Operating basic switches toward zero-power computing

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Noise in Physical Systems


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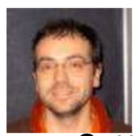
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WISEPOWER

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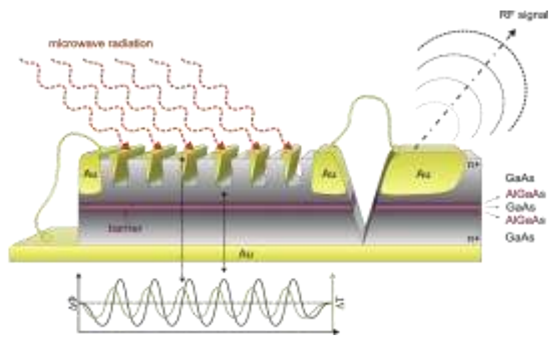
Energy required to operate the portable devices



Autonomous wireless sensors

Energy available from portable sources

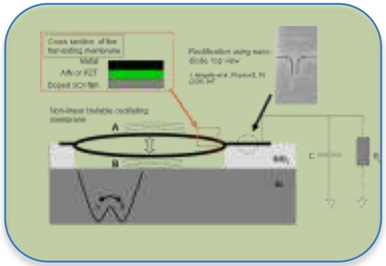
Energy required to operate the portable devices

We need to bridge the gap by acting on both arrows

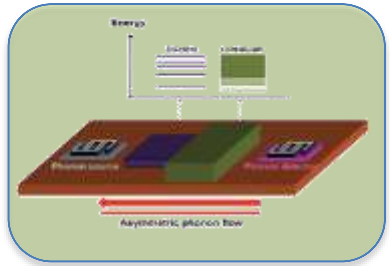
Energy available from portable sources

Energy harvesting NANOPOWER FET Proactive

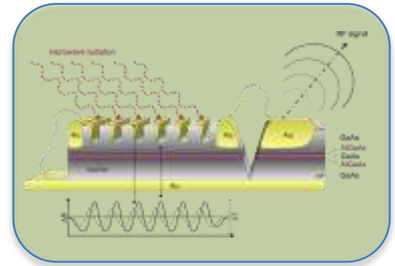
Three classes of potential nanoscale energy harvester devices have been studied.



Nonlinear nano oscillators

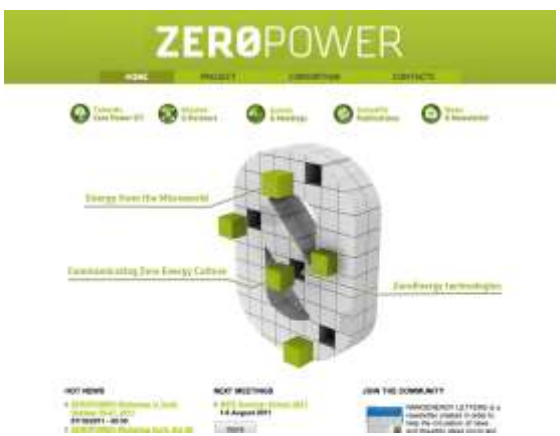


Heat rectification harvester



Quantum harvester

More detail here:
www.zero-power.eu



ZEROPOWER Research Agenda

A research agenda for "ICT-Energy" roadmapping, including strategic objectives, identification of research drivers and measures for assessment.

Energy required to operate the portable devices

Key issue: **energy dissipation at micro and nanoscale**

Why there is some energy dissipation instead of none ?

Key issue: **energy transformation at micro and nanoscale**

Key issue: **energy dissipation at micro and nanoscale**

They both sits on a common scientific ground:

Micro and nano scale energy management

Why there is some energy dissipation instead of none ?

ON A BROADER PERSPECTIVE

The well-known laws of heat and work transformation that lie at the base of the classical thermodynamics are going to **need a rethinking**. The very basic mechanism behind energy dissipation requires a new definition when non-equilibrium processes involving only few degrees of freedom are considered.

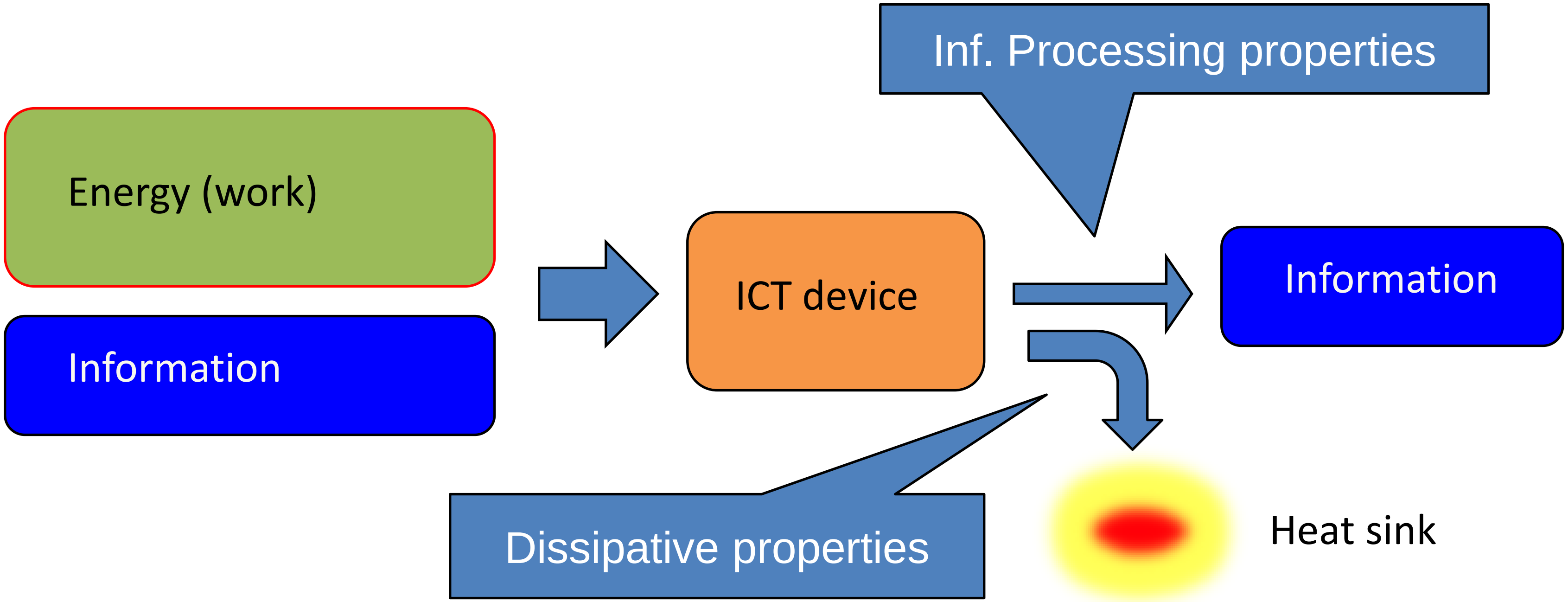
Industrial Revolution XVIII-XIX	ICT Revolution XX-XXI
Heat-Work relations	Fluctuation-Dissipation relations Information is physical !!!

CHALLENGE:

the description of **energy transformation processes at the nanoscale** aimed at unveiling new mechanisms for powering next generations of ICT devices.

A different approach to heat production: an ICT device is a special thermal machine

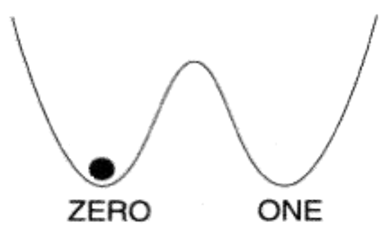
An **ICT device** is a machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

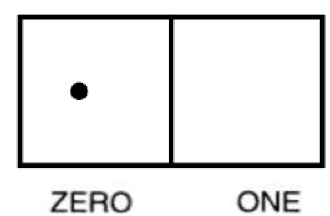


L. Gammaitoni, There's plenty of energy at the bottom, Contemporary Physics, vol. 53, issue 2, pp. 119-135

The Physics of switches

In order to describe the physics of a switch we need to introduce a **dynamical model** capable of capturing the main features of a switch.





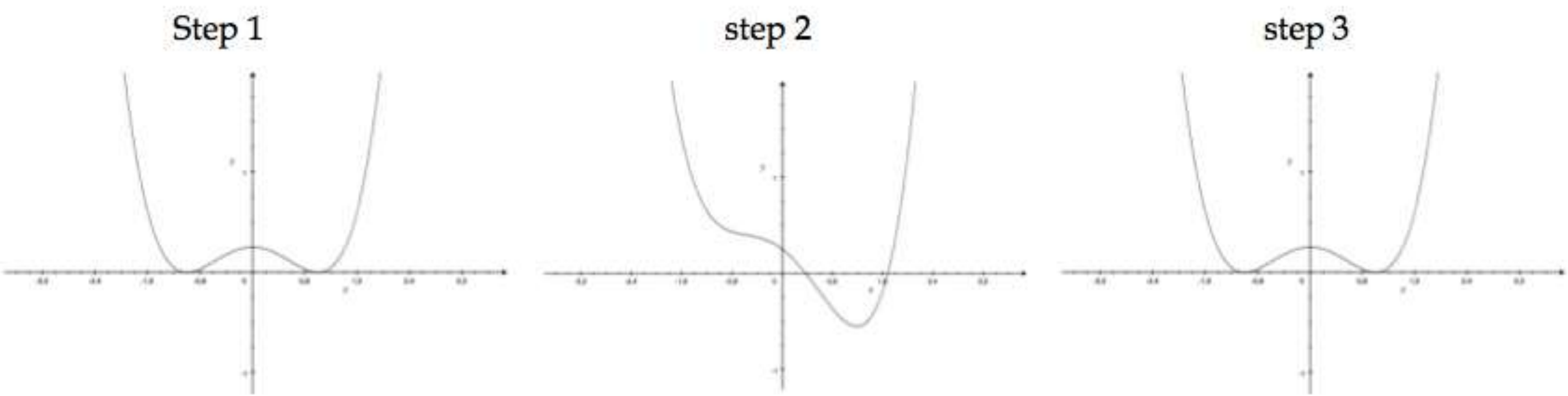
The two states, in order to be dynamically stable, are separated by some energy barrier that should be surpassed in order to perform the switch event.
This situation can be mathematically described by a second order differential equation like:

$$m\ddot{x} = -\frac{d}{dx}U(x) - m\gamma\dot{x} + F$$

The Physics of switches

To produce a switch event we need to apply an external force F capable of bringing the particle from the left well (at rest at the bottom) into the right well (at rest at the bottom). Clearly this can be done in more than one way.

As an example we start discussing what we call the **first procedure**: a three-step procedure based on the application of a large and constant force $F=-F_0$, with $F_0 > 0$



We can ask what is the minimum work that the force F has to perform in order to make the device switch from 0 to 1 (or equivalently from 1 to 0).
The work is computed as:

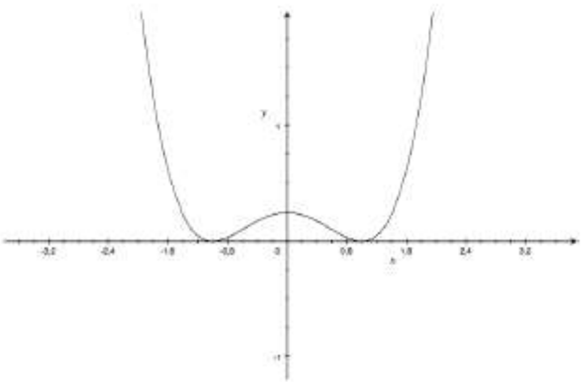
$$L = \int_{x_1}^{x_2} F(x)\,dx \qquad \text{Thus } L = 2F_0$$

The Physics of switches

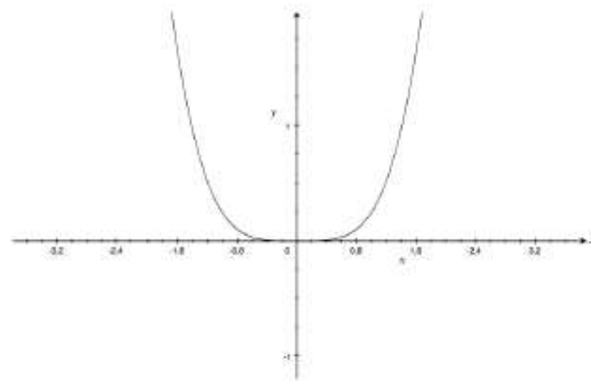
Is this the minimum work?

Let's look at this other procedure (**second procedure**):

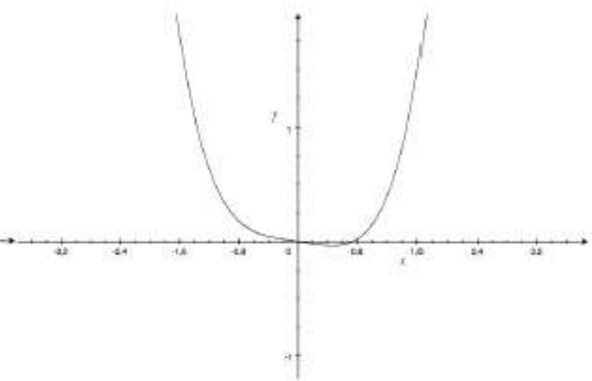
step 1



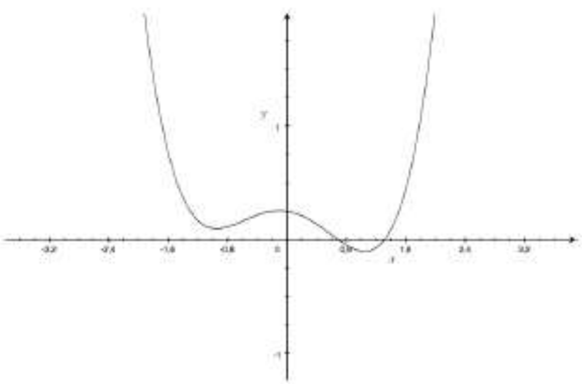
step 2



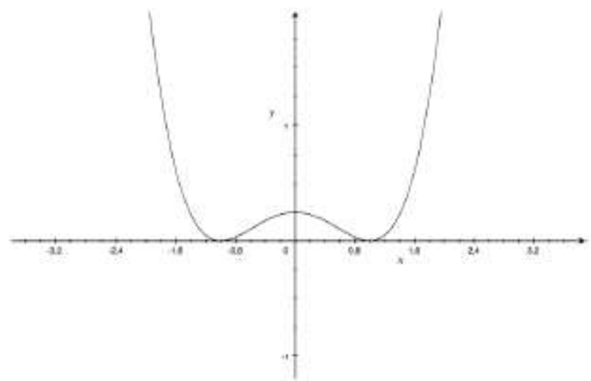
step 3



step 4



step 5



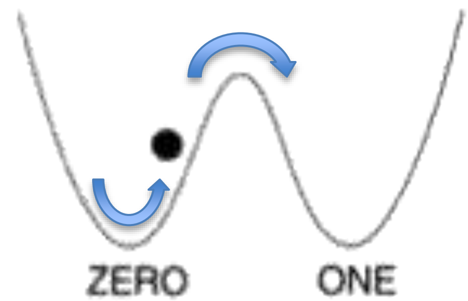
The only work performed happened to be during step 3 where it is readily computed as $L_1 = 2\ F_1$. Now, by the moment that $F_1 \ll F_0$ we have $L_1 \ll L_0$

Remark:

In a real world scenario we need to chose a barrier high enough to prevent accidental switches.

Thus when we switch we need to overcome such a barrier.

The height of the barrier thus sets the minimum energy requirement.



This idea is based on a naïve argument and is biased by the technology employed to build switches: e.g. microelectronics.
In fact in a CMOS based system the switch is realized by charging a capacitor and this is technologically a lossy operation. There is no fundamental reason in this argument.

Let's give a deeper look at the physics of switches and the role of fluctuations.

The Physics of realistic switches

This analysis, although correct, is quite naïve, indeed. The reason is that we have assumed that the work performed, no matter how small, is completely dissipated by the frictional force.

In order to be closer to a reasonable physical model we need to introduce a fluctuating force and thus a Langevin equation:

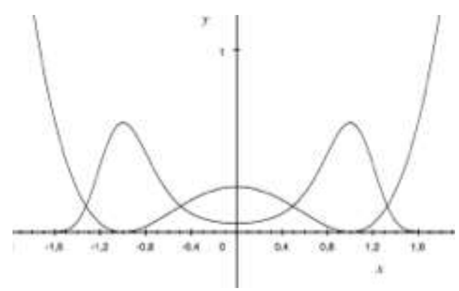
$$m\ddot{x} = -\frac{d}{dx}U(x) - m\gamma\dot{x} + \xi(t) + F$$

The relevant quantity becomes the probability density *P(x,t)* and

$$p_0(t) = \int_{-\infty}^{0} P(x,t)dx \quad and \quad p_1(t) = \int_{0}^{+\infty} P(x,t)dx$$

Represent the probability for our switch to assume “0” or “1” logic states

This calls for a reconsideration of the equilibrium condition



The Physics of realistic switches

In this new physical framework we have to do with exchanges of **both work and heat** (constant temperature transformation approximation).
Thus we have to take into account both the exchanges associate with work and the changes associated with entropy variation.

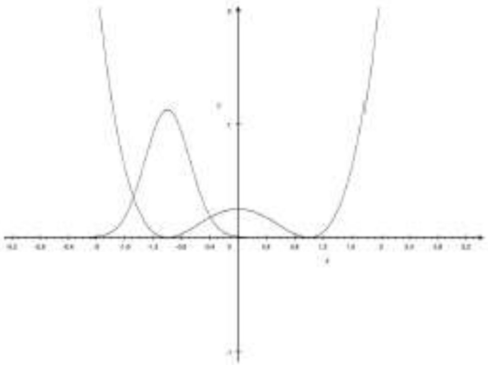
Entropy here is defined according to Gibbs: $$S = -K_B \sum_i p_i \log p_i$$

Based on this new approach let's review the previous procedure:

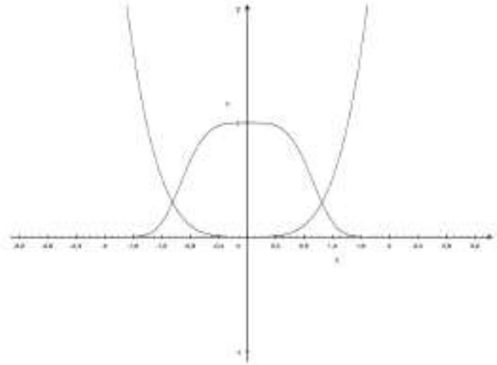
The Physics of realistic switches

Based on this new approach let's review the previous procedure:

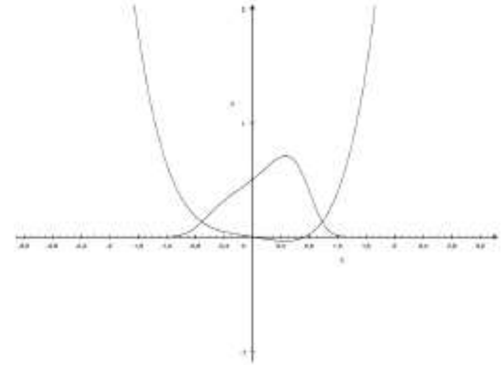
step 1



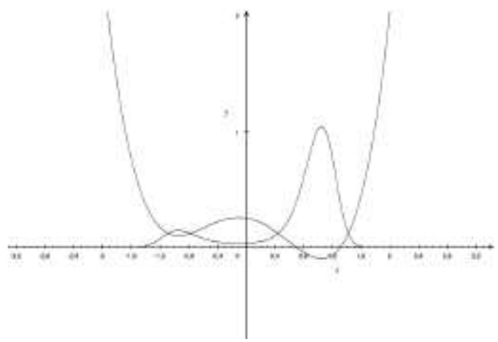
step 2



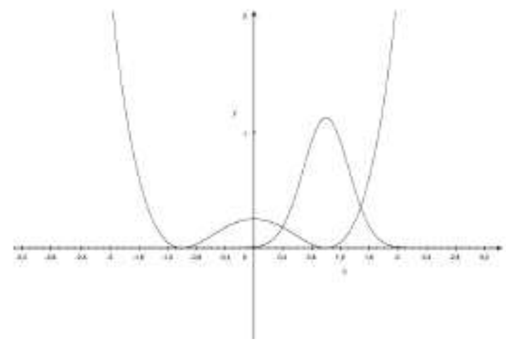
step 3



step 4



step 5



we observe a change in entropy:

$S_1 = S_5 = -K_B \ln 1 = 0 \qquad S_2 = -K_B\,(½ \ln ½ + ½ \ln ½) = K_B \ln 2.$

The Physics of realistic switches

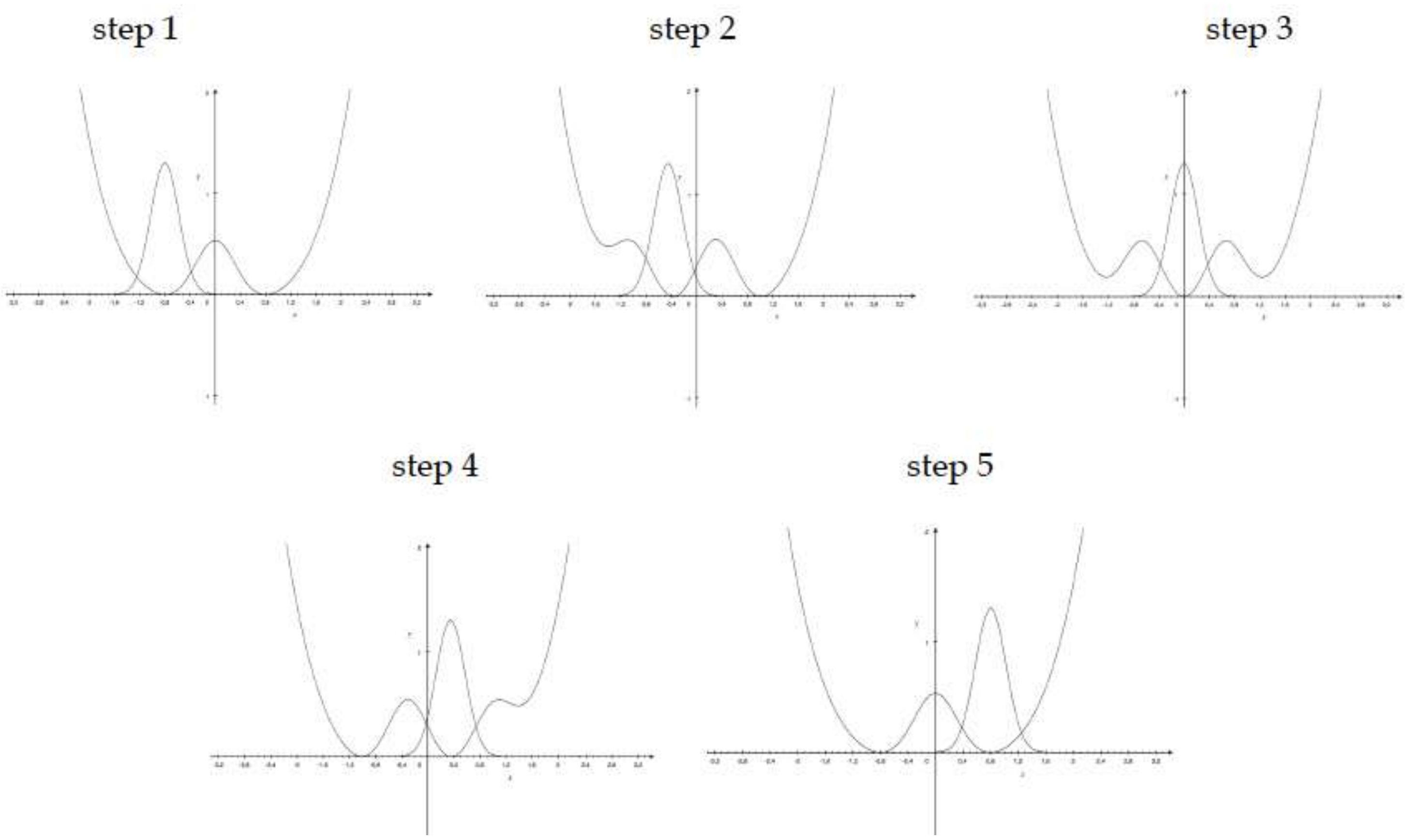
Based on these considerations we can now reformulate conditions required in order to perform the switch by spending zero energy:

1) The total work performed on the system by the external force has to be zero.
2) The switch event has to proceed with a speed arbitrarily small in order to have arbitrarily small losses due to friction.
3) The system entropy never decreases during the switch event.

Is it possible?

The Physics of realistic switches

Yes… at least in principle…



Experiments in progress…

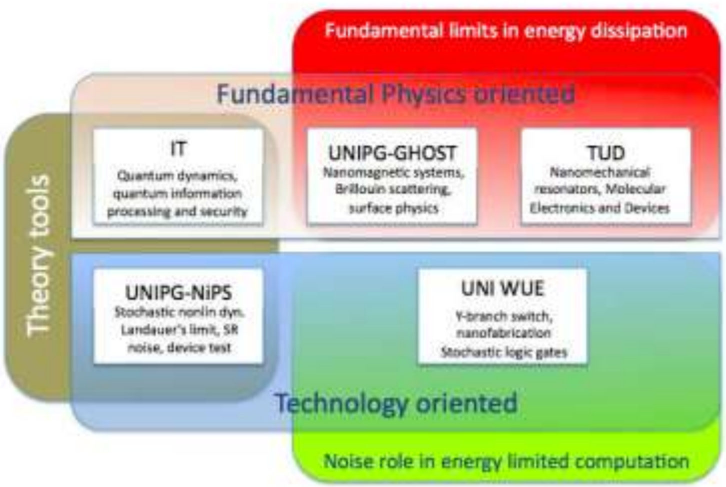
The MINECC initiative

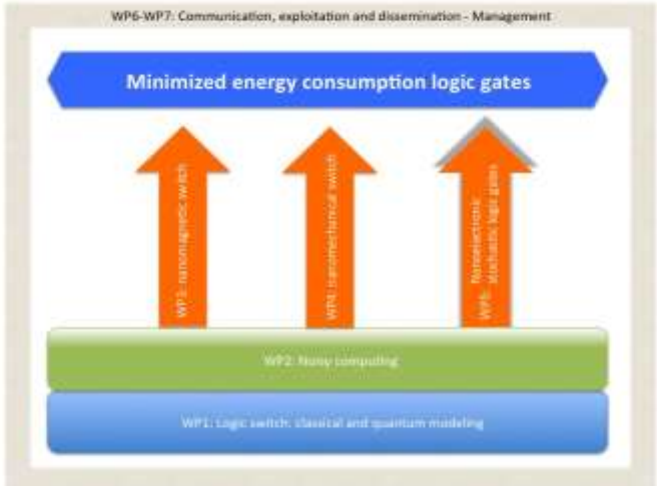
Minimizing Energy Consumption of Computing to the limit - FET Proactive

LANDAUER

Operating ICT basic switches below the Landauer limit

- UNIVERSITA DEGLI STUDI DI PERUGIA, ITALY (UNIPG-NiPS, UNIPG-Ghost)
- JULIUS-MAXIMILIANS UNIVERSITAET WUERZBURG, GERMANY
- INSTITUTO DE TELECOMUNICACOES, PORTUGAL
- TECHNISCHE UNIVERSITEIT DELFT, NETHERLANDS

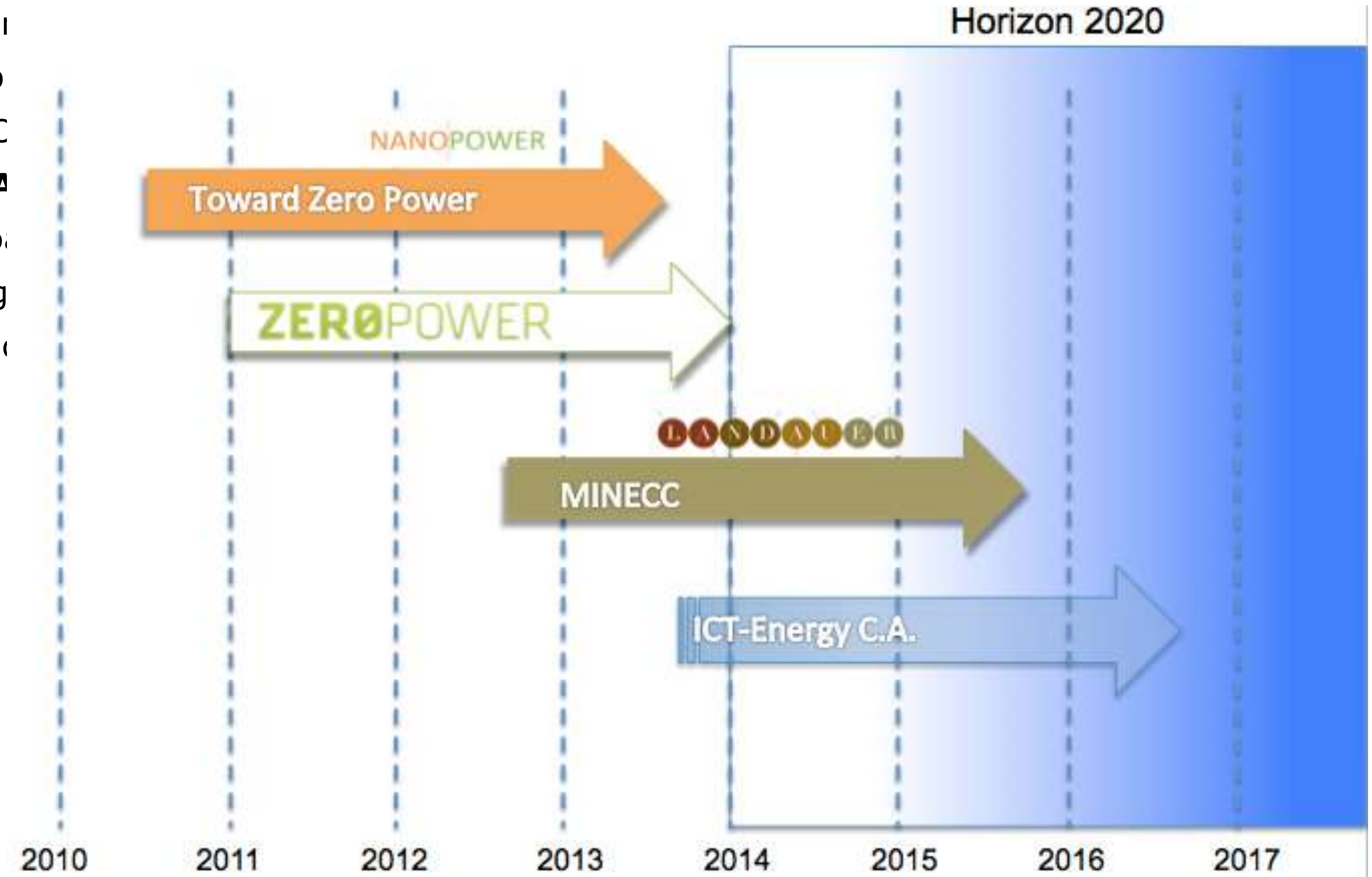




More info available at www.landauer-project.eu

This is part of an ongoing effort at European level within the FET scheme

- Jan 2008, Expert Consult. on "Molecular-scale Information Systems"
- July 2009, **FP7 CALL 5**, ICT-2009-5 - ICT 2009.8.6 Towards Zero-Power ICT
- Feb 2010, Expert Coı
- Aug.1st 2010 three p
- Jan 1st 2011 ZEROPC
- 26 July 2011 **FP7 CA**
- 12 Oct 2011 FET Pro
- 1 Sept 2012 Starting
- 1 Oct 2013 Starting



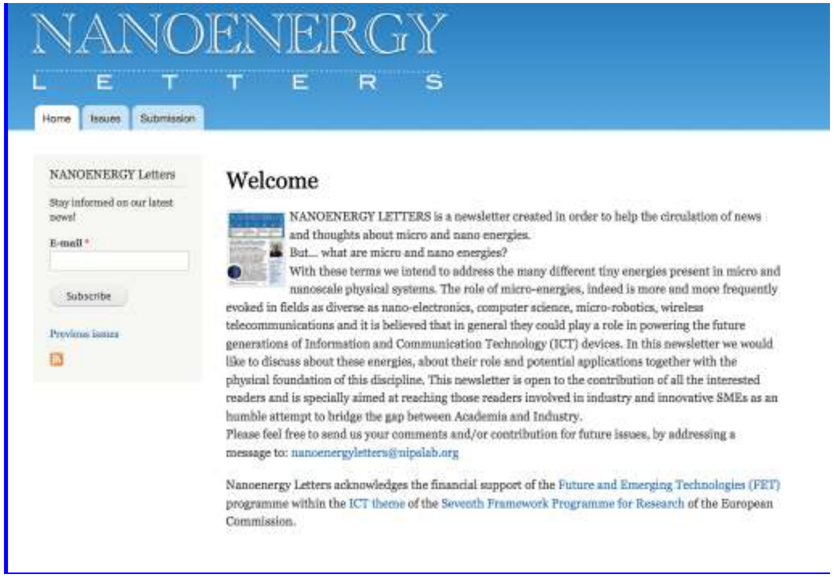
ICT-Energy consortium/community

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Università di Perugia	UNIPG	IT
2	Roskilde University	RUC	DK
3	Karlsruher Institut fuer Technologie	KIT	DE
4	Barcelona Supercomputing Center	BSC	SP
5	Ecole Polytechnique Federale de Lausanne	EPFL	CH
6	Aalborg University - Denmark	AAU	DK
7	Hitachi Europe Limited	HCL	UK
8	University of Bristol	UNIVBRIS	UK
9	University of Glasgow	UGLA	UK
10	University College Cork, National University of Ireland	TNI-UCC	IR

NANOENERGY LETTERS

A new devoted web site has been realized and opened at www.nanoenergyletters.eu.

In the last two issues we have started a special session devoted to the publication of original scientific papers. Instruction for submission procedure is available at:
http://www.nanoenergyletters.eu/submission



issue N. 4 (Jul. 2012)

issue N.5 (Jan. 2013)

NANOENERGY2013

www.nanoenergy2013.eu

International Conference July 10-13, 2013 – Perugia (IT)

The first International Conference on Nanoenergy will be held in Perugia, Italy during July 10-13 2013.

Important dates

- **Paper Submission** - April 1, 2013
- **Notification of Acceptance** - April 15, 2013
- **Early Registration** - May 1, 2013
- **Final registration** - June 1 2013
- **Conference Dates** - July 10-13 2013

Latest News

Submission procedure now open

NiPS Laboratory Noise in Physical Systems

www.nanoenergy2013.eu

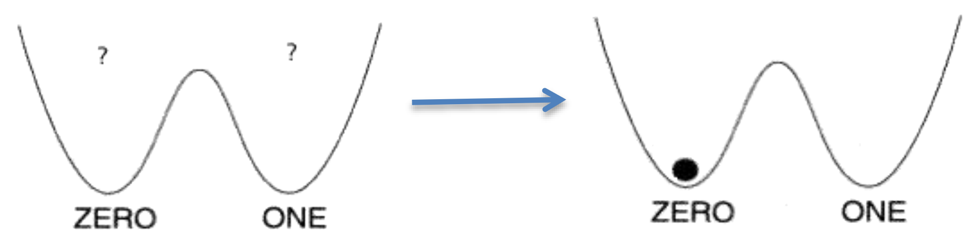
Proceedings freely available at www.nanoenergyletters.eu, issue N.6 (Aug. 2013)

THE LANDAUER LIMIT

The Landauer's principle* states that erasing one bit of information (like in a resetting operation) comes unavoidably with a decrease in physical entropy and thus is accompanied by a minimal dissipation of energy equal to

$$Q = k_B T \ln 2$$

More technically this is the result of a change in entropy due to a change from a random state to a defined state:



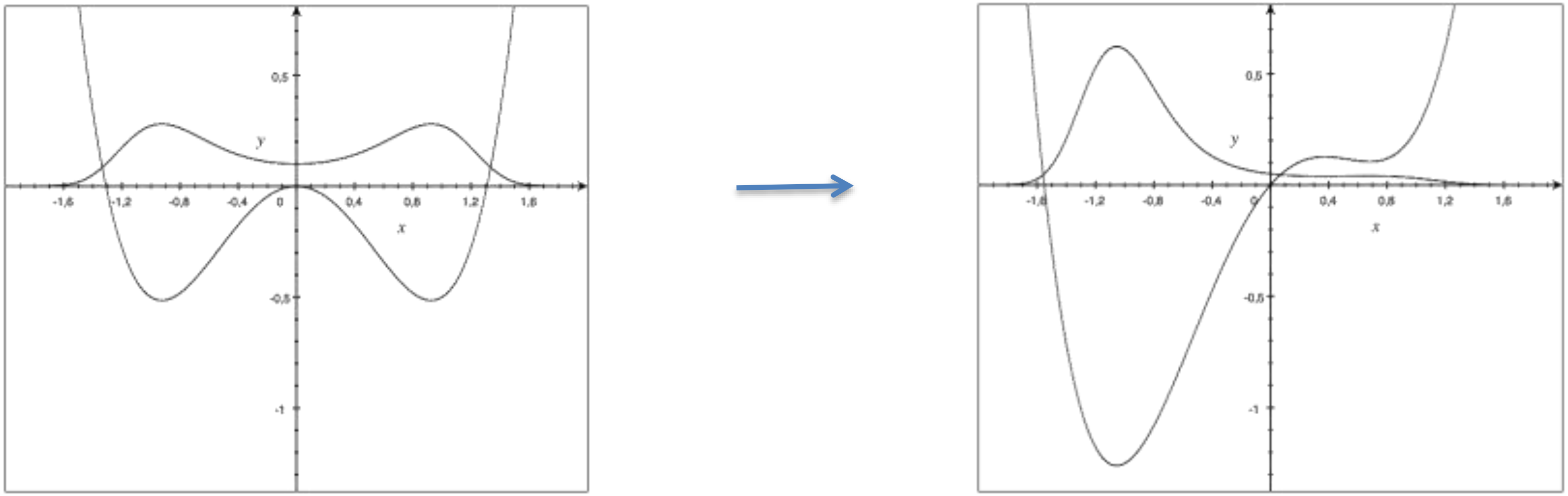
Number of possible config. 2 Number of possible config. 1

Any logically irreversible operation (information=entropy decreases) comes with a cost.

* R. Landauer, "Dissipation and Heat Generation in the Computing Process" *IBM J. Research and Develop. 5,* 183-191 (1961)

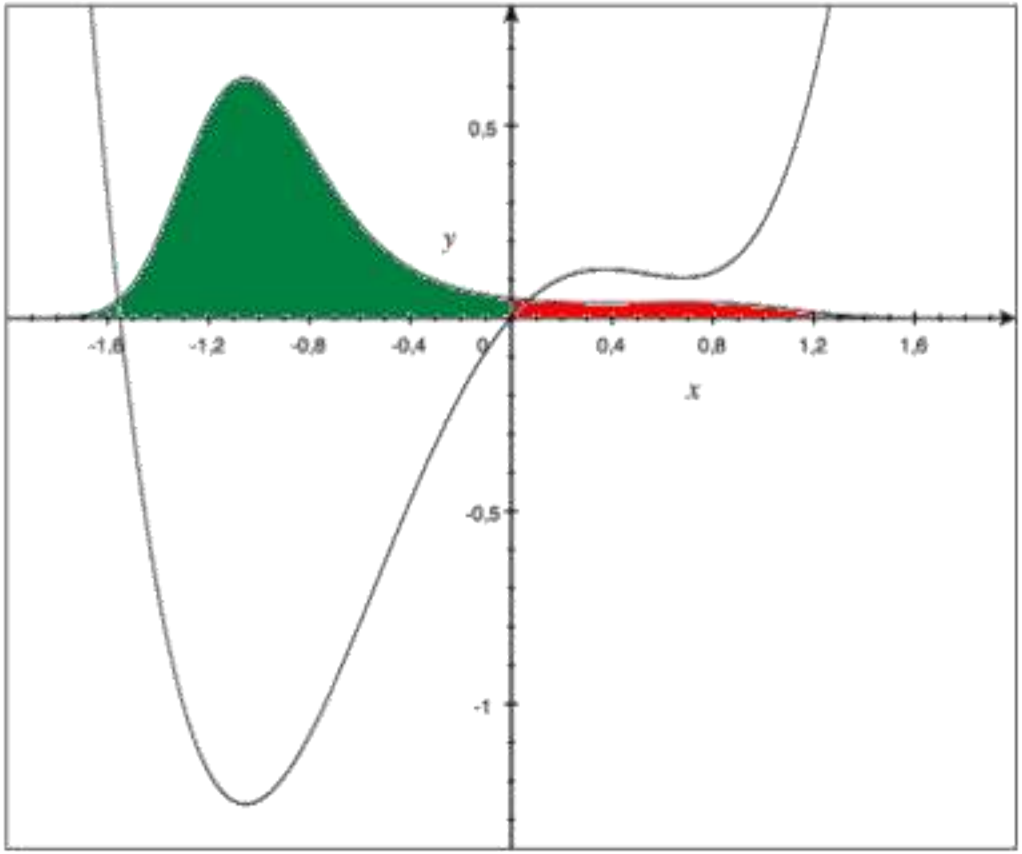
Remarks on the Landauer principle

Let's consider a resetting operation:



Probabilities

In a real world switch there is a finite probability that the reset operation generate errors

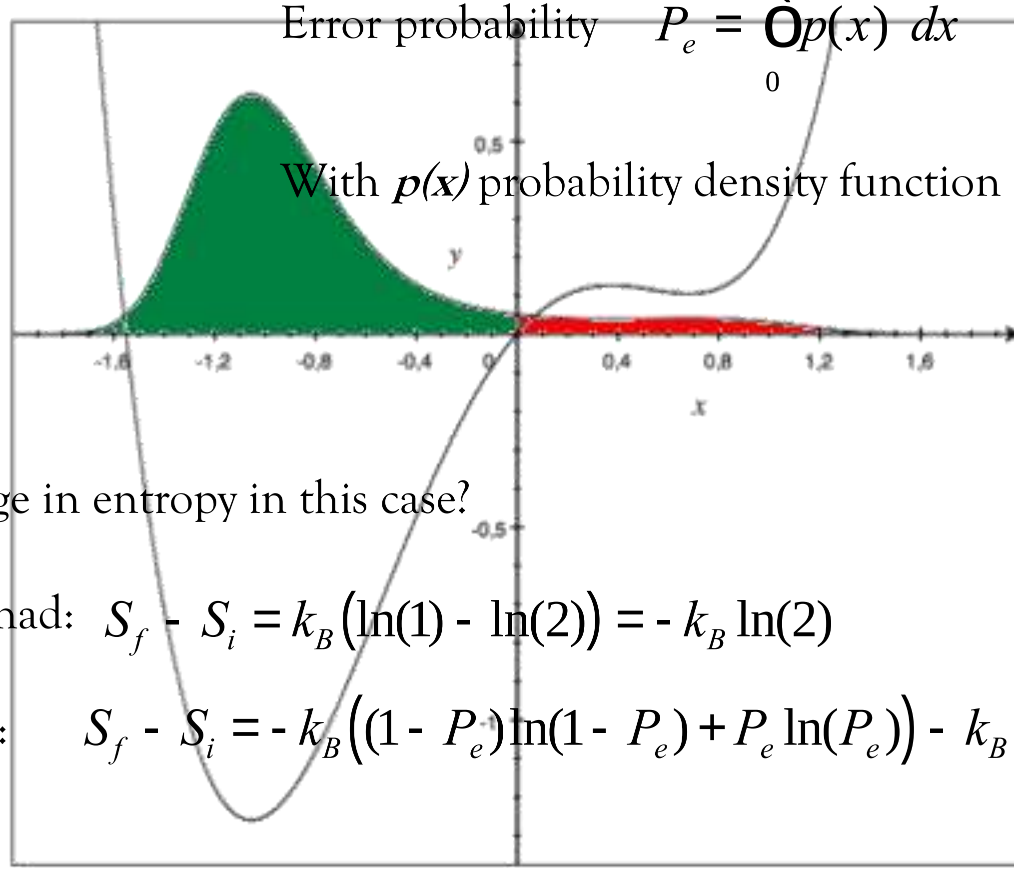


Probabilities

In a real world switch there is a finite probability that the reset operation generate errors

Error probability $P_e = \int_0^{\infty} p(x)\, dx$

With ***p(x)*** probability density function

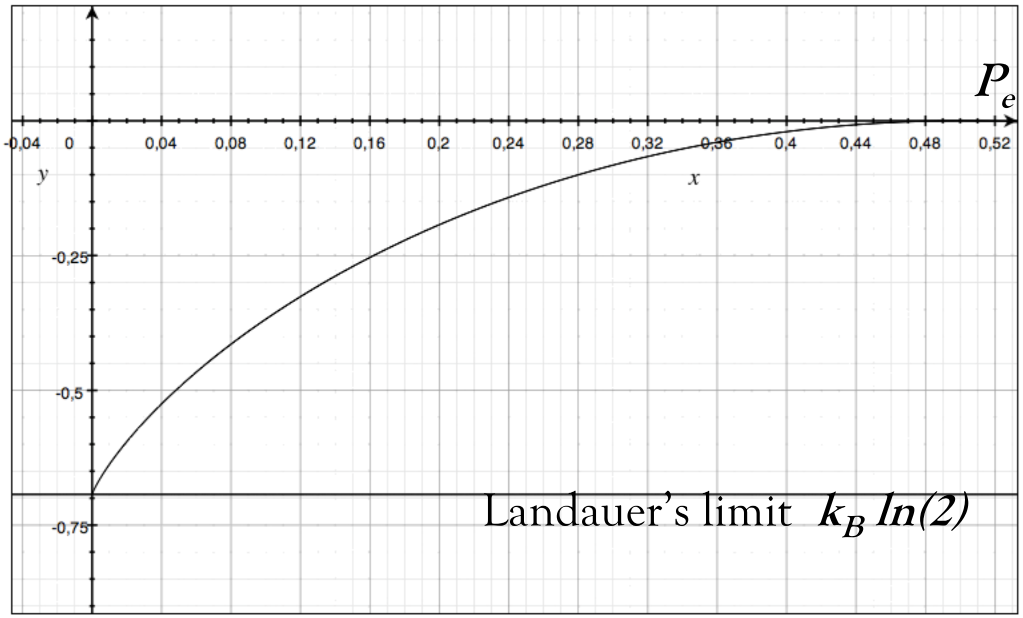


What is it the change in entropy in this case?

With Landauer we had: $S_f - S_i = k_B\left(\ln(1) - \ln(2)\right) = -k_B \ln(2)$

In this case we have: $S_f - S_i = -k_B\left((1-P_e)\ln(1-P_e) + P_e \ln(P_e)\right) - k_B \ln(2)$

- Entropy difference as a function of $\boldsymbol{P_e}$



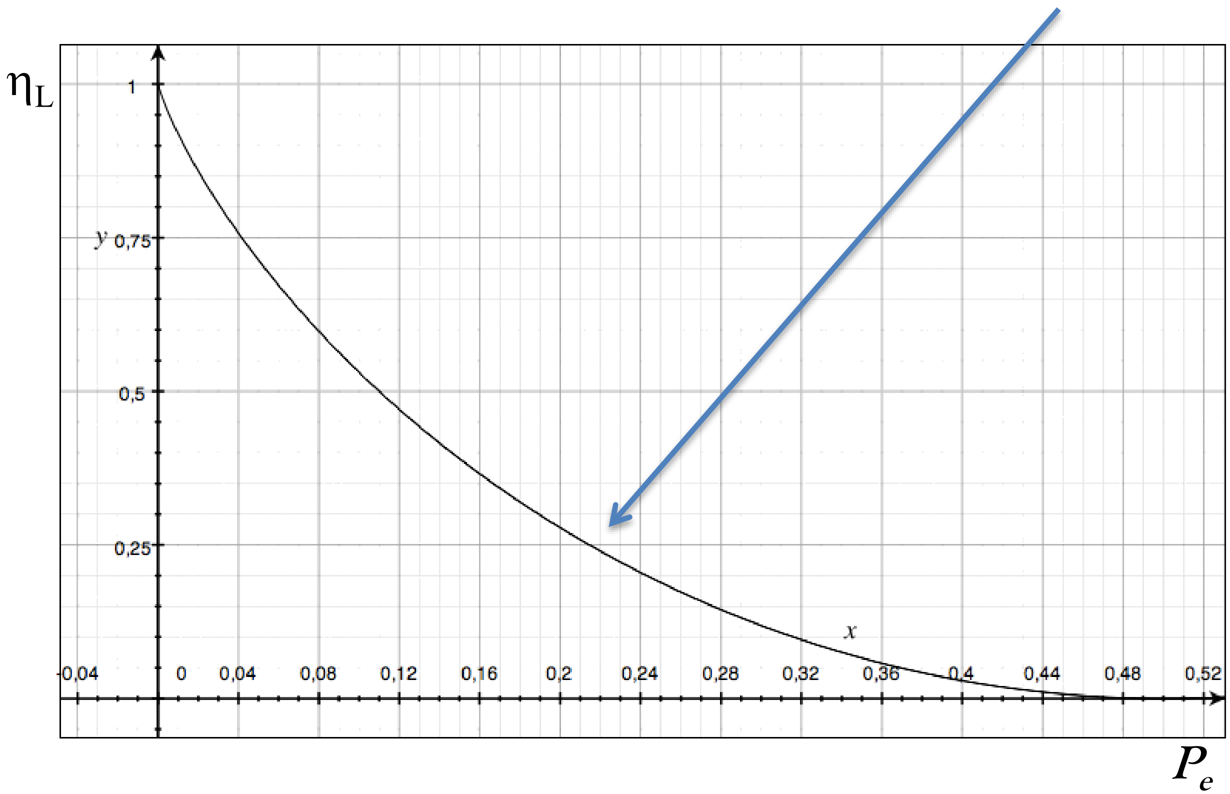
The more increases the probability of error
The more decreases the entropy difference
…and thus the dissipated energy.

When the probability of error is zero we recover the Landauer's limit.

Minimum energy ratio for reset operation*

$$h_L(P_e) = \frac{Q(P_e)}{Q} = 1 + \frac{(1-P_e)\ln(1-P_e) + P_e\ln(P_e)}{\ln(2)}$$

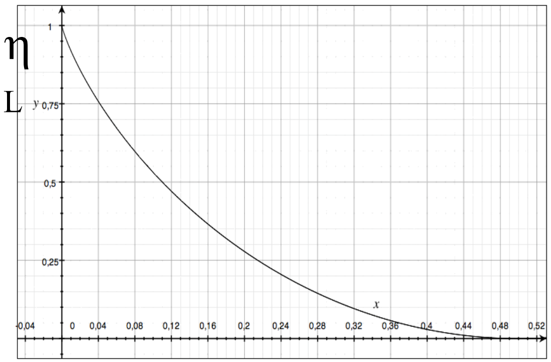
With 20% probability of error
The minimum energy is about ¼ of Landauer's limit.



- L. Gammaitoni, *Beating the Landauer's limit by trading energy with uncertainity*, 2011, arXiv:1111.2937
- L. Gammaitoni, Nanoenergy Letters, 5, 2013.

Minimum energy ratio for reset operation*

η_L



P_e

In general it is possible to build a resetting procedure that accepts a significant resetting error in exchange for Some energy savings…

This opens up to a renewal of interest for computation in the presence of large fluctuations*.

- *von Neumann, J. (1963). "Probabilistic logics and the synthesis of reliable organisms from unreliable components". The Collected Works of John von Neumann. Macmillan..