., Scientific Uncertainty and Information, (Academic Press, New York) 1964.

As we have seen, Brillouin's result is correct only as a weak lower limit of energy because this value would result in 50% error probability. The more general relation is:

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

Now, we can address the next item:

- Are reversible computers possible or their concept violates thermodynamics?

We have seen that each step of switching, changing information or control in a computer will irreversibly dissipate heat due to thermal excitations. Thus the answers:

Are reversible computers possible? ***NO.***

Or do their concept violates thermodynamics? ***YES***

John Norton has arrived at the same conclusions, and

Much earlier, in a historical debate (with Landauer and Bennett, etc.) Wolfgang Porod and Dave Ferry have also arrived at similar conclusions: ***even logical reversibility would not imply physical reversibility***.

An incomplete list of papers with the correct view:

J.D. Norton, “Waiting for Landauer”, *Stud. Hist. Philos. Mod. Phys*. 42 (2011) 184-198.

J.D. Norton, “Eaters of the lotus: Landauer’s principle and the return of Maxwell’s demon”, *Stud. Hist. Philos. Mod. Phys.* 36 (2005) 375–411.

W. Porod, "Comment on energy requirements in communication", *Appl. Phys. Lett.* 52, 2191 (1988)

W. Porod, R.O. Grondin, D.K. Ferry, "Dissipation in Computation", *Phys Rev. Lett.* 52, 232-235, (1984)

W. Porod, R.O. Grondin, D.K. Ferry, G. Porod, *Phys. Rev. Lett.* 52, 1206, (1984); and references therein.

L.B. Kish, C-G Granqvist, Electrical Maxwell Demon and Szilard Engine Utilizing Johnson Noise, Measurement, Logic and Control. PLoS ONE 7 (2012) e46800

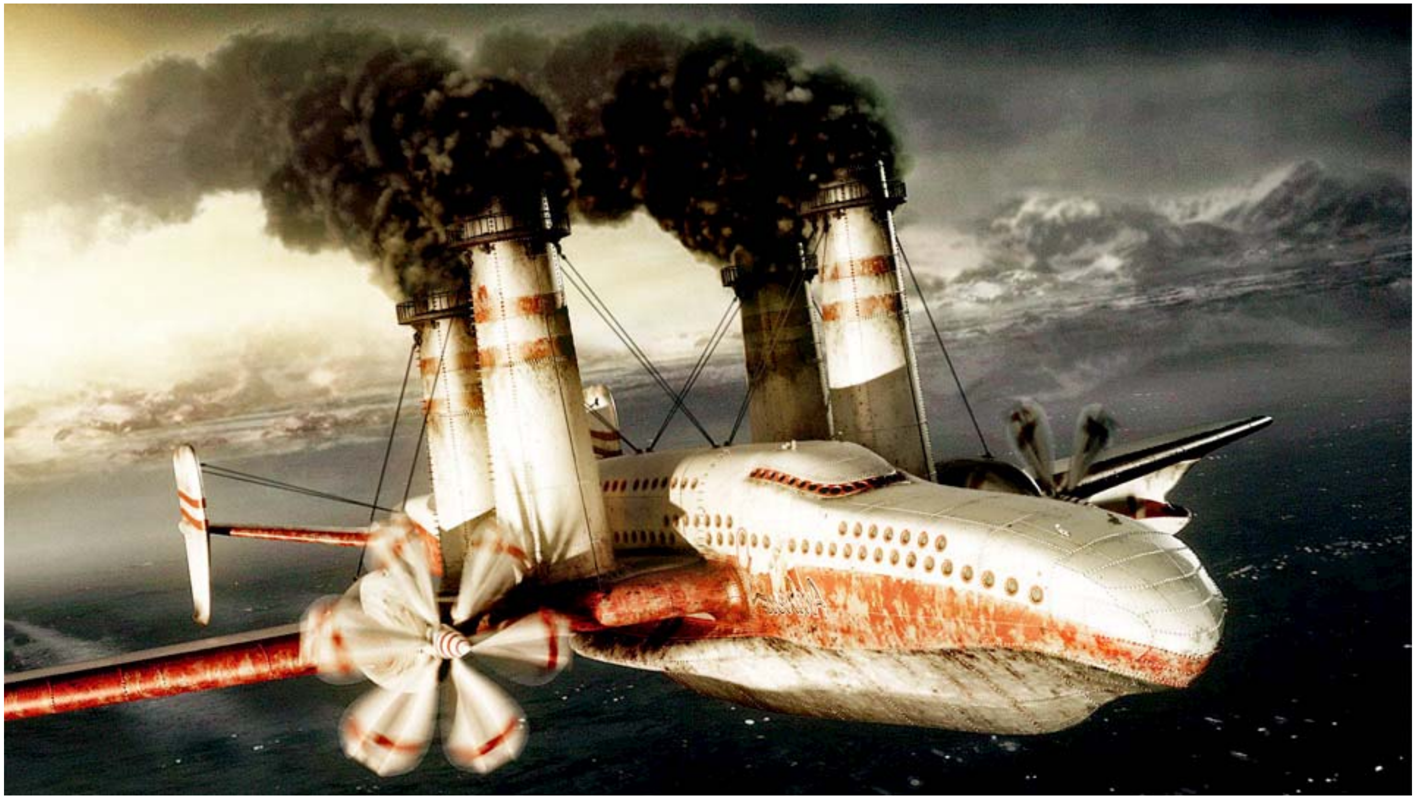
L.B. Kish, C.G. Granqvist, "Energy requirement of control", EPL 98 (2012) 68001

- **Szilard Engine, Maxwell demon, Landauer principle: typical mistakes in the high-profile literature (Nature, PRL, etc).**

  - Incomplete systems thus incomplete analysis; still drawing general conclusions

  - Neglecting energy dissipation of control even if the controlled element is shown

  - Illegal and/or unjustified assumptions



- Incomplete systems thus incomplete analysis; still drawing general conclusions

Examples:

- Minimal energy dissipation in the Szilard engine and Maxwell demon

- Quantum Szilard engines

General directive for a quick preliminary test of validity of an analysis:

If you see a result on the energy analysis of Szilard Engine, Maxwell demon or the minimal energy dissipation of a memory, and if

you don't see error probability explicitly in the final result, then that result cannot be correct!

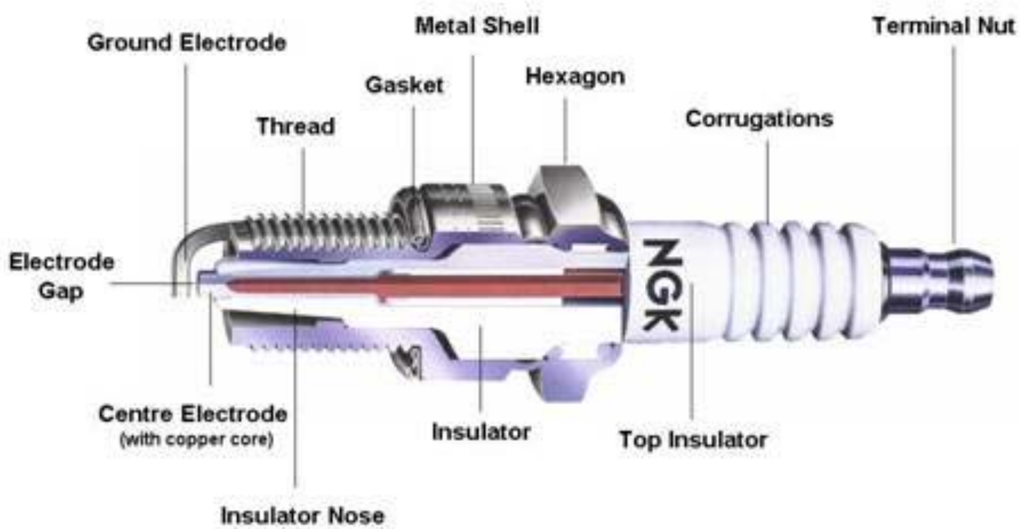
Fortunately all the Pro Teams Members had error probability there ☺

The result maybe valid in some physical or unphysical limit, which however must be identified before the application of that result!

But before that some illustration...

Is this a car engine?

Control-execution: Spark plug: energy dissipation/cycle: around **0.1 Joule**



Is this a car engine?

Honda Piston: energy dissipation/cycle >> **0.1 Joule**

Is this a car engine?

Honda Cylinder: energy dissipation/cycle >> **0.1 Joule**

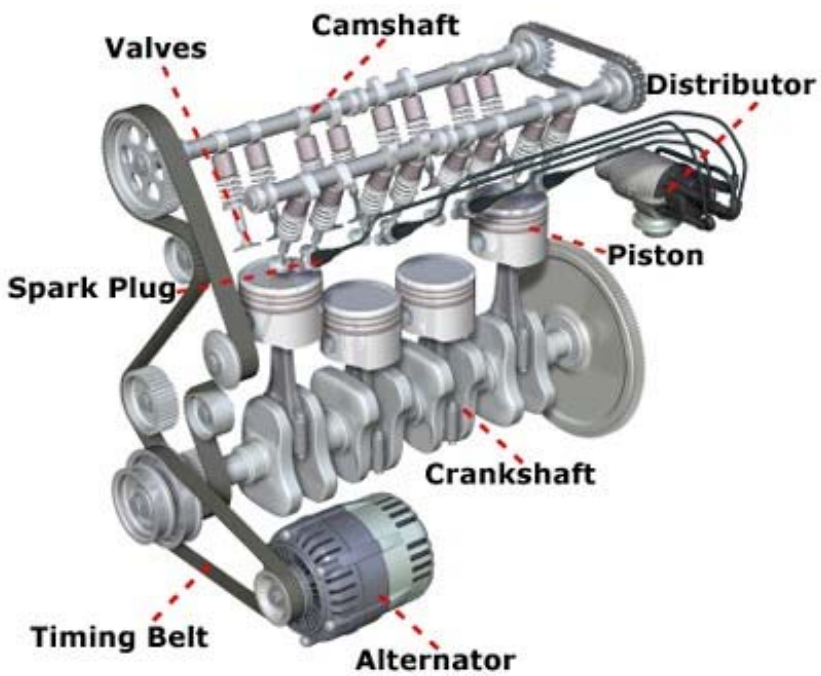
Is this a car engine?

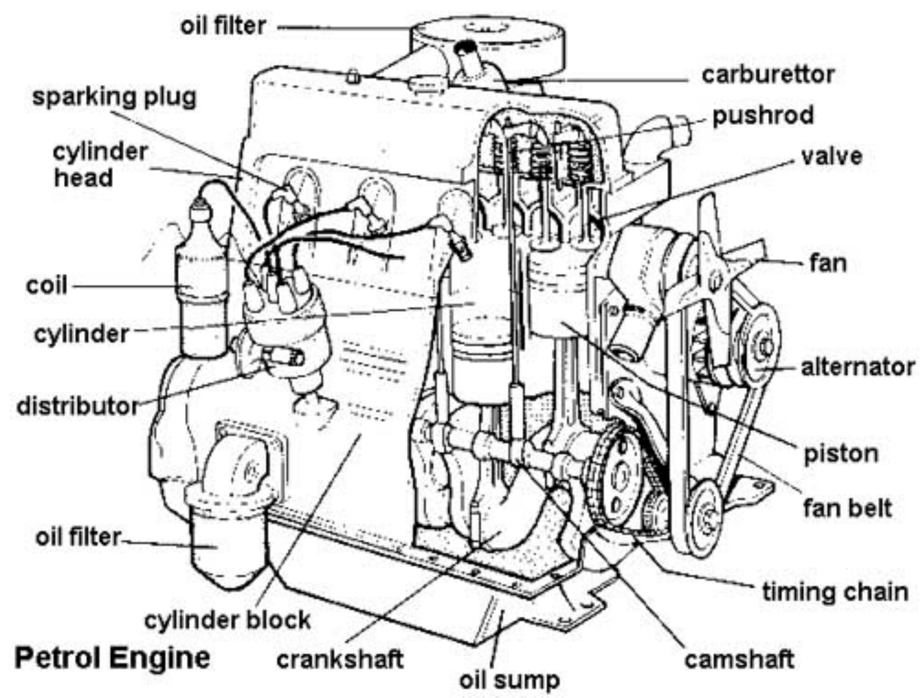
Control-execution: Honda Valve: energy dissipation/cycle >> **0.1 Joule**

Is this a car engine?

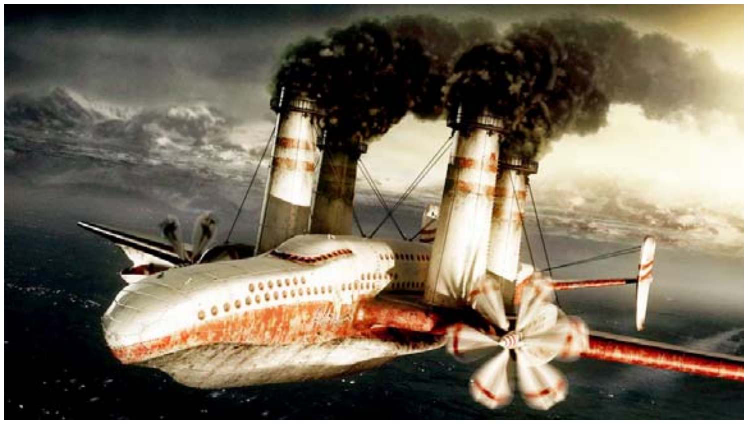
Control-logic: Honda Turbo Computer: energy dissipation/cycle around **0.1 Joule**

These are car engines!





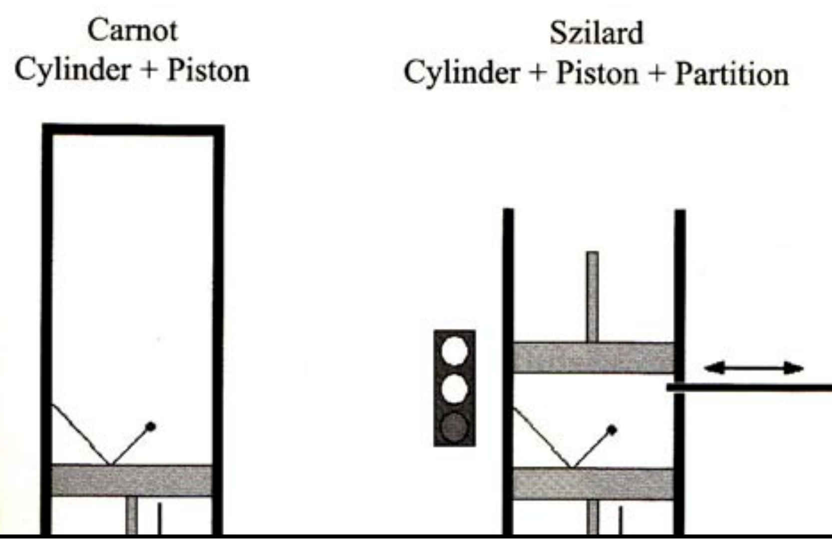
Landauer's principle in demons. In mainstream mathematical physics, the belief is that the memory erasure is the key player for energy dissipation in a thermal demon.



Ch. Bennett, "Demons, engines and the second law, Scientific American 11/1987, p. 88.

"We have, then, found the reason the demon cannot violate the second law: in order to observe any single molecule, it must first forget the results of previous observations. Forgetting results or discarding information is thermodynamically costly."

The differences between a single-atom Carnot engine and a single-atom Szilárd engine are summarized in Fig. 5.2 and Tab. 5.1.

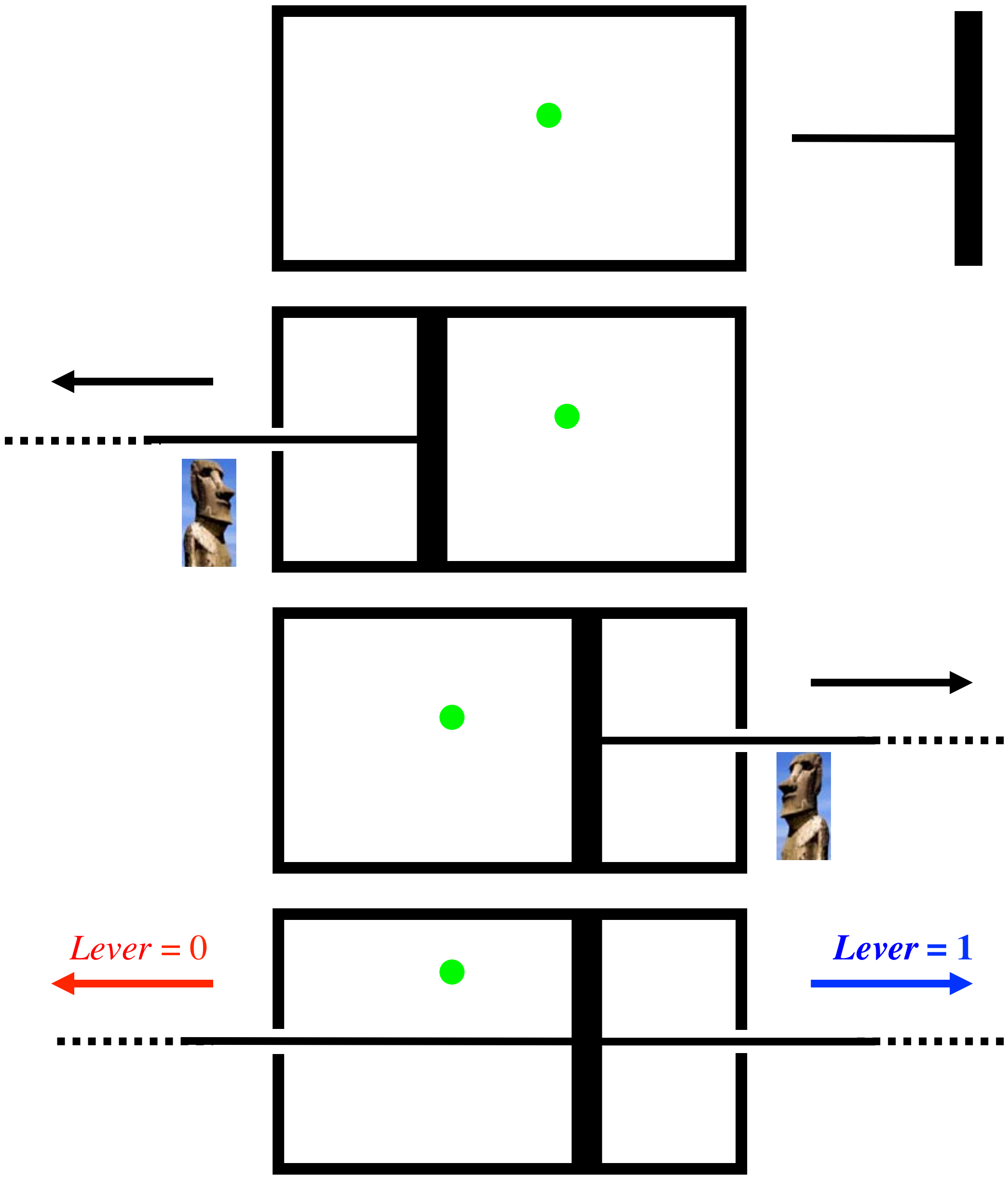


from the book R. Scully, "The Demon and the Quantum" (Whiley)

The Szilard engine

Work is extracted by *utilizing the measured information for control.*

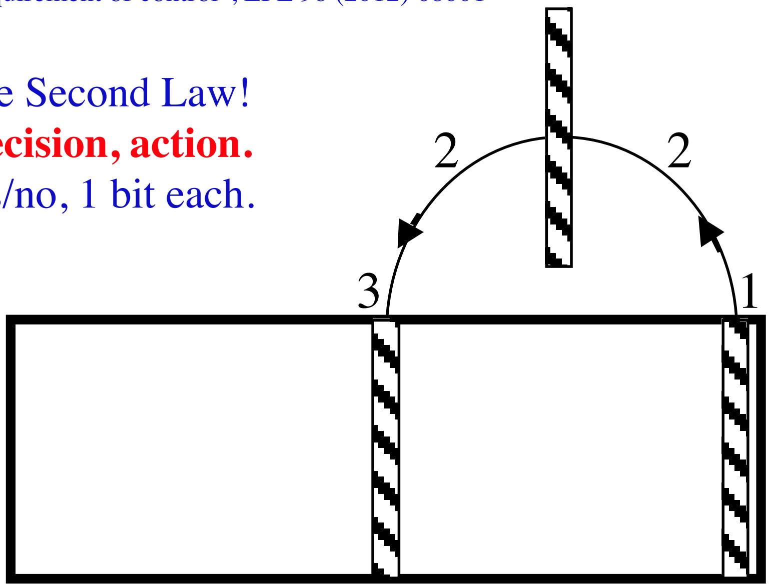
NOTE: Control dissipation scales with the number of parallel systems because these are random system.



Measurement, Control.
Molecule-Locator and
Piston-Placer or Lever.

L.B. Kish, C.G. Granqvist, "Energy requirement of control", EPL 98 (2012) 68001

There is much more to the Second Law!
Control! Monitoring, decision, action.
The information side: yes/no, 1 bit each.



Leo Szilard also missed this.

> 5 bits

$$\boxed{E_{\min} > 5kT\ln\left(\frac{1}{\varepsilon}\frac{t_o}{\tau}\right)}$$

- When the piston reaches the end of the cylinder, disengaging the clutch that couples the piston to the gearbox: 1 bit
- Starting the motion: checking if the thermal velocity of the piston points in the correct direction; otherwise injecting energy/momentum to reverse it: 1 bit (if it is in the correct direction, more if not)
- Continuous motion to the desired position (monitoring/deciding): >1 bit
- Stopping the motion when the piston reaches its final position: 1 bit
- Reengaging the clutch to couple the piston to the gearbox: 1 bit

- Quantum Szilard engines

No Hermitian or other operator can ever open a trapdoor or a realize a decision; not even to execute a measurement.

Classical physical parts and the analysis of their operation for the energy balance is unavoidable!

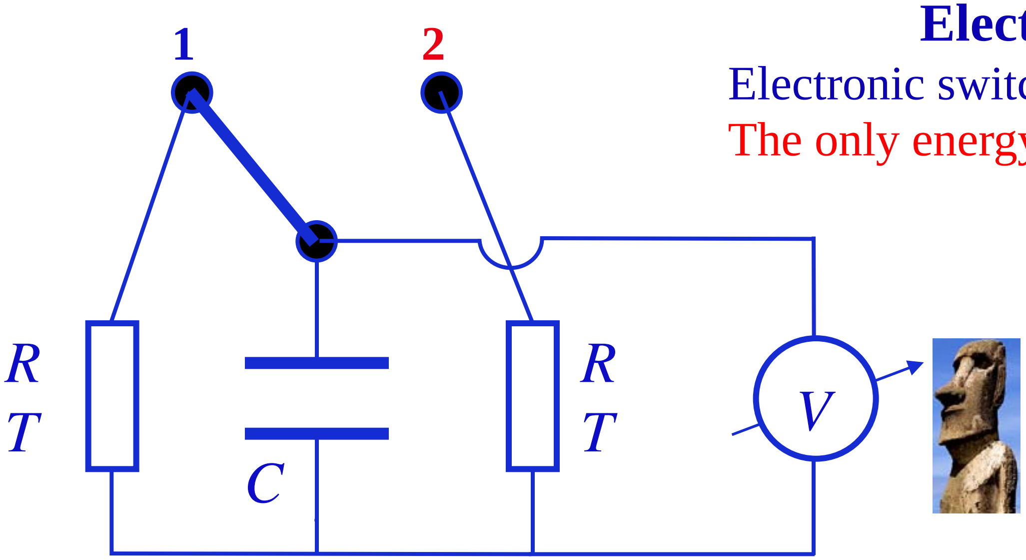
For conclusions about the whole engine the whole engine must be studied !

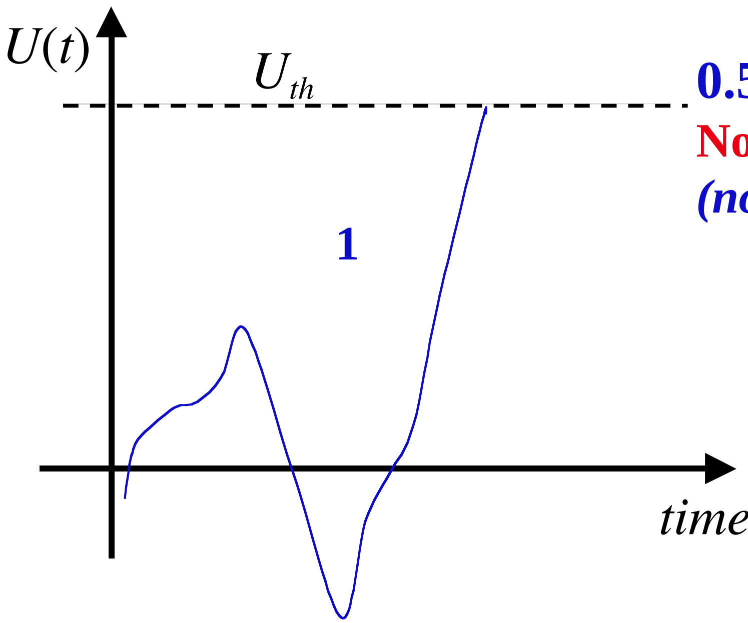
Example of a more complete analysis.

Electrical Johnson noise demon.

Electronic switches, no mechanical motion in the system.

The only energy types here are electricity and heat.





0.5 CU_{th}^2 energy

Note: the energy pumped can be arbitrarily large!

(note exponential slowdown versus energy)

L.B. Kish, C-G Granqvist, Electrical Maxwell Demon and Szilard Engine Utilizing Johnson Noise, Measurement, Logic and Control.

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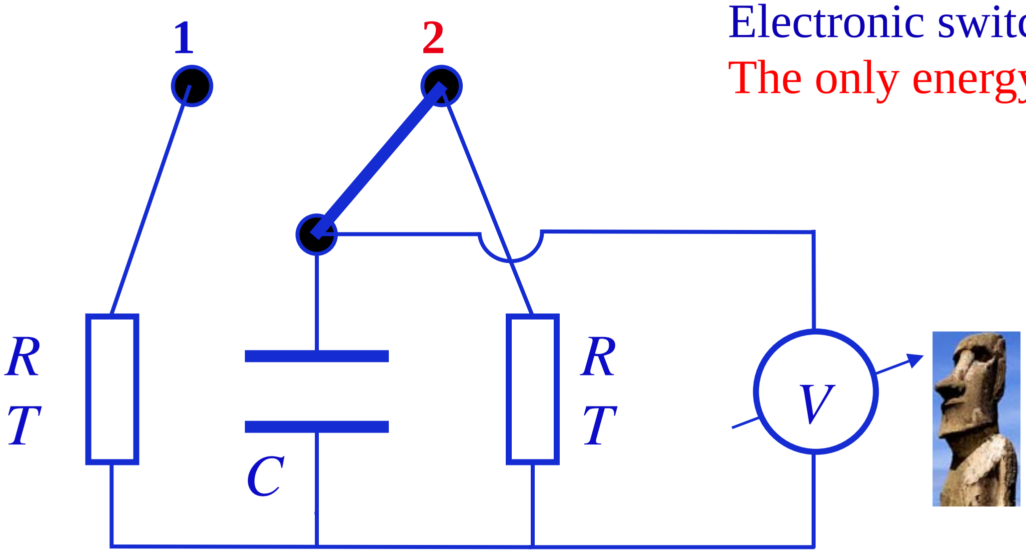

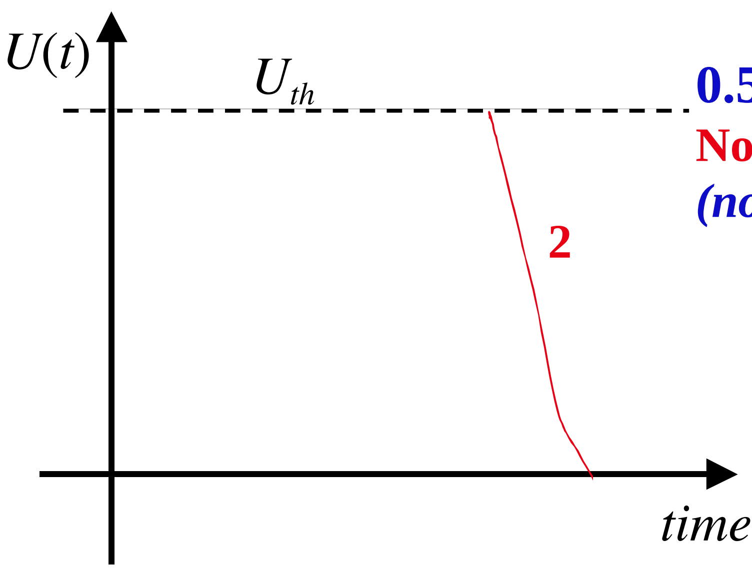

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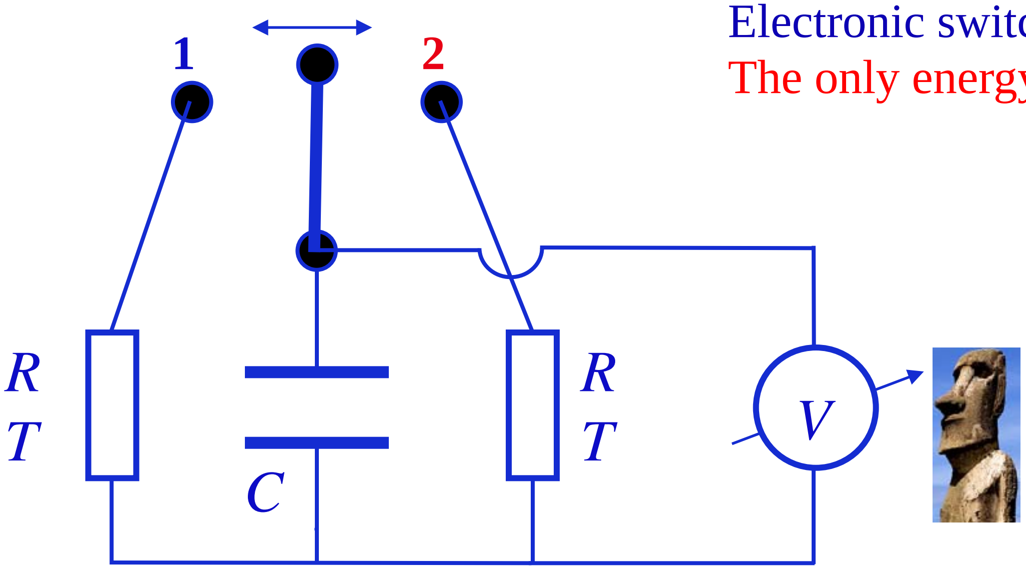

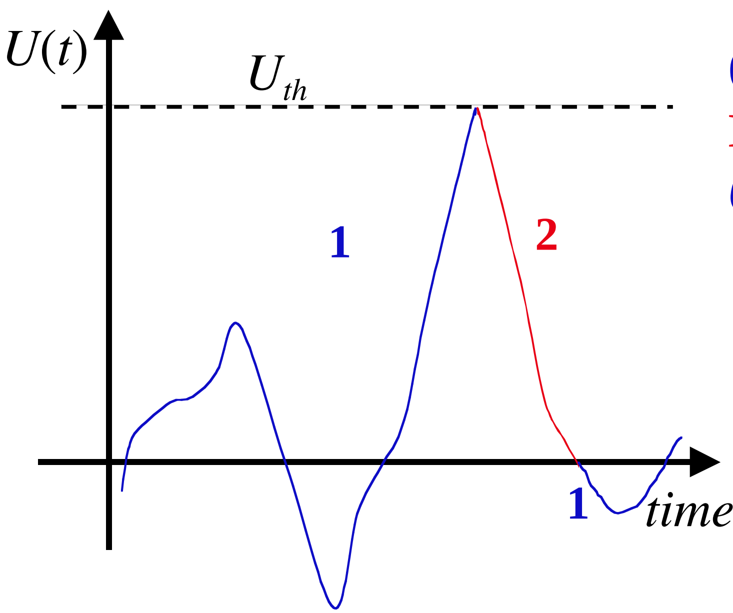

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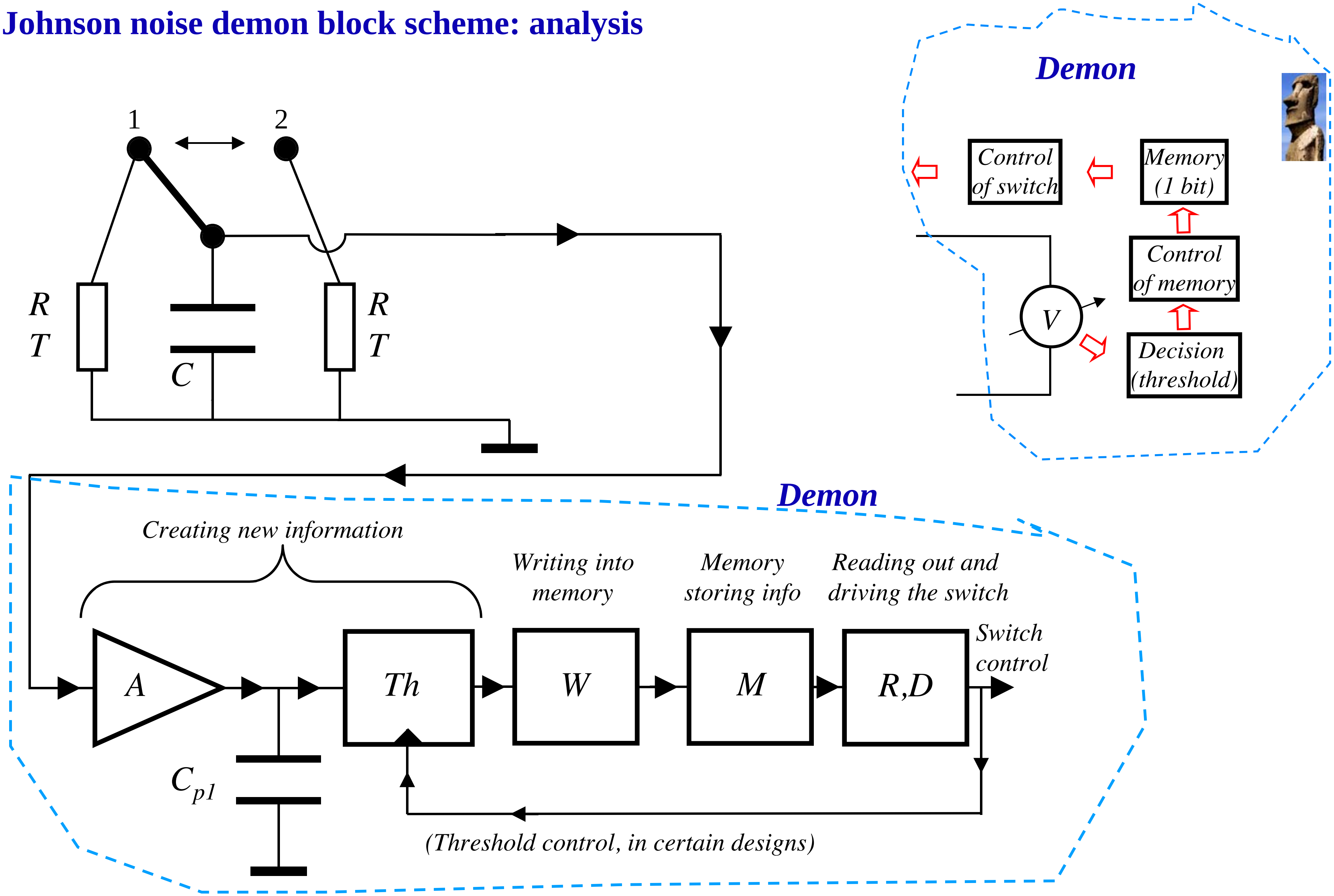
Johnson noise demon block scheme: analysis



L.B. Kish, C-G Granqvist, Electrical Maxwell Demon and Szilard Engine Utilizing Johnson Noise, Measurement, Logic and Control.

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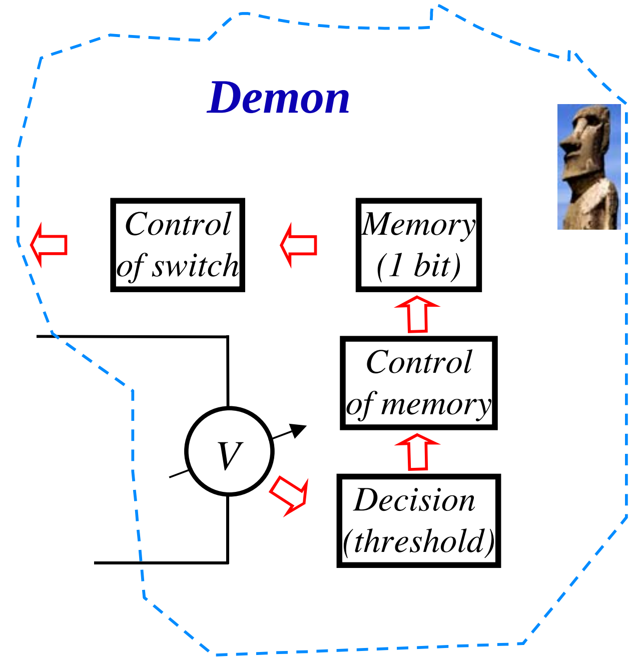


Energy dissipation in the binary parts, including the **memory** saves the Second Law:

$$E_{d,bin} \geq E_{th} + kT\left[\ln\left(\frac{1}{\varepsilon_c}\sqrt{\frac{kT}{E_{th}}}\right)\right]$$

E_{th} : pumped energy during a cycle

ε_c : error probability during a cycle

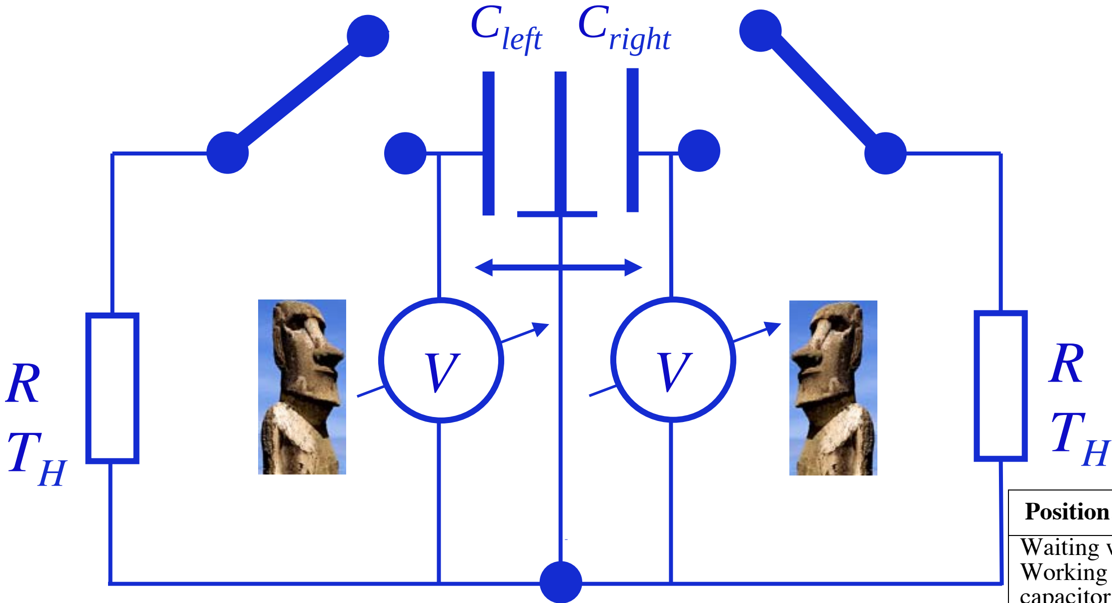
But analog parts, *which are parts of the measurement system*, at fixed error probability, have much greater dissipation and scales as:

$$E_{d,an} \propto E_{th} + kT \exp\left(\frac{E_{th}}{kT}\right)$$

L.B. Kish, C-G Granqvist, Electrical Maxwell Demon and Szilard Engine Utilizing Johnson Noise, Measurement, Logic and Control.

Thermal noise demon producing work (Szilard engine).

Electronic switches, no mechanical motion in the system except the piston.



Cylinder-1

Position, motion, voltages during a cycle	Switch status and energy conditions
Waiting with piston at right position. Working charge $Q_w = C_R U_R$ is in the right capacitor.	$0.5CU_R^2 >> kT/2$. Left switch is on, right switch is off.
Threshold $U_L >> (kT/C_L)^{0.5}$ corresponding to Q_w is reached.	When threshold is reached, left switch goes off. $0.5C_L U_L^2 >> kT/2$
Working charge $Q_w = C_L U_L$ stored in left capacitor.	Right switch goes on.
Threshold $U_R = 0$ is reached at the right side.	When it is reached, right switch goes off.
Piston moves left.	Work is executed: $0.5Q_w^2(1C_{Lmin}\text{-}1/C_{Lmax})$
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Note: the cylinders cannot be synchronized neither in space nor in time thus these energy saving methods applied at the thermal noise engines are inapplicable here.

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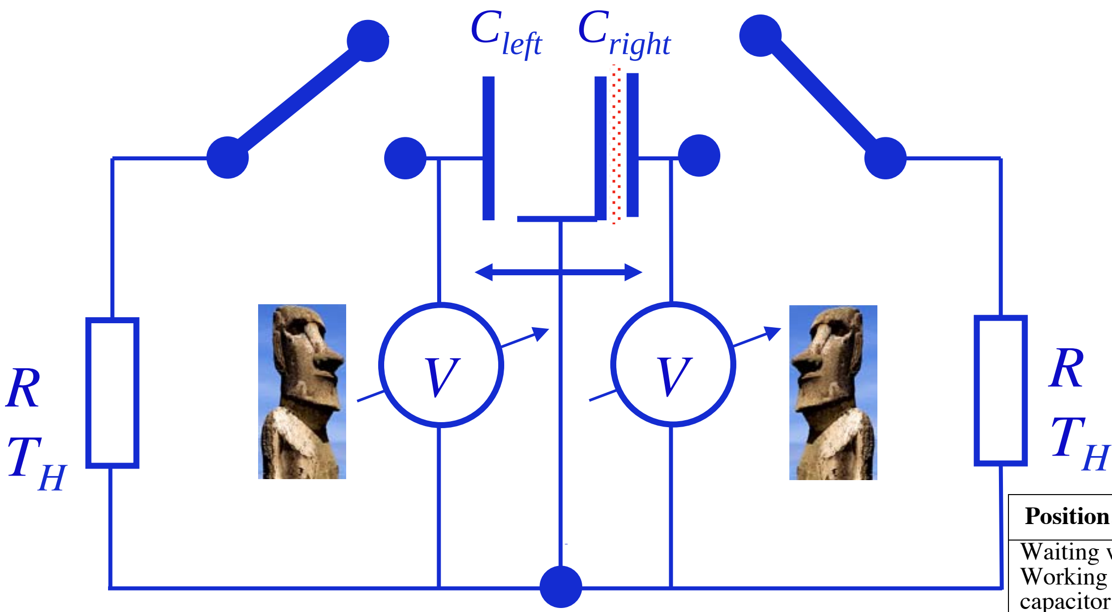

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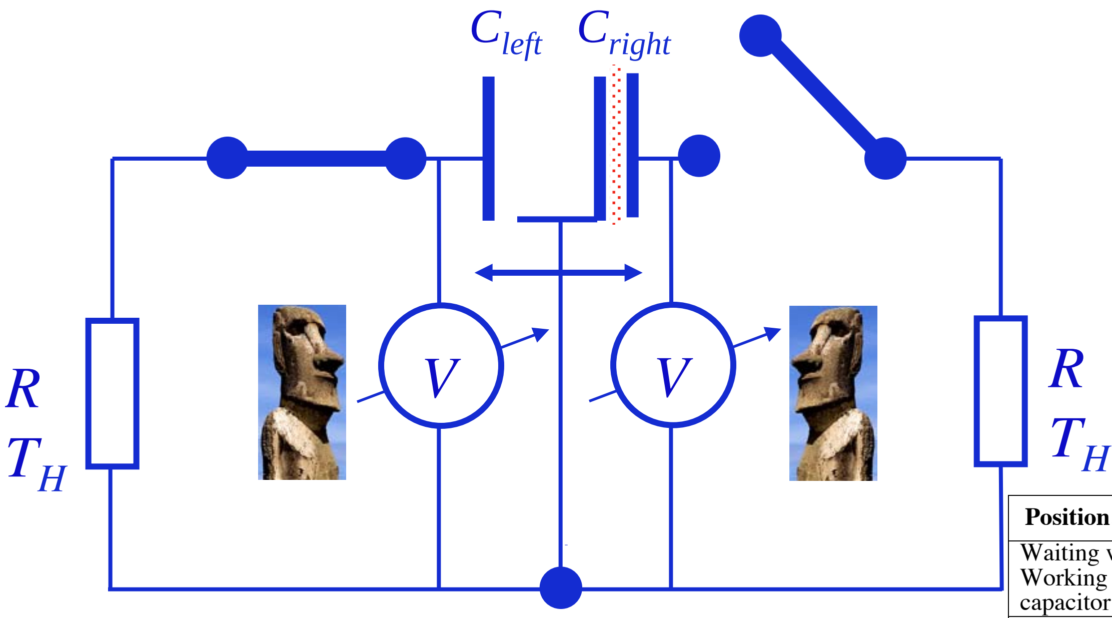

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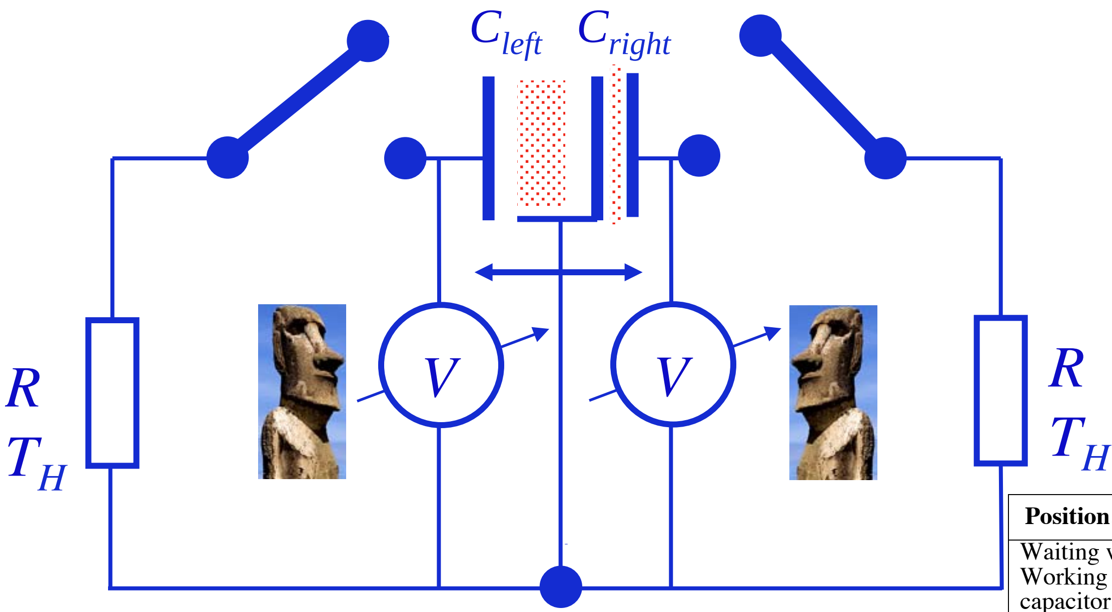

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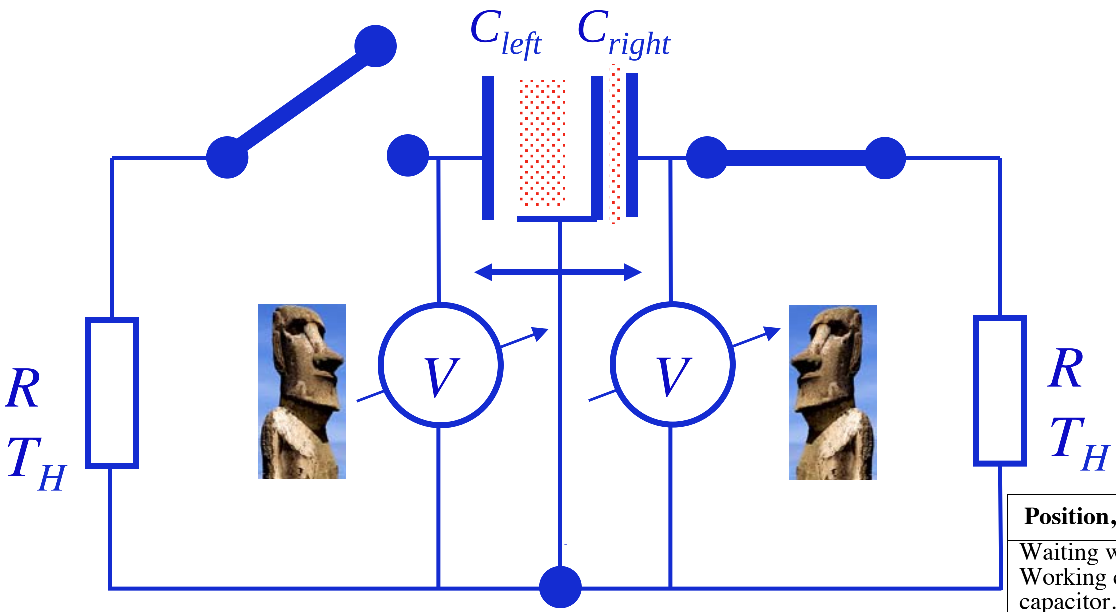

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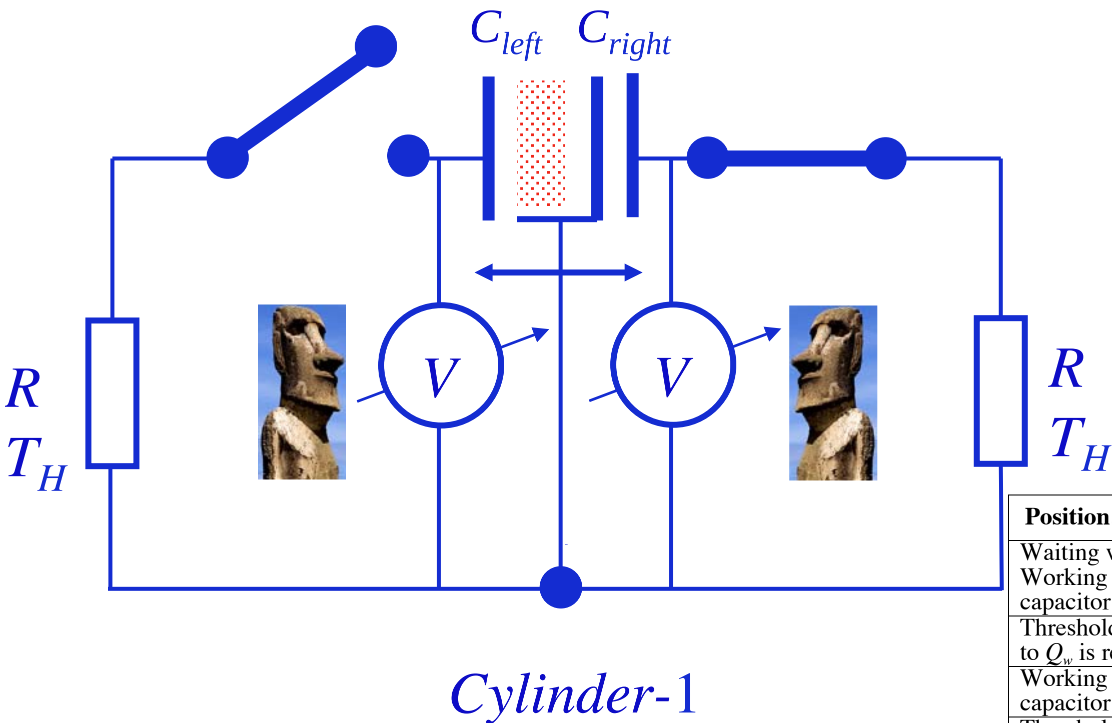

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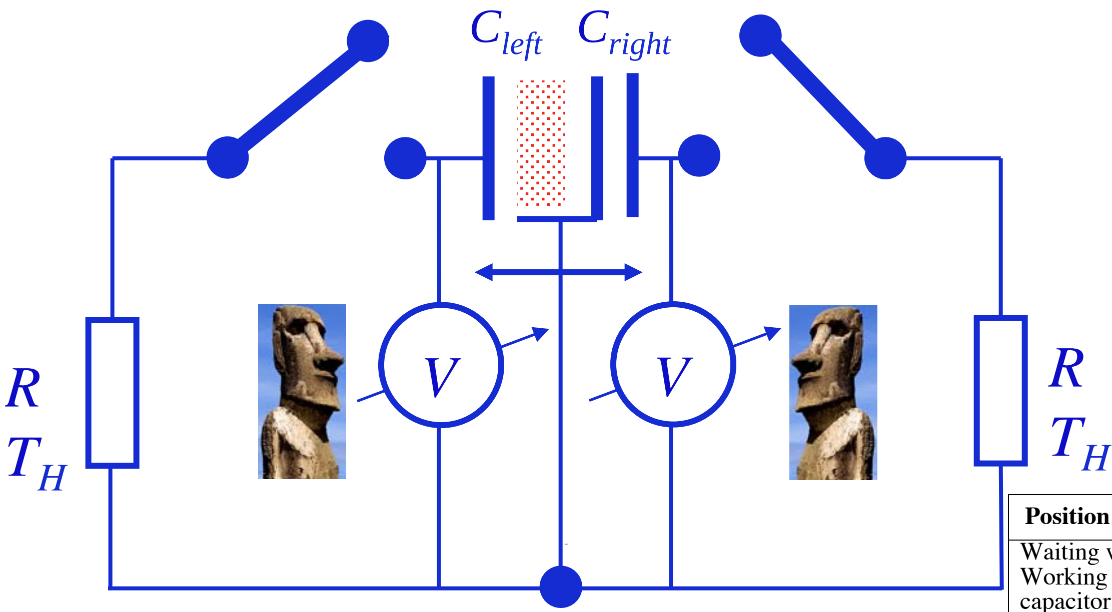

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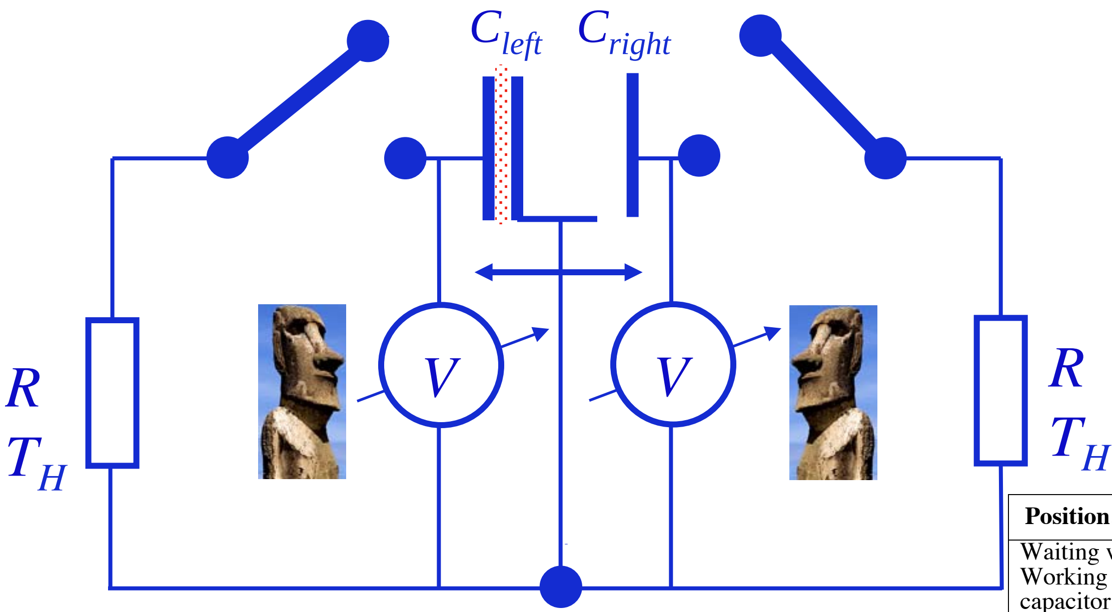

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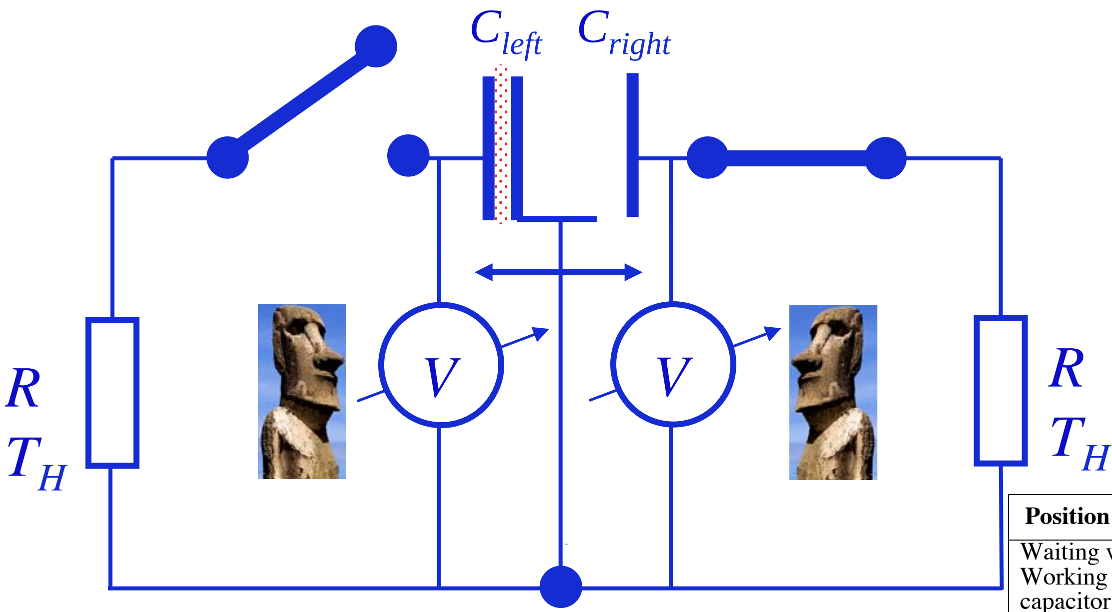

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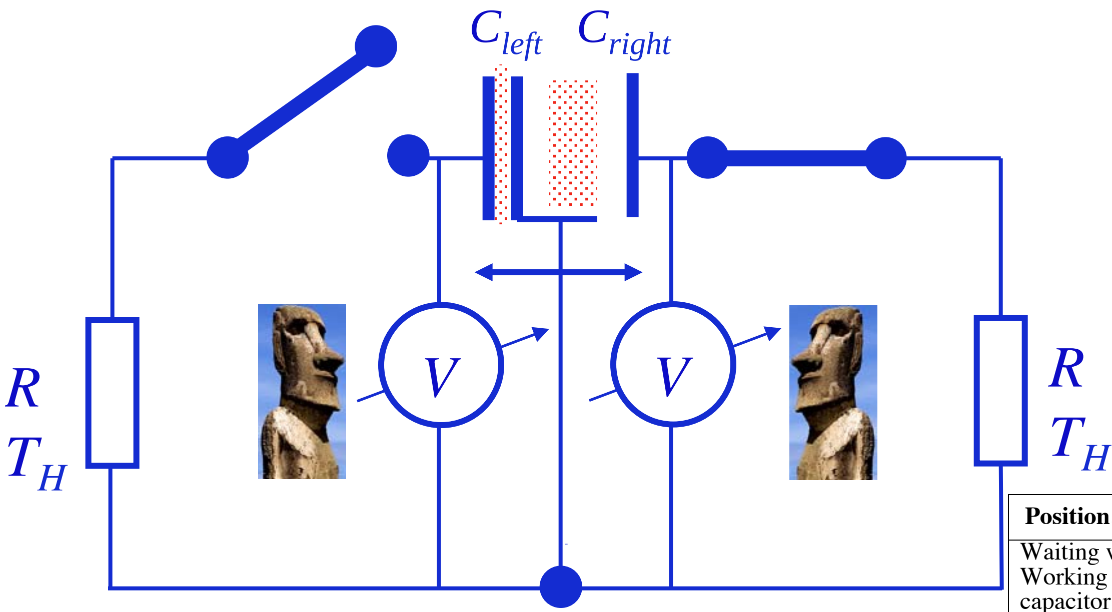

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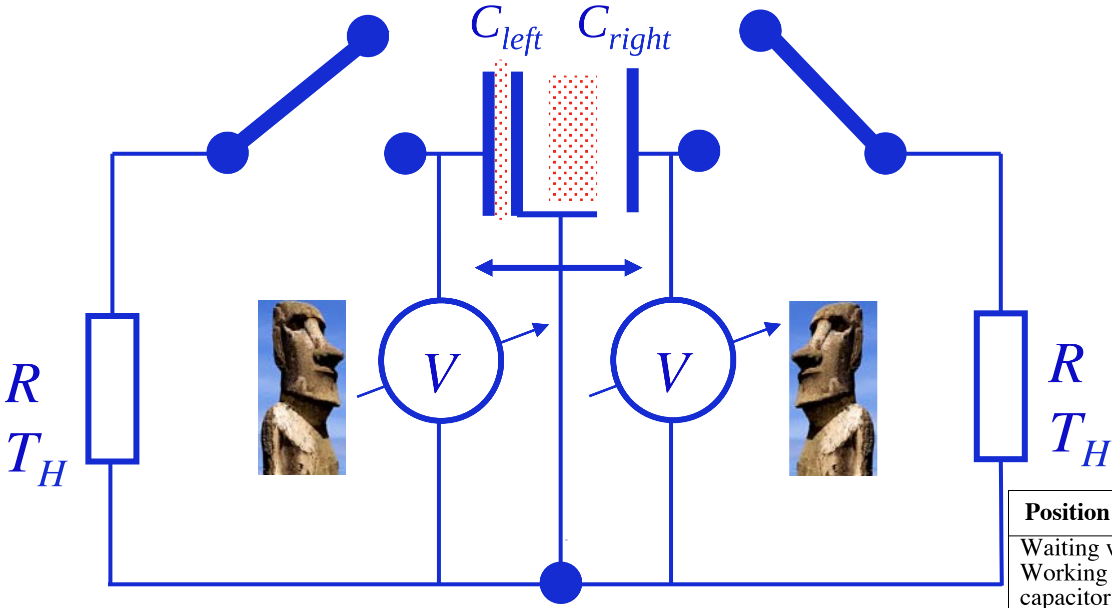

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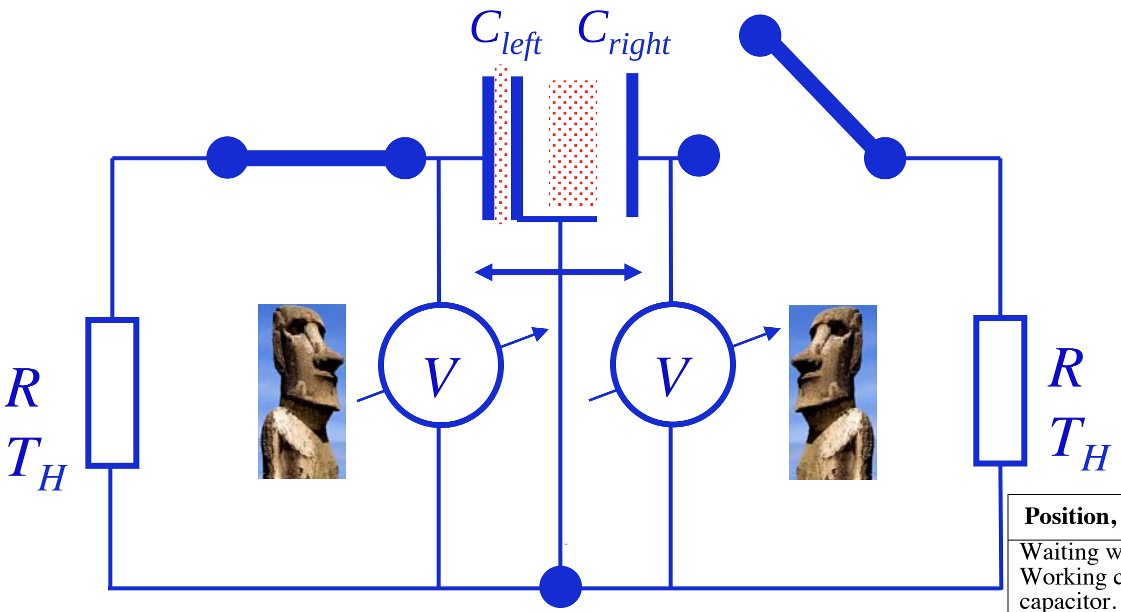

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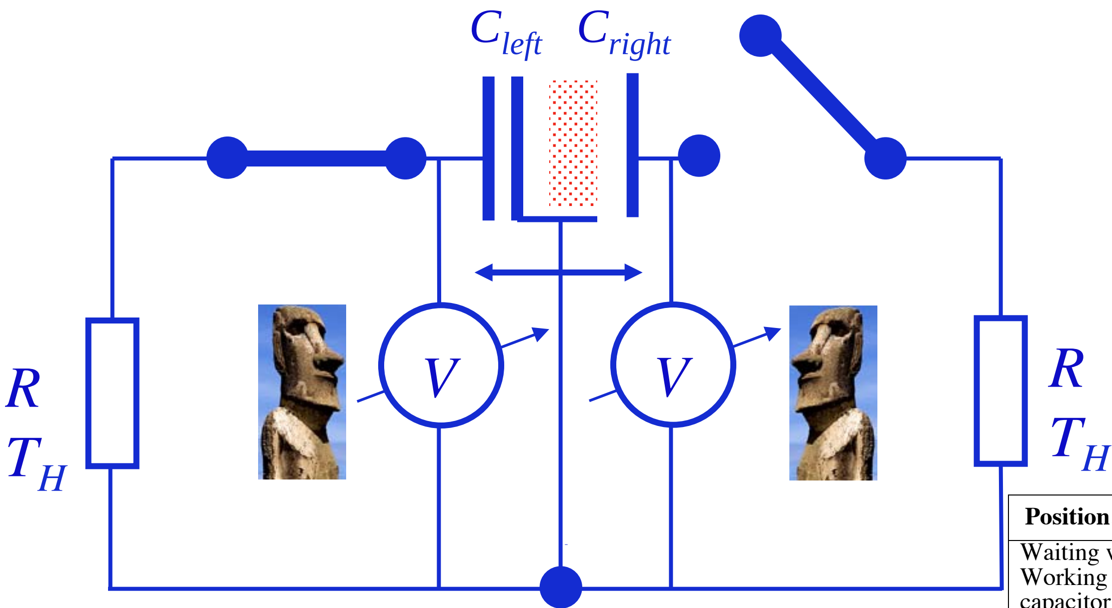

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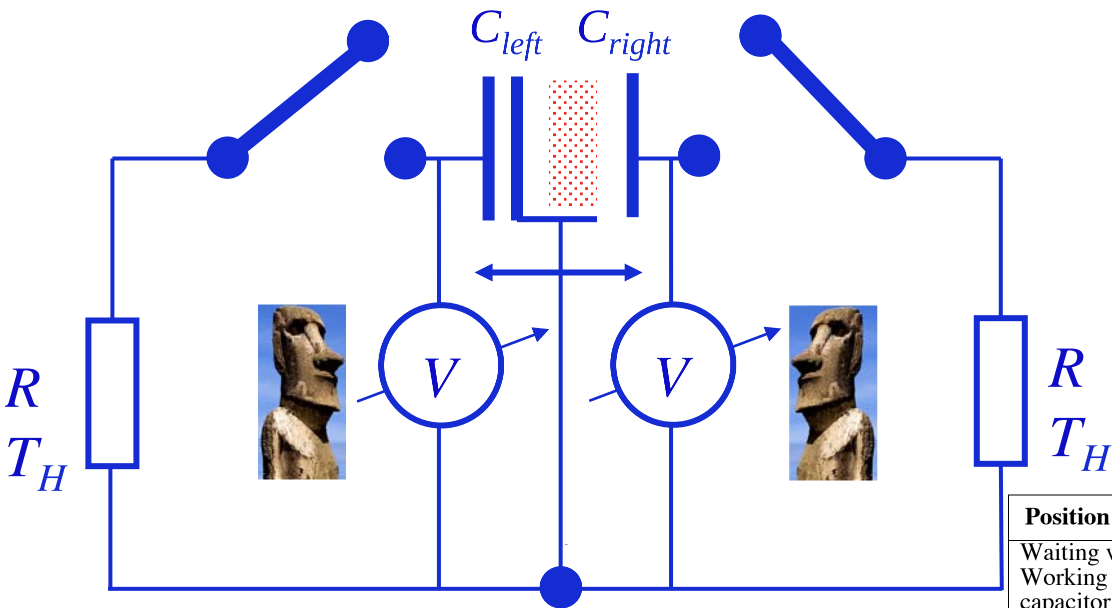

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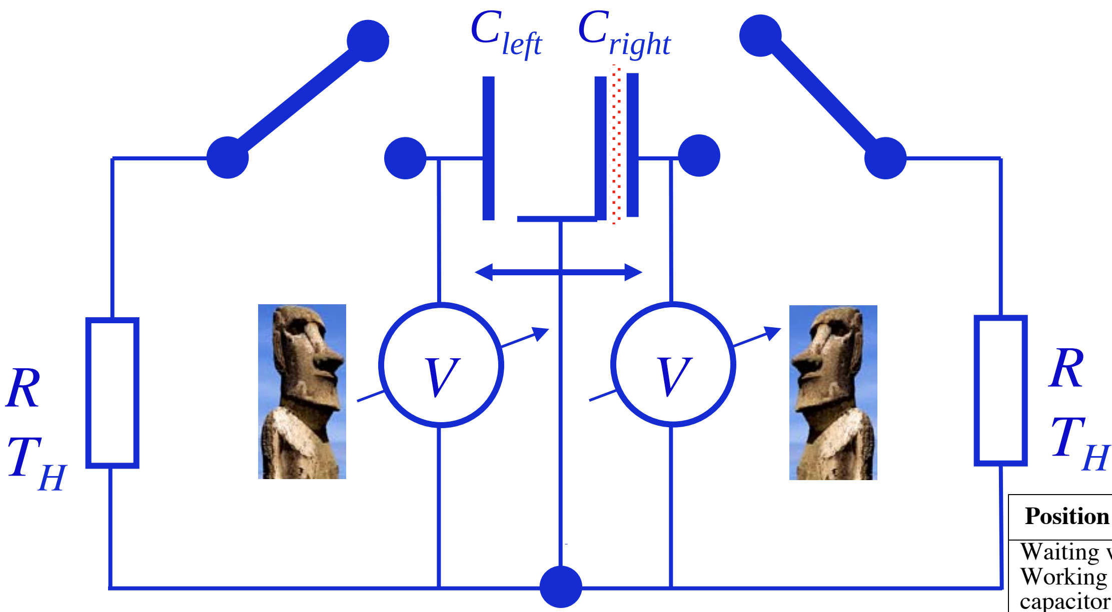

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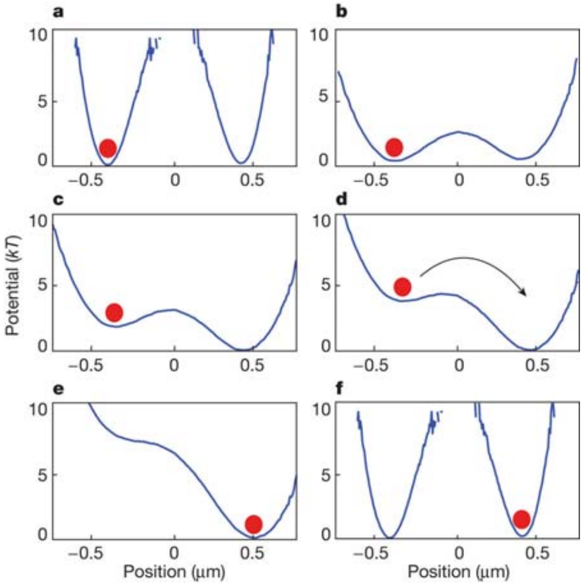
Experiments! Example.

(Quick note about *hype in media*: kT energy was not measured but calculated from measured velocity and viscosity. In any case, kT is not something "very tiny", *any electronic circuit showing thermal noise shows the fraction of kT energy*.)

A. Bérut, A. Arakelyan, A. Petrosyan, S. Ciliberto, R. Dillenschneider & E. Lutz
"Experimental verification of Landauer's principle linking information and thermodynamics",
Nature **483** (2012) 187–189

" Specifically, we lower the barrier from a height larger than 8kT to 2.2kT over a time of 1s *by decreasing the power of the laser*. This time is long compared with the relaxation time of the bead. "

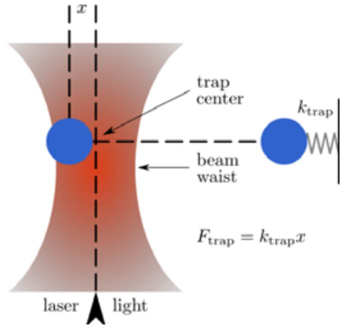


"One bit of information stored in a bistable potential is erased by first lowering the central barrier and then applying a tilting force. In the figures, we represent the transition from the initial state, 0 (left-hand well), to the final state, 1 (right-hand well). We do not show the obvious 1 - 1 transition. Indeed the procedure is such that irrespective of the initial state, the final state of the particle is always 1. The potential curves shown are those measured in our experiment."

- Is this indeed a single-bit erasure? *Why not the writing of a single-bit information*? Nothing would change!

- *Memory with a friction during changing the state not damping after the change is completed. What if we reduce the friction coefficient (viscosity) and force the particle over the same path with the same speed?* No such test have been done, neither distance between the well was varied.

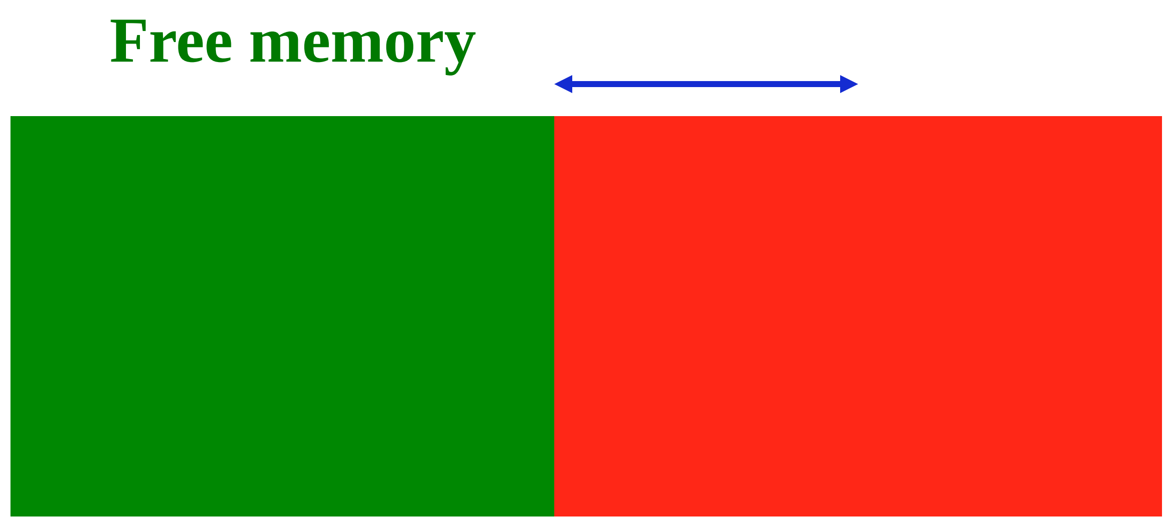
- What was the potential well? An optical field of focused laser light (optical tweezer) where the collisions with the photon gives the control force. Highly non-equilibrium system, **strongly driven system in steady state**! *Rigorously speaking, it does not even have a temperature!*



- **The energy dissipation of holding/modifying the potential barrier during the process**, which is at least 10^{20} kT, is totally neglected! Note, Landauer has also committed a similar error in his analysis.

Epilog; reality comparison with Landauers principle.

***Actually, how much is the energy requirement to erase the memory in our computers*???** **Renato's 1 Gbyte iPAD example.**



Epilog:

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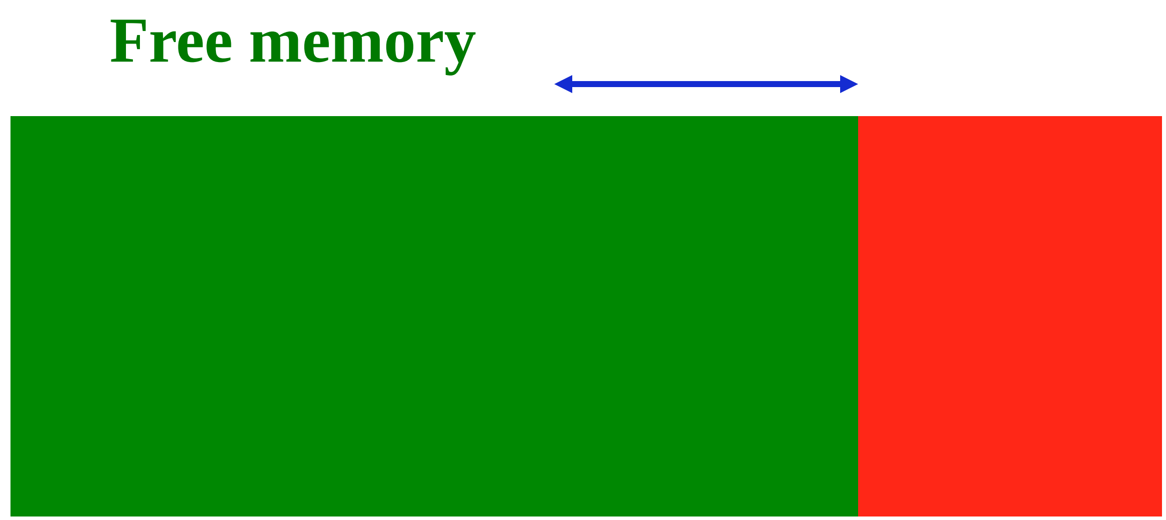

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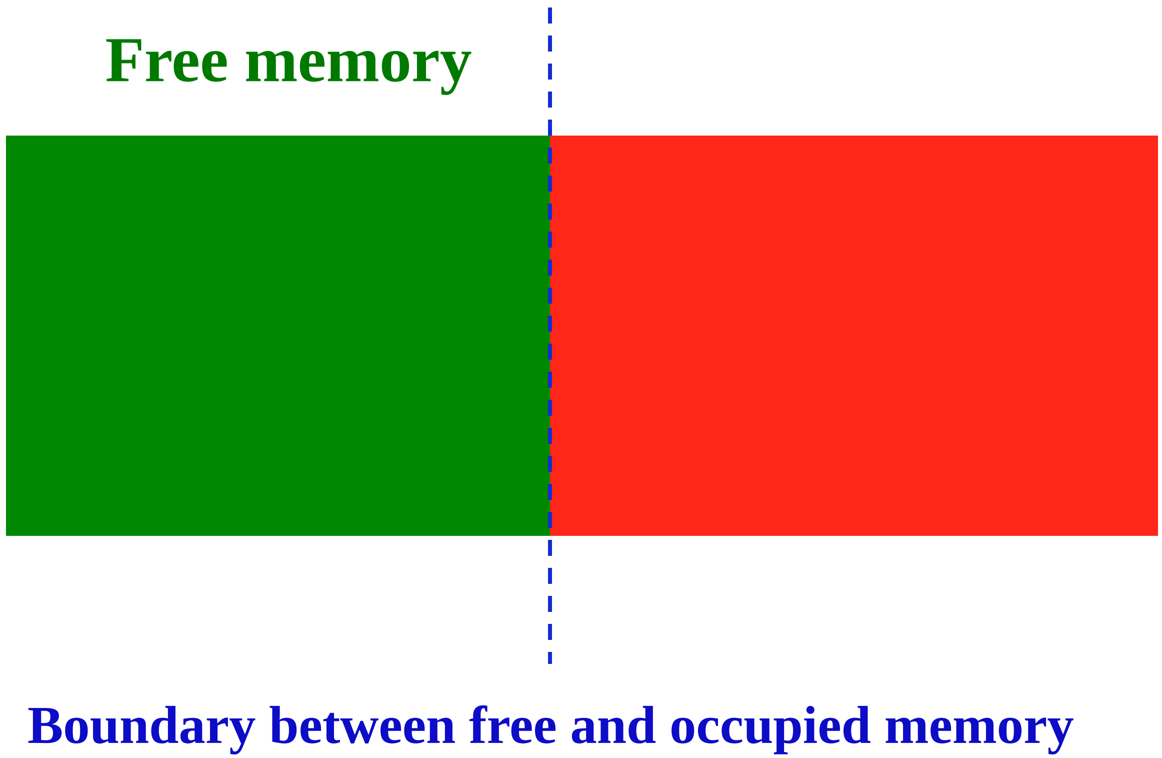

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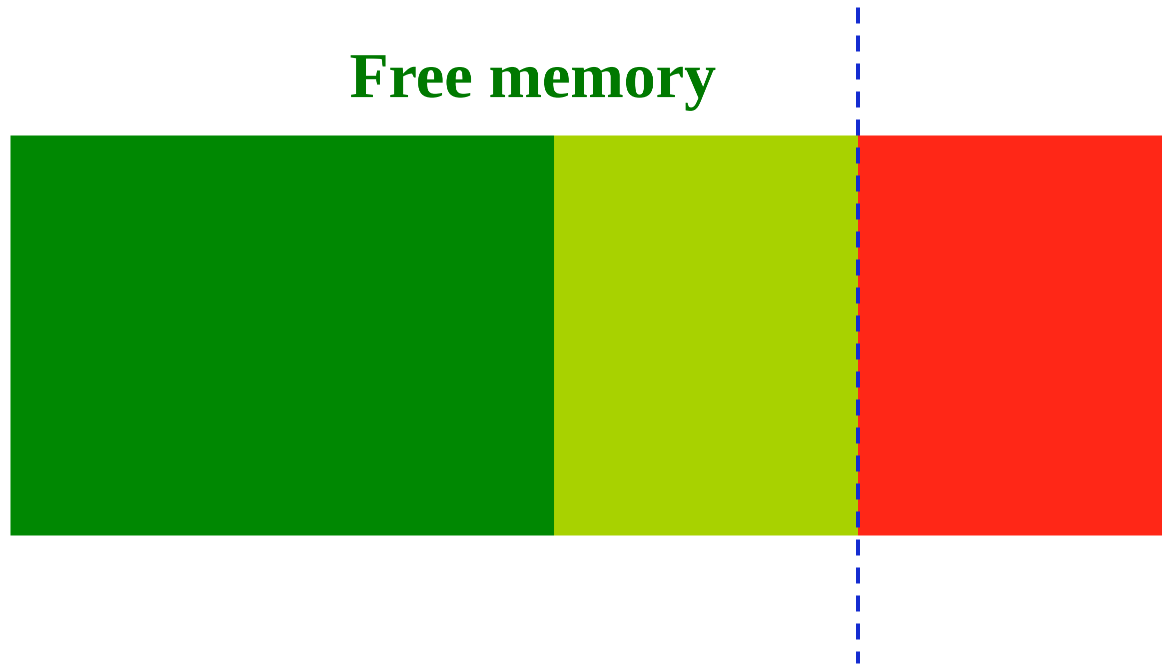

We change the *address* of the boundary between free and occupied memory

Epilog:

***Actually, how much is the energy requirement to erase the memory in our computers*??? NOT SECURE ERASURE BUT FOR EVERYDAY OPERATION.**

Based on the considerations at the beginning of this talk, the answer depends on the error probability and observation time however *at fixed error probability and observation time* it scales as:

$$\boxed{E = kT \ln\left(\frac{1}{\varepsilon}\frac{t_0}{\tau}\right)\log_2 N \propto \log_2 N}$$

where N is the *number of bits in the whole memory*. The logarithmic term shows the number of the address bits. *This is logarithmic scaling resulting in negligible energy dissipation/bit in large memories.*

This result is in strong contrast with the Landauer principle, which predicts linear scaling between the number of erased bits and the energy dissipation.

If N goes to infinity, the dissipation of single erasure goes to zero!

Conclusions (proper to ignite the debate):

- Energy dissipation limits of switches, memories and control. $\boxed{E_{\min} \approx kT \ln\left(\frac{1}{\varepsilon}\,\frac{t_o}{\tau}\right)}$

- Are reversible computers possible? **NO.** Or do their concept violates thermodynamics? **YES**

- Szilard Engine, Maxwell demon, Landauer principle mistakes: ESSENTIAL and ABUNDANT. Examples include neglecting the energy dissipation of various control steps including the control of the potential barrier shape, which is a general error, it makes entropy calculations invalid, and was started by Landauer himself in his famous paper about the issue.

  Demons and engine concepts with lacking a functional system due to missing essential elements have the same type of flaws. Experiments with arbitrary settings instead of systematic check, claiming energies in the order or kT and neglecting 10^{20} + kT at the control side are strong examples. Most often no mathematical error analysis; the lack of that usually makes the result not only incomplete but also questionable.

- Is Landauer's erasure-dissipation principle valid; or the same is true for writing the information; or it is simply invalid? **VALID** for a single bit, and it it is not Landauer principle but **Brillouin negentropy principle** because it is the same as writing the information. **INVALID** for multi-bit memories.

- Does (non-secure) erasure of memories dissipate the more heat, or the writing of the same amount of information? **NO**, erasure dissipates **LESS**.

"Everything should be made as simple as possible, but not simpler." **Albert Einstein**

Demons: Maxwell demon; Szilard engine; and Landauer's erasure-dissipation

Laszlo B. Kish[(1)], Claes-Göran Granqvist[(2)], Sunil P. Khatri[(1)], He Wen[(3)]

[(1)]*Texas A&M University, College Station;* [(2)]*Uppsala University, Sweden;* [(3)]*Hunan University, Changsha*