"We can't solve problems by using the same kind of thinking we used when we created them."
Albert Einstein

Energy Requirement of Control: Comments on Maxwell's Demon and Szilard's Engine

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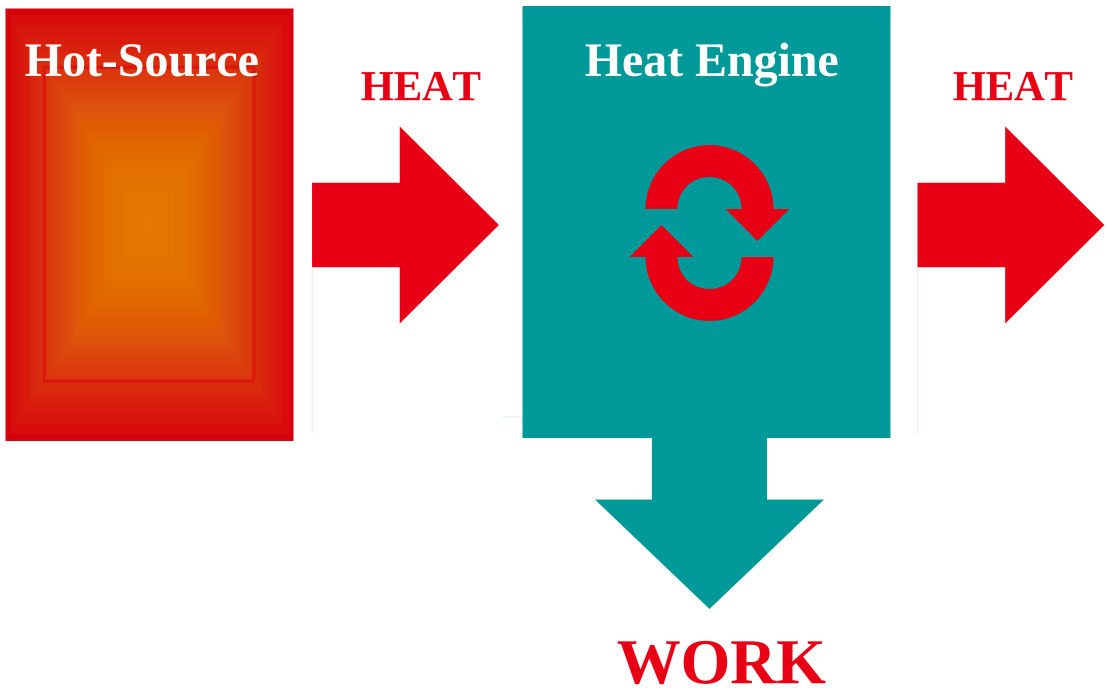
In mathematical physical analyses of Maxwell's demon and Szilard's engine, a general assumption (explicit or implicit) is that one can neglect the energy needed for driving the trap door in the Maxwell demon and for relocating the piston in the Szilard engine. If this basic assumption is wrong, then the conclusions of a vast literature on the implications of the Second Law of Thermodynamics and Landauer's erasure theorem are incorrect too. Our analysis indicates that the permitted errors in the control, the friction, the velocity versus the thermal velocity, and the quantization of electrical charge play crucial roles in determining the minimum energy requirement of velocity control. The analysis further indicates that the ultimate minimum energy requirements of controlling the trapdoor and the piston are much greater than the energy that the Maxwell demon and Szilard engine are able to produce even if all other sources of dissipation (measurement, decision, memory, etc) are neglected.

***All the colors of noise*, Lecce, Italy, November 14, 2011.**
Images are from Google Image.

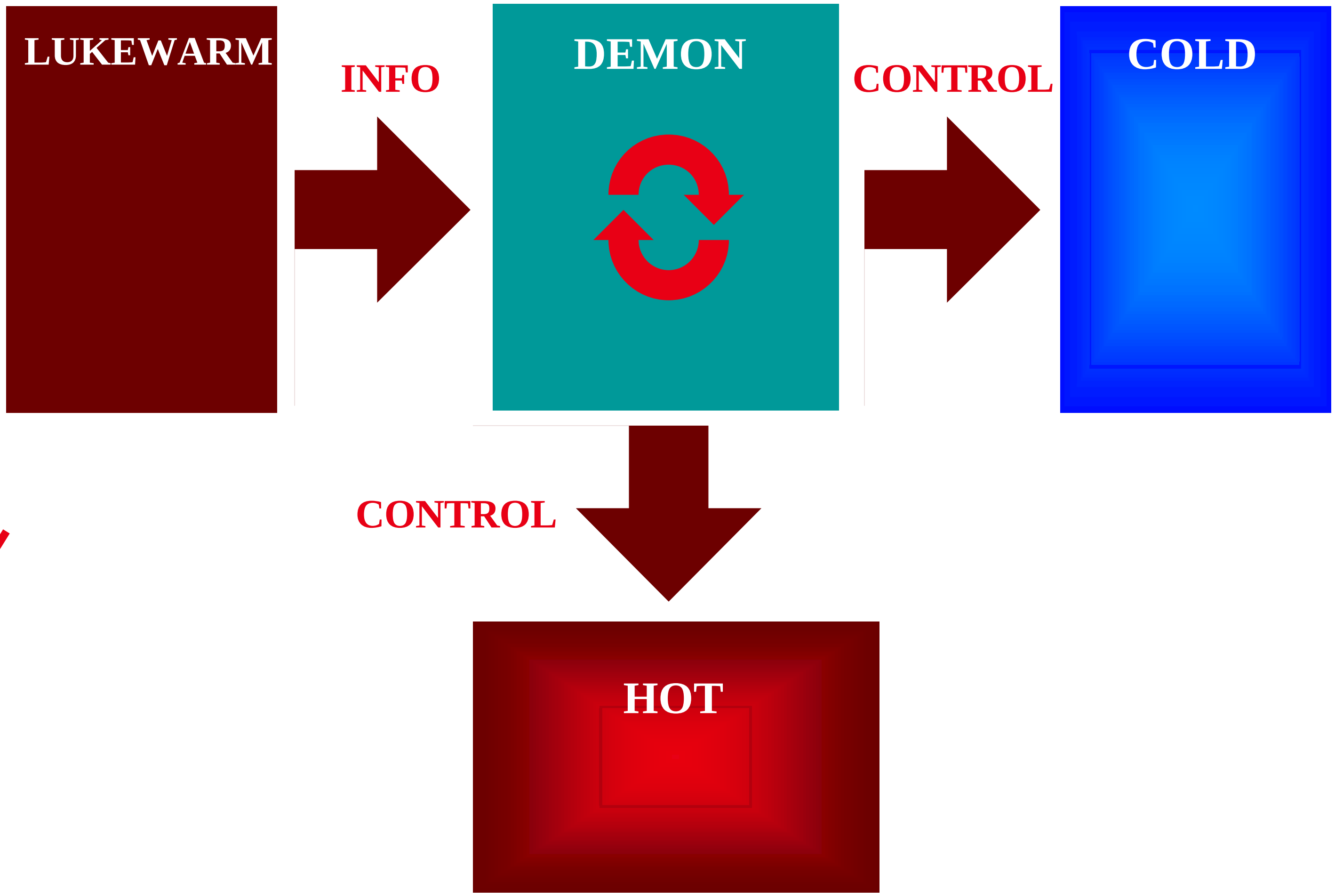
Heat Engine: Utilizes temperature difference to produce work.

Result: the temperature difference in a closed system will decrease unless we invest energy to keep it.



Maxwell demon: Utilizes information to produce temperature difference.

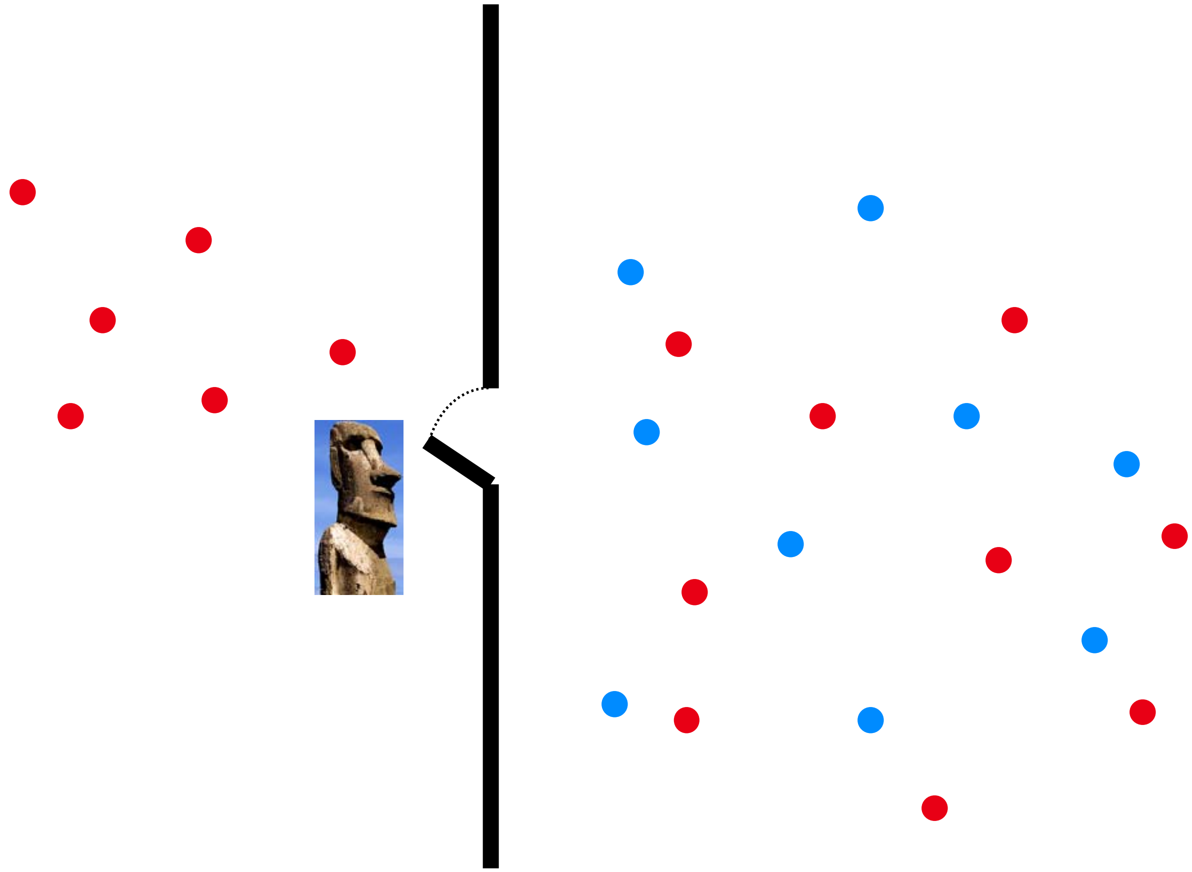
Result: temperature difference.



Maxwell demon.

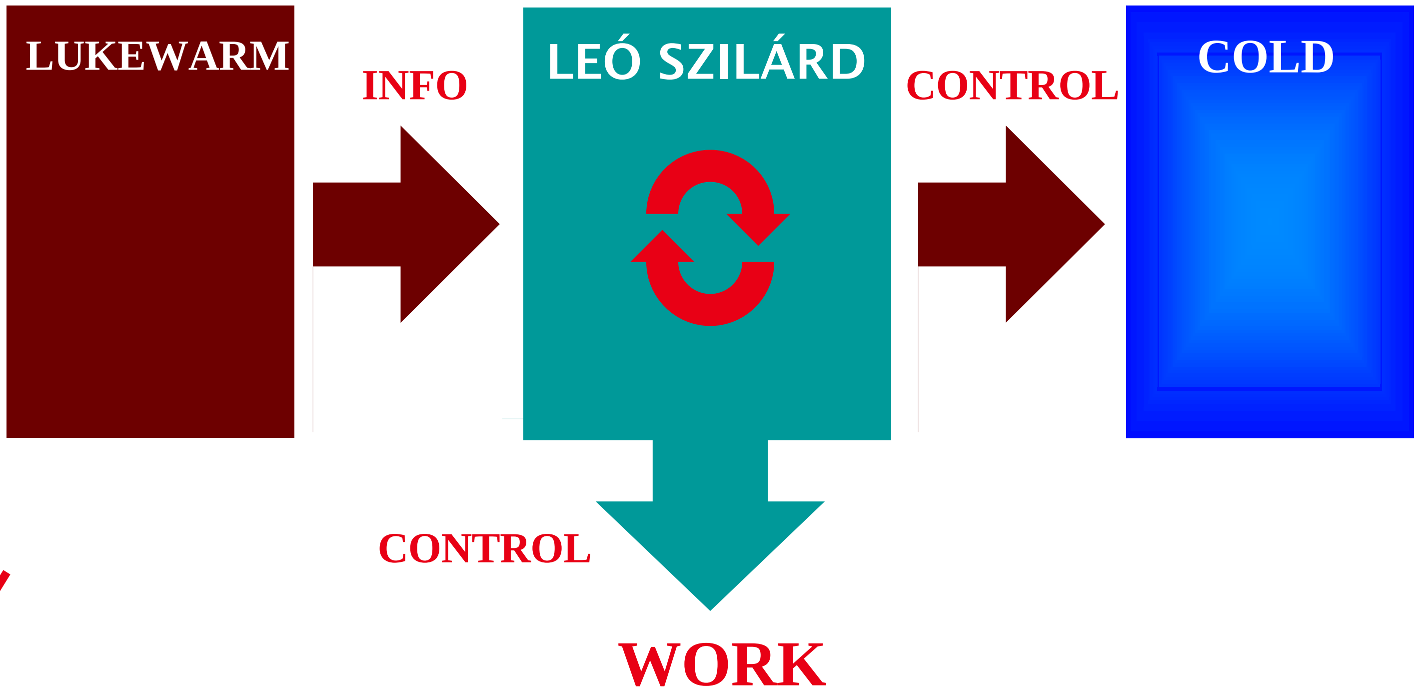
Fast molecules are collected at the left side by measurements and controlling the trapdoor.

Heat is pumped to the left side ***by utilizing the measured information for control.***



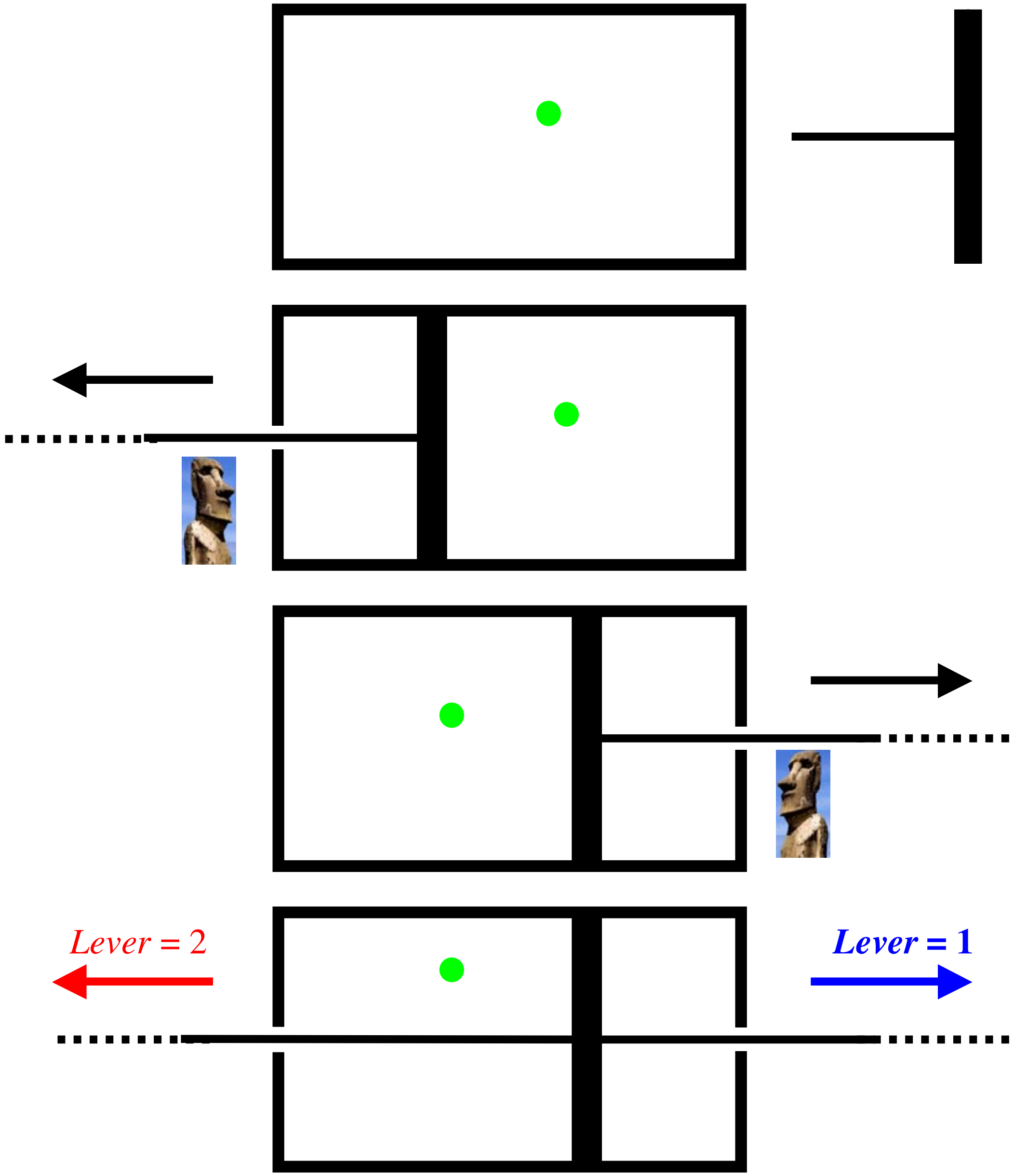
Szilard engine: Utilizes information to produce work .

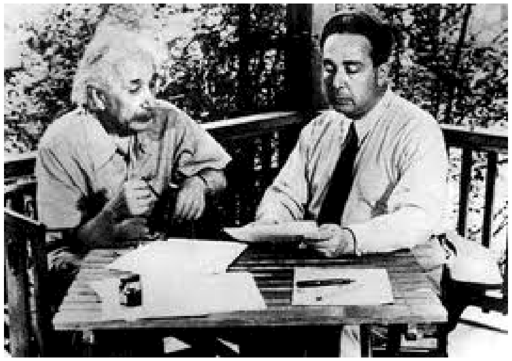
Result: work and temperature difference.



The Szilard engine

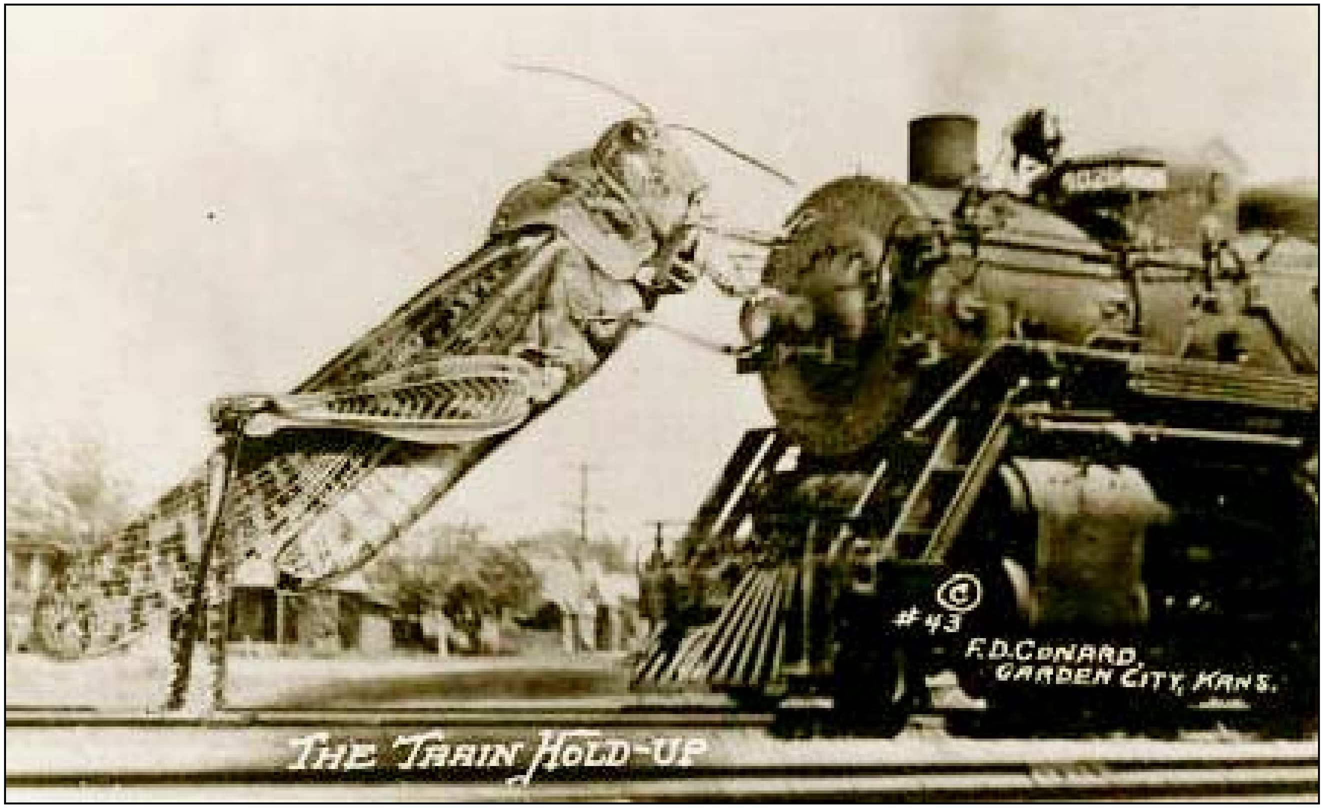
Work is extracted by *utilizing the measured information for control.*





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

!!! The *Second Law of Thermodynamics* prohibits:

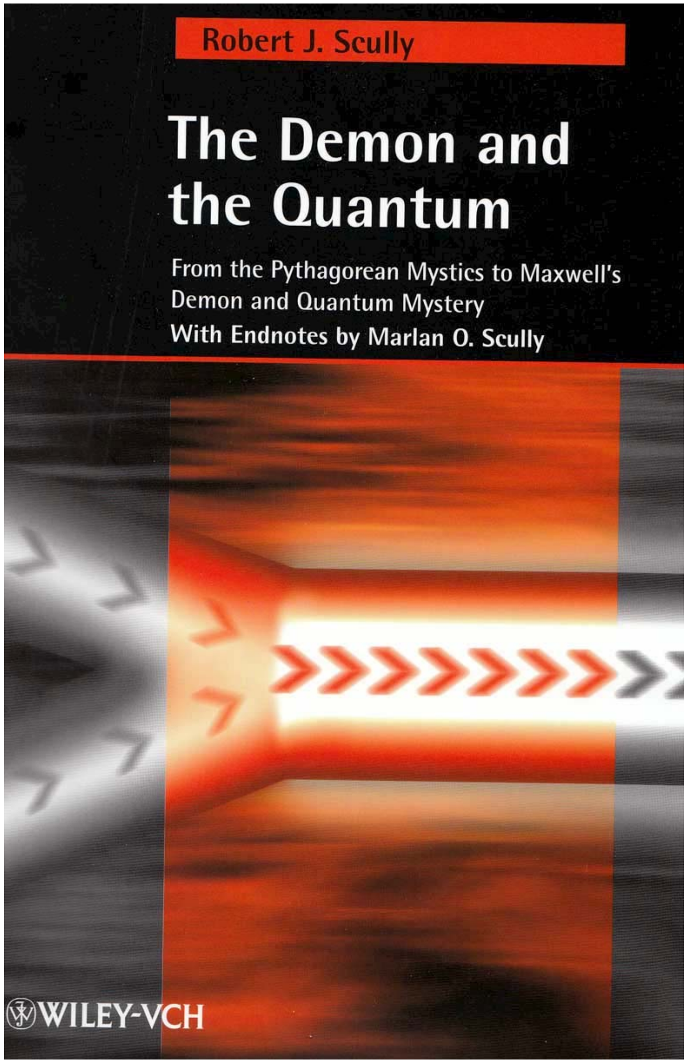


Engines with single heat reservoir

or

Extracting net power from thermal equilibrium

In mainstream mathematical physics, the belief is that the erasure of memory is the key player.



Ch. Bennett
R.Landauer

"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.

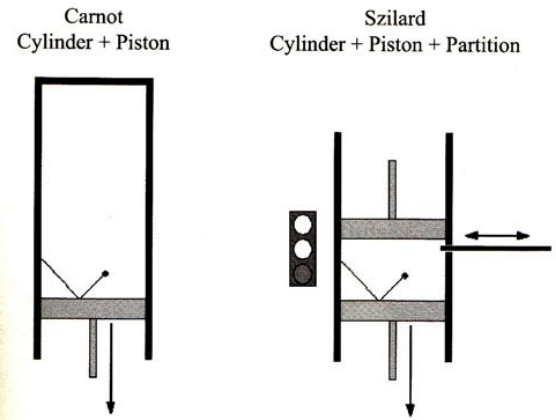


Fig. 5.2 Illustrations of the single-atom Carnot engine and the single-atom Szilárd engine.

Table 5.1 Comparison of single-atom Carnot and Szilárd engines.

	Carnot engine	**Szilárd engine**
Useful work	Power to shaft	Power to shaft
Working fluid	Atomic motion	Atomic motion
Energy source	Hot bath (e.g., nuclear reactor or coal furnace), T_h	Hot bath (boiler), T_h
Entropy sink mechanism	Cold bath (e.g., cooling tower or automobile radiator), T_c	Reset monitor
Entropy discarded via	Compression at T_c	Erasing information

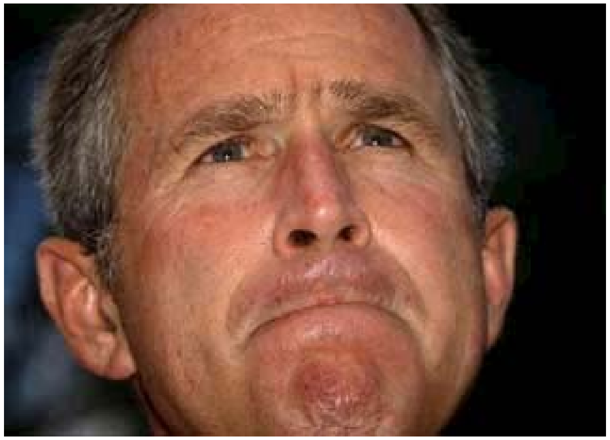
One of the goals of this ongoing project has been to clarify:

Is it indeed true that ***forgetting*** needs the most energy dissipation, ***not learning and creating***???

It is very difficult to believe this!

Especially when we consider our own experiences with learning and creating, and the fact that how easy and effortless is to forget something :-)

People do not sweat while they are forgetting things.



But they sweat when they try to reconstruct their memory, or want to solve a complex problem.

The general statement is that, in the Szilard engine model of the Maxwell demon, the ***energy produced*** in a single cycle and the lower bound of the ***dissipation during the erasure of the memory*** are equal and they are:

$$\boxed{kT \ln 2 \approx 0.7kT}$$

The claim is that the dissipation due to the erasure of the information in the memory is needed to satisfy the Second Law of Thermodynamics, the fact, that no energy can be extracted from thermal equilibrium.

In the present talk, we focus on the ***energy need of controlling the trapdoor/piston.*** We show that ***this action alone dissipates more energy than kT* ln 2 *therefore itself this energy need saves the Second Law***.

For thorough discussions about the pitfalls around the Landauer principle, see:

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)

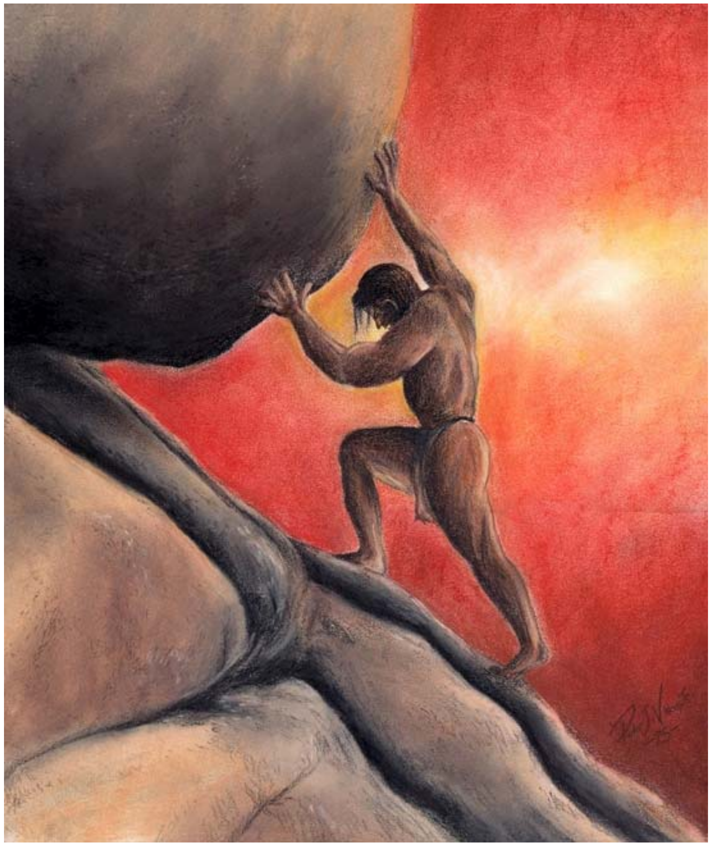
W. Porod, R.O. Grondin, D.K. Ferry, "Dissipation in Computation", *Phys Rev. Lett.* **52**, 232-235, (1984)

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

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

General remarks about quantum physical treatments of Szilard engine:

A quantum operation alone can never open or close a trapdoor, which is a macroscopic, classical physical body and/or to act as a deterministic active control. Thus we cannot expect such elementary quantum models alone to fully address a complex system such as the Maxwell demon or Szilard engine.



Neglecting the energy dissipation concerning controlling ***macroscopic bodies*** such as a mechanical trapdoor, the repositioning of a piston, and the control of a lever, while the demon's expected energy output is in the ***order of kT***, *is simply unacceptable* ***unless the validity of this step is rigorously proven***.

Currently, *electronic amplifiers are the only ones* that have the potential to provide the control in a Maxwell demon and Szilard engine. Such a complete system would be *electromechanical*. In the field of electromechanics, they transform the mechanical part of the system into an electronic system.

Therefore, in our models, we work with purely classical physical systems and all the energy dissipation concerning measurement, decision, control and memory takes place in the framework of electronics.

In this way, we can avoid the ***errors regarding the different types of energies*** and their dissipation, especially concerning measurements, decision, memory, mechanical motion and its ***control***.

$\text{Force}: F \Leftrightarrow \text{Current}: I$

$\text{Velocity}: v \Leftrightarrow \text{Voltage}: U$

$\text{Mass}: M \Leftrightarrow \text{Capacitance}: C$

$\text{Friction constant}: \gamma \Leftrightarrow \text{Conductance}: 1/R$

$\text{Spring constant}: K \Leftrightarrow \text{Reciprocal inductance}: 1/L$,

$\text{Momentum}: \theta = Ft = Mv \Leftrightarrow \text{Charge}: Q = It = CU$

$$\boxed{\begin{array}{l} \text{Energy}: E = \frac{1}{2}Mv^2;\ \frac{1}{2}\frac{F^2}{K};\ \frac{1}{2}CU^2;\ \frac{1}{2}LI^2 \\ \\ \text{Power}: P = Fv;\ UI \end{array}}$$

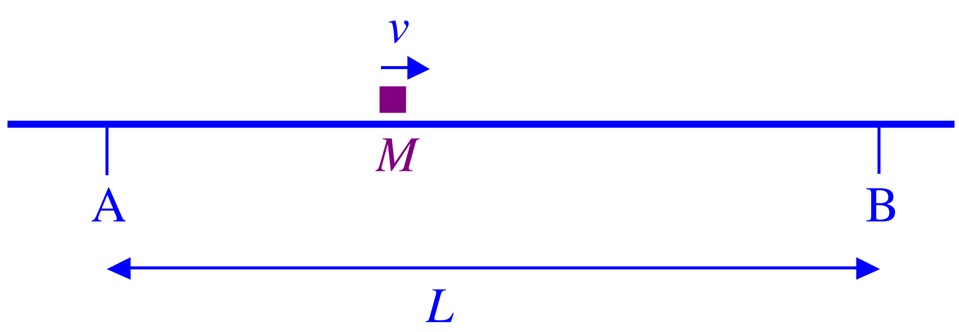
$\text{Friction force}: F_f = \gamma v;\ \text{Ohm's law}: I = U/R$

$$\text{Resonance frequency}: f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{M}};\ \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Electro-mechanical equivalence theory (this version fits best our conditions) for a simple picture, consider a magnet and a coil.

Alternative picture: mass-inductance, force-voltage, velocity-current.

E, P, same units in both systems!

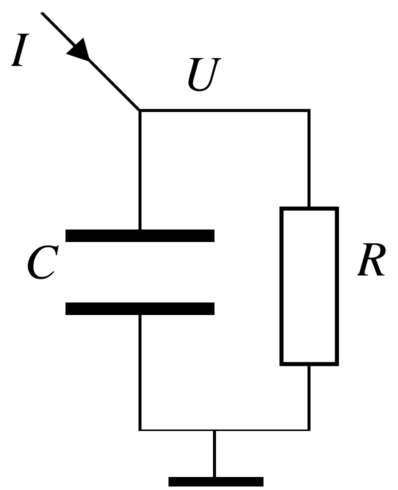


τ_m flying time

τ_r energy relaxation time

deterministic velocity: $v_m = L/\tau_m$

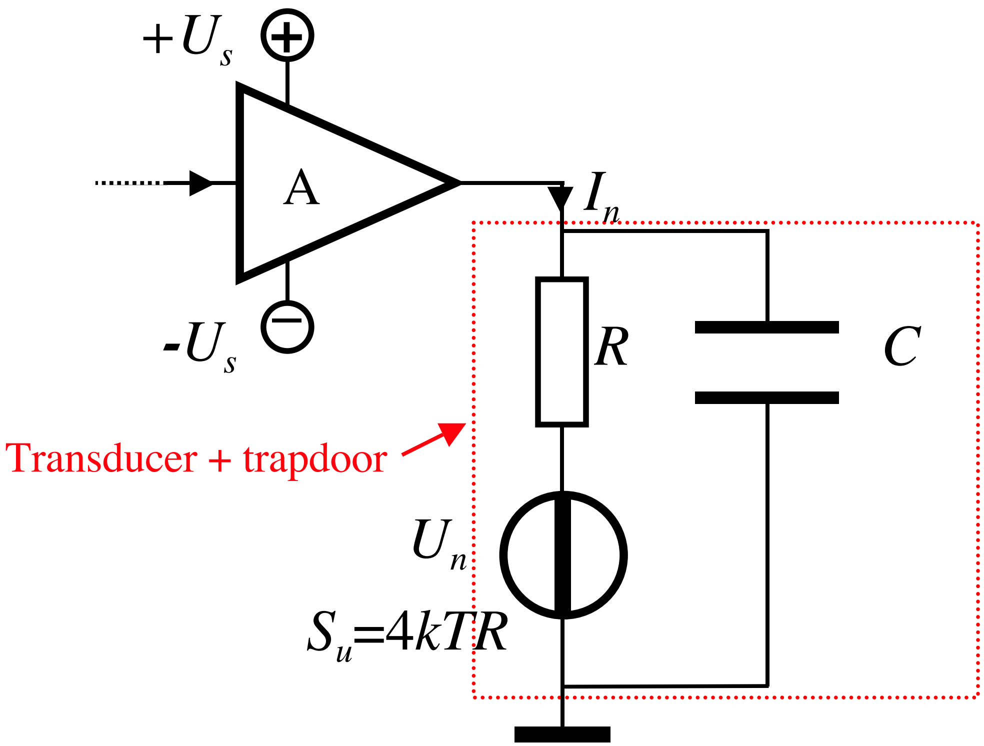
A free-floating trapdoor represented by a body with mass M coupled to a heat reservoir via a friction constant.

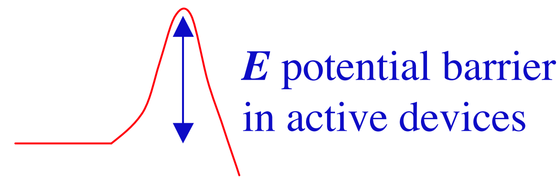


Equivalent circuit of this system. The current (representing the force) charges up the capacitor (representing the mass) to a voltage (representing the velocity); power is then dissipated on the resistor (with conductance representing friction).

Electronic model of linear active control of the velocity. Tthis model holds generally in any linear system where inertia, friction (damping) and temperature exist. The reason of using electronic model is twofold:

a) the available analytical tools in electronics;
b) such system must contain electronics that it is preferred to transform the mechanical parts of the system into equivalent electronic model.





Observe: the absolute minimum energy dissipation for ***active control*** is:

$$\boxed{E_{\min} = U_s q}$$

where q is the electron charge.

Meindl's limit: $\boxed{U_s \geq 4kT/q}$

J.D. Meindl, "Low Power Microelectronics: Retrospect and Prospect", *Proc. IEEE* **83** (1995) 619-635.

When the thermal noise voltage on the resistor is suppressed by the amplifier, the thermal noise current of the resistor flows through $+U_s$ or $-U_s$ depending on the polarity of the current.

Observe: the absolute minimum energy dissipation for ***active control*** is:

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where q is the electron charge.

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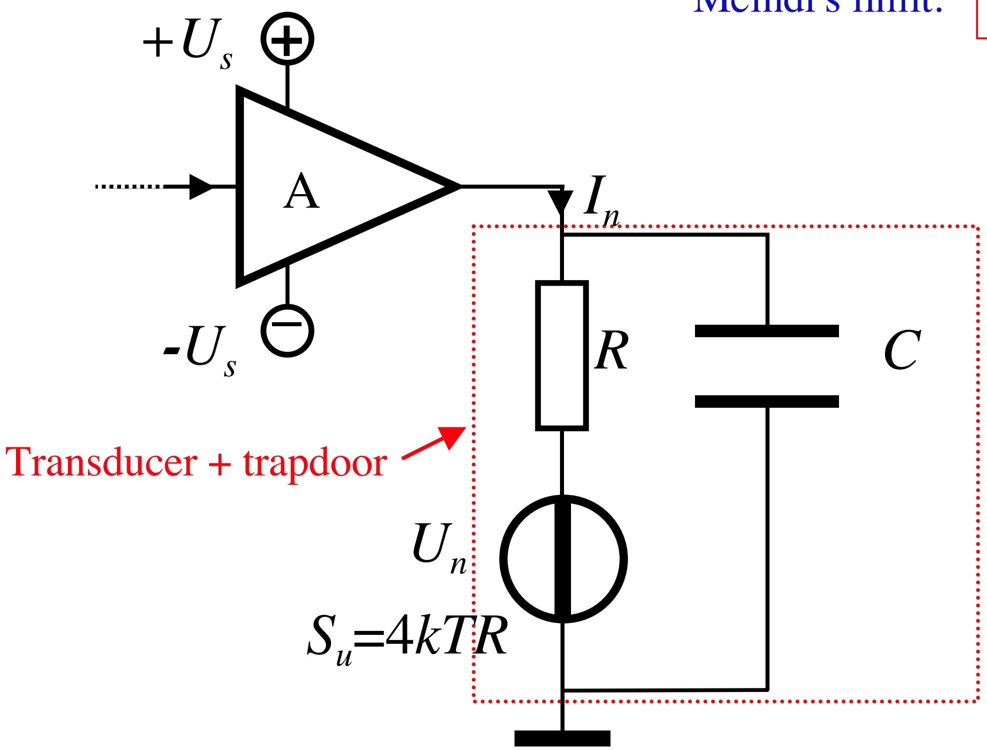


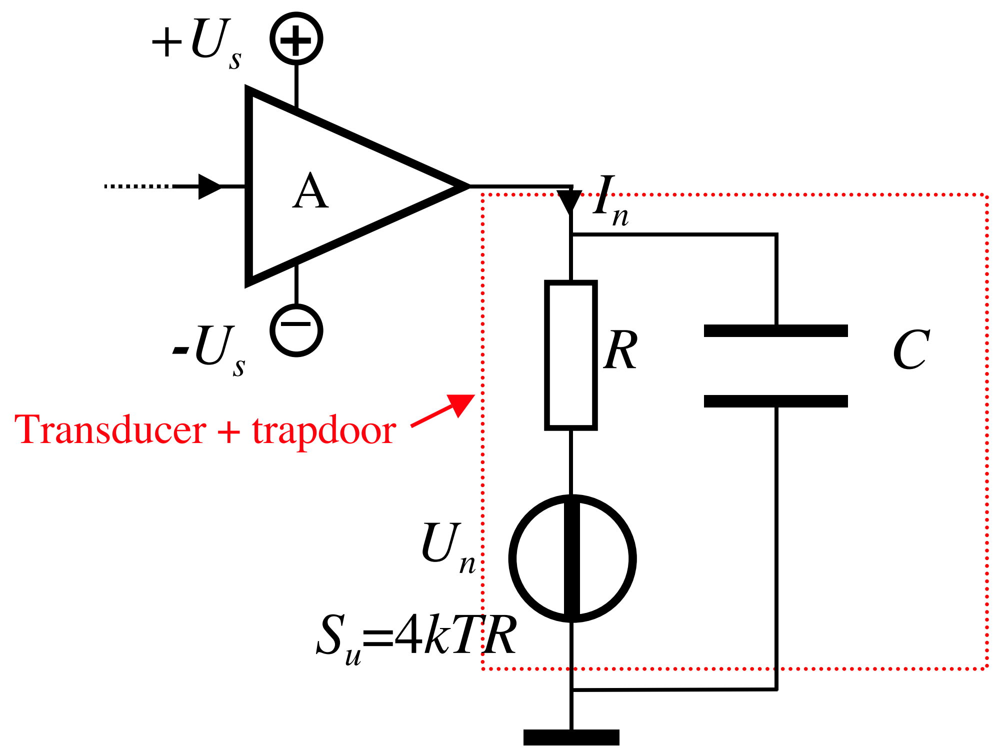
$$\boxed{E_{\min} > 4kT >> 0.7kT}$$

Thus, we are done: the quantized nature of electrical charge guarantees a hard lower limit for the energy dissipation of control by ***electronic amplifiers***.

$$\boxed{E_{\min} > 4kT >> 0.7kT}$$

However, this limit is valid only for control with ***electronic amplifiers*** thus the "Memory-People" can say that the proof is not generally valid. Still, in any case, the claims must add:

If the energy dissipation of controlling the trapdoor and the relocation of the piston are neglected in the analysis of the energy balance of the Szilard-engine, the electronic control of the trapdoor and piston must be explicitly excluded from the considerations!

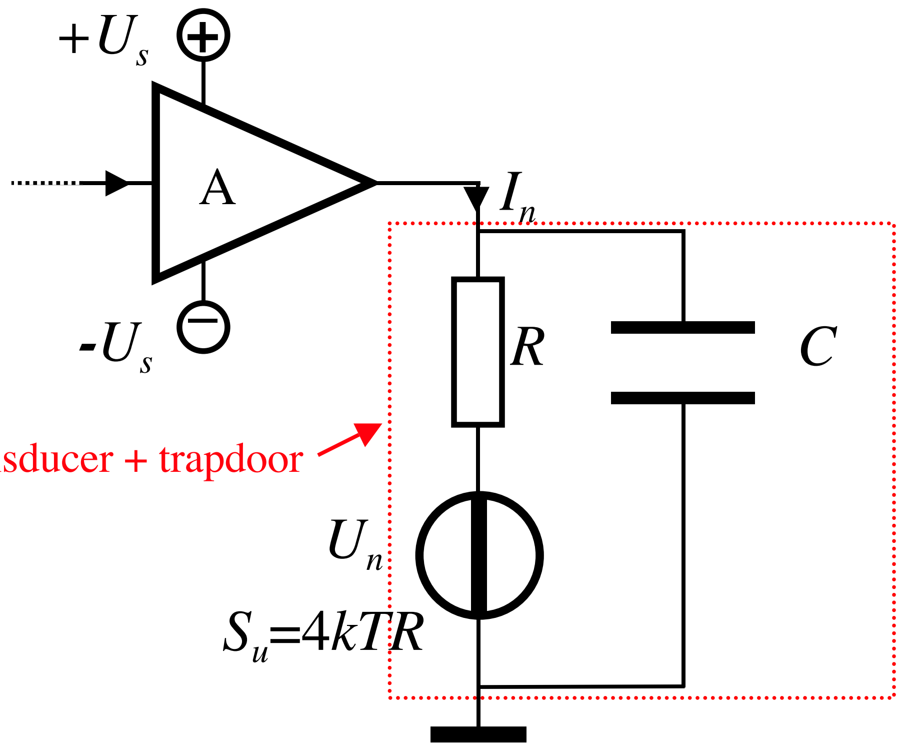


CHALLENGE:

I pay a beer to anybody who shows a non-electronic way to do the active control of the trapdoor and the piston, which can handle thermal fluctuations and does that with less energy dissipation then an electronic system.

First question: what will move the trapdoor? Electromagnetic, piezo, and electrostatic transducers are excluded, of course! (hydraulics is out of question due to its large energy need and low sensitivity).

$$\boxed{E_{\min} > 4kT}$$

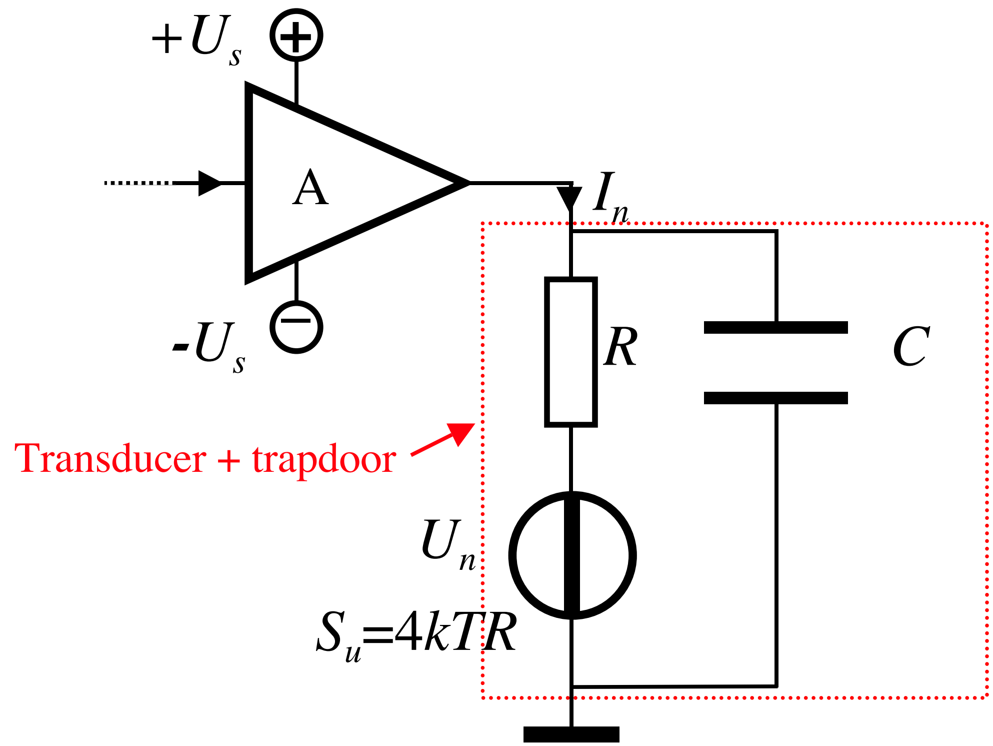


First, we analyze continuum motion (no starting, no stopping) without the ability to gain the energy back

1. If the deterministic voltage is greater than $\boxed{\sqrt{2kT\ln 2/C} \approx 1.4\sqrt{kT/C}}$ the energy price is greater than $kT\ln 2$. Thus the only hope is moving with speeds below thermal velocity $\boxed{U << \sqrt{kT/C}}$!

2. But then the suppression of thermal noise voltage is essential (current generator drive excluded).

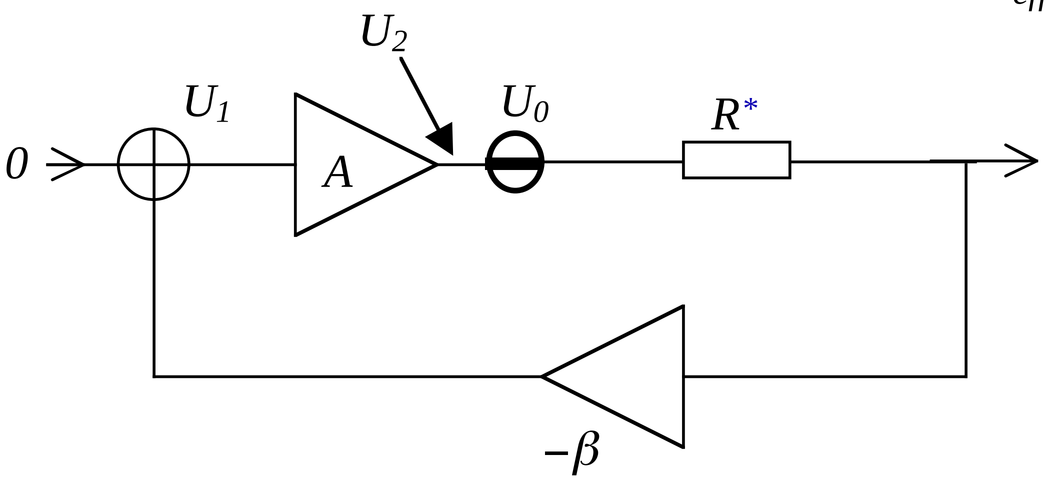
3. Thus on of the essential question is: how large energy does suppressing thermal noise voltage need?

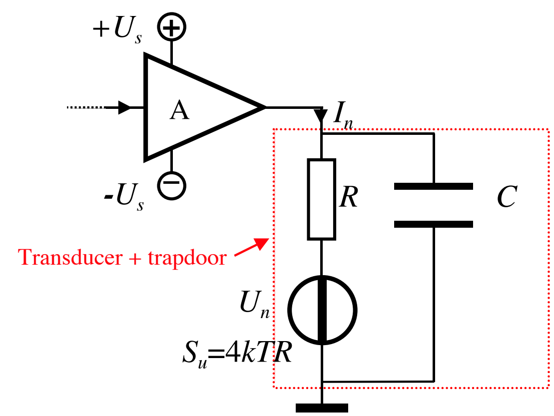


- Can we suppress the thermal motion of the trapdoor (suppress the noise voltage on the RC element representing it)?

- How about the noises in the amplifier? If they get to the output, they will dissipate.

$$A_{eff} = \frac{U_{out}}{U_{in}} = \frac{A}{1 + A\beta}$$





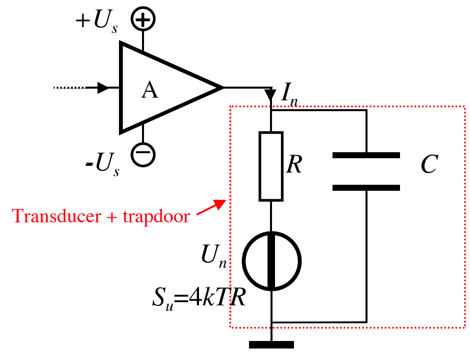
Both U_0 and R^* get multiplied by a factor of $1/(1 + A\beta)$ (reduced).

Thus the thermal noise temperature of R is multiplied by $\sqrt{1/(1 + A\beta)}$ (also reduced).

Thus the theoretical answer is yes: we can suppress thermal noise in an idealistic system. we don't believe we would be able to suppress it below the kT/C limit in a real system, but we do not have a general proof.

Some of the results: the ratio of deterministic and noise-control energy loss is

$$\frac{E_d}{E_{nc}} = 2\sqrt{\frac{E_{kin}}{kT}} \quad \text{where} \quad E_{kin} = Mv_m^2/2$$



The the energy dissipation of noise control is:

$$\boxed{E_{nc} = \frac{\tau_m}{\tau_r}\frac{U_s}{U_n}kT}$$

where τ_m is the time of motion, $\tau_r = RC$ is the energy relaxation time due to friction (the *RC* time constant), U_s is the supply voltage and U_n is the thermal noise voltage on the free-standing *RC* element.

Thus large quality factor $Q = \tau_r / \tau_m$, which means negligible friction loss during the motion,

with sub-thermal motion velocities could work provided the motion is continuous. *Look later for the switching problem that shows why even this approach is invalid.*

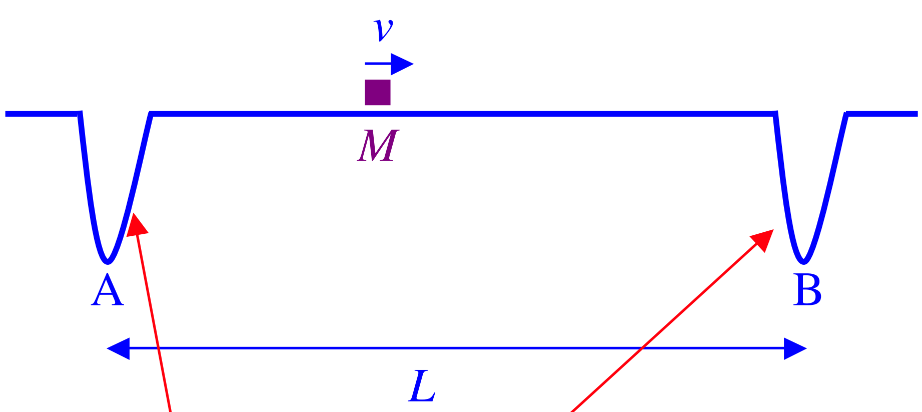
That indicates extreme practical problems but that is not a proof:

1. Long flying time, consequently extraordinary standby energy dissipation in the amplifier.
   Note: even passing a single electron through the amplifier requires more than 4kT energy.

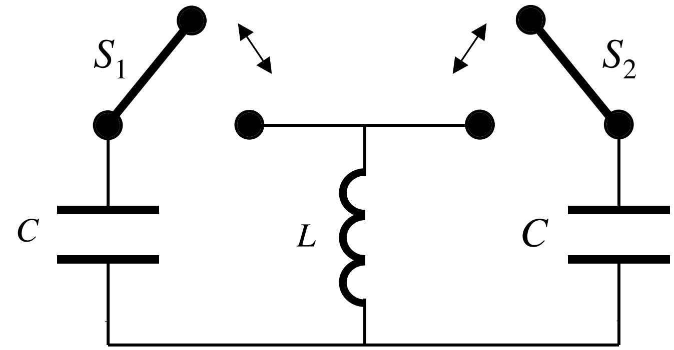
2. How to design the amplifier so that the noise temperature of its output impedance is less than the ambient temperature? Is that possible?

Now, suppose, we have a mechanism to save the kinetic energy and no friction: it can be high-speed motion; thermal noise neglected. Non-active control.

Switching control **with high velocity (non-active control)**



electronic, timed version (avoiding damping)



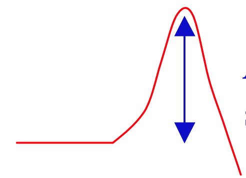
Problems:

1. Dissipation of switch control.

2. Timing is needed: ***Dissipation in the timer unit.*** **This timed system is needed to avoid damping need and the related dissipation in the potential wells.**

Switching control with high velocity (not active control)

Problems: 1. Dissipation of switching with certain error rate. Zero error rate requires infinite power.
This has been done back in 2004.



E potential barrier in switches

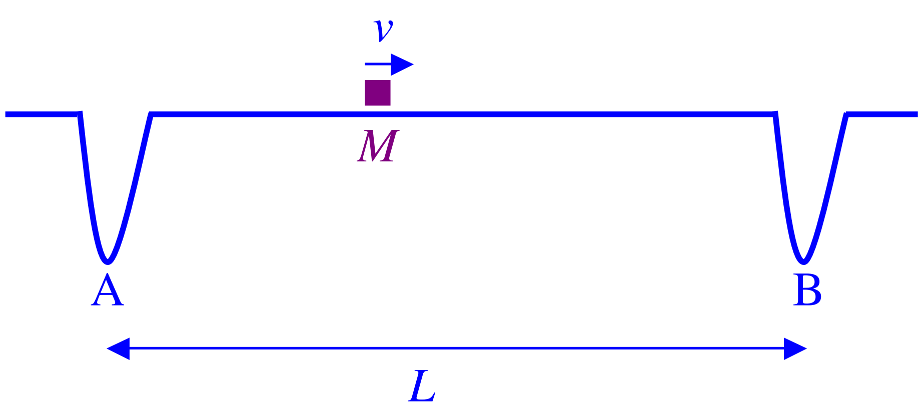
$$\boxed{E_{\min} = kT\ln\left(\frac{2}{\sqrt{3}}\frac{1}{\varepsilon}\right) \approx kT\ln\left(\frac{1}{\varepsilon}\right)}$$

for each switch operation!

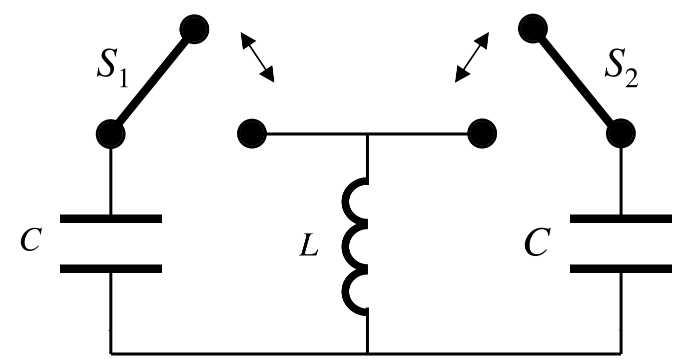
L.B. Kish, "Moore's Law and the Energy Requirement of Computing versus Performance", *IEE Proc. - Circ. Dev. Syst.* **151** (2004) 190-194.

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

For error probability $\boxed{\varepsilon < 0.5}$ **the energy dissipation need to control a switch is greater than the famous result for the Szilard engine:** $\boxed{E_{\min} > kT\ln 2}$



electronic version:

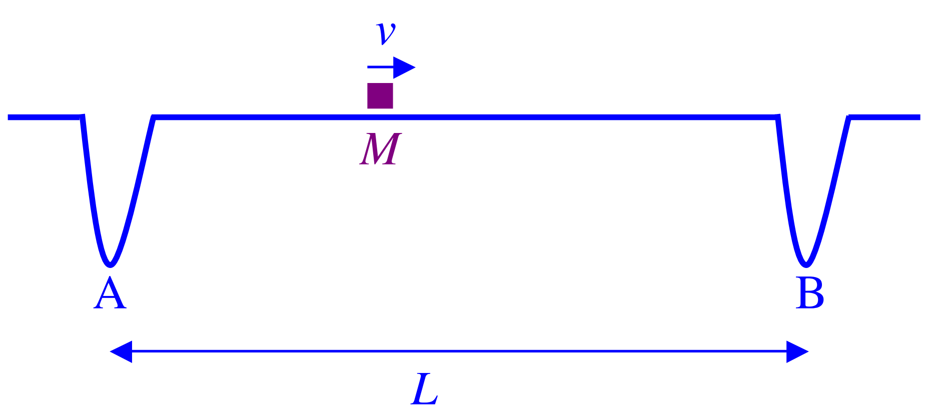


Switching control. Conclusion; at least 2 switches needed for one-way motion with stopping, and at least 3 switches are needed for 2-way motion:

piston: $$\boxed{E_{\min} > 2kT\ln 2}$$

trapdoor: $$\boxed{E_{\min} > 3kT\ln 2}$$

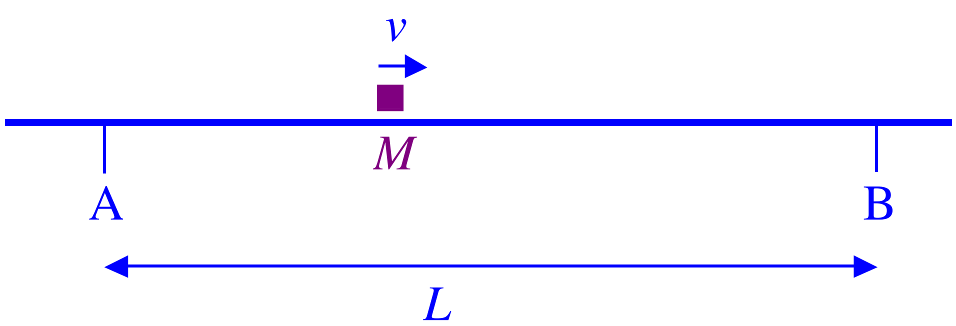
The energy requirement for control during a cycle is greater than the energy the Szilard engine representation of the Maxwell demon would produce. This limit is system independent; holds for any (*even non-electronic*) system where the dominant errors in the switches are thermally activated. If the dominant errors are not thermally activated then the minimal energy requirements is even greater.



Let us return to the low-friction-sub-thermal-velocity case and discuss the need for starting and stopping the motion.

Switching control is needed even for the active control case whenever the status of motion is changed.

Decide and switch when the body should move or stop or, to which direction it should move.



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

This situation kills even the possibility of sub-thermal motion speed with negligible friction as potential solution!

Conclusions:

1. Sub-thermal active velocity control of the objects with negligible friction could be a potential solution to keep the energy dissipation of control below kT*ln(2) however the need of switching the control parameter (to initiate, stop or reverse the motion) **will require many kT energies**. **This result is system-independent**.

2. If we are required to use electronic control (*I am challenging you to show any electronics-free solution of control that works with less energy*) then the absolute minimum of control is passing a single electron through the system and that dissipates beyond $4kT$ due to Meindl's limit for electronic devices.

3. Szilard was unable to fully demystify the "intelligence" part of the Maxwell demon. He kept a small demon in the control part. We hope that this work will contribute to the ultimate exorcism of demons and myths from these system.

Epilogue. First criticisms (have arrived November 10, 2011):

Comment: "*While you neglected the source of dissipation, resolving the Maxwell's demon paradox is very important to consider the demon memory.*"

My response: Mt 23:24 ... you filter out a mosquito but to swallow a camel :-) (Up to the audience to decide if this presentation is the proof for that.)

Comment: "*The Maxwell demon is a paradox only in a closed system. Your system is open*".

My response: Suppose, this demon and its control form a closed system. The amount of energy the demon can extract is less than the control requires for functioning. Thus the demon and the engine will stay dead. Paradox solved.

"We can't solve problems by using the same kind of thinking we used when we created them."
Albert Einstein

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