Operating basic switches in the presence of large fluctuations: minimal energy considerations

Luca Gammaitoni

NiPS Laboratory, Università di Perugia, Italy

Researchers

Luca Gammaitoni

Helios Vocca, Ric. Univ.

Flavio Travasso, Assegnista

Francesco Orfei,
Dottorando/Assegnista

Igor Neri,
Dottorando/Assegnista

Francesco Cottone
RTD

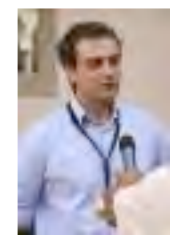
Maurizio Mattarelli
RTD

Marzia Colombini,
Post-doc/Assegnista

Staff

Silvia Lombardi, Project Manager

Valbona Ramci, segretaria



Leonardo Alfonsi
Media manager

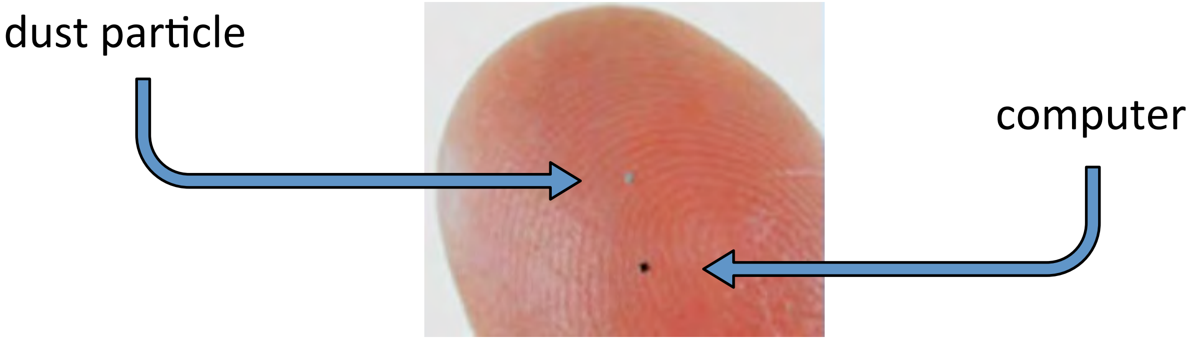
+ students + tecnicians

Presently:
- 2 laureande triennali
- 3 laureandi magistrali

Long time announced promised land

The land of portable electronics

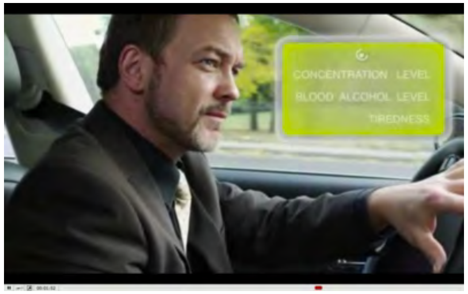
The promised land



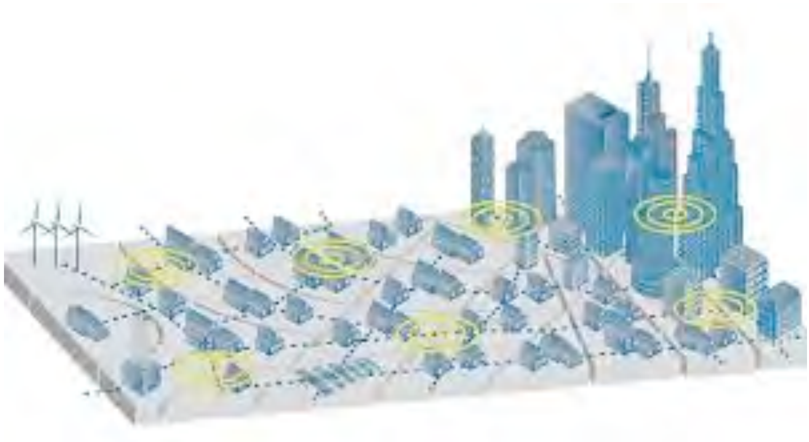
The land where computers are as small as dust particles

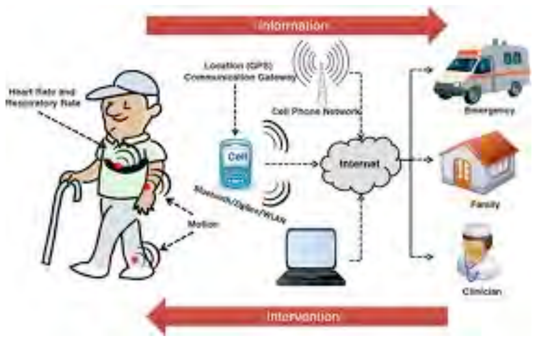
and more powerful than the human brain

The promised land



This is the land of wireless micro-sensors that continuously and ubiquitously measure, process and transmit data to improve our living.





This is the long-time announced revolution where the cities become smart and the human and animal health is monitored and controlled.

The promised land

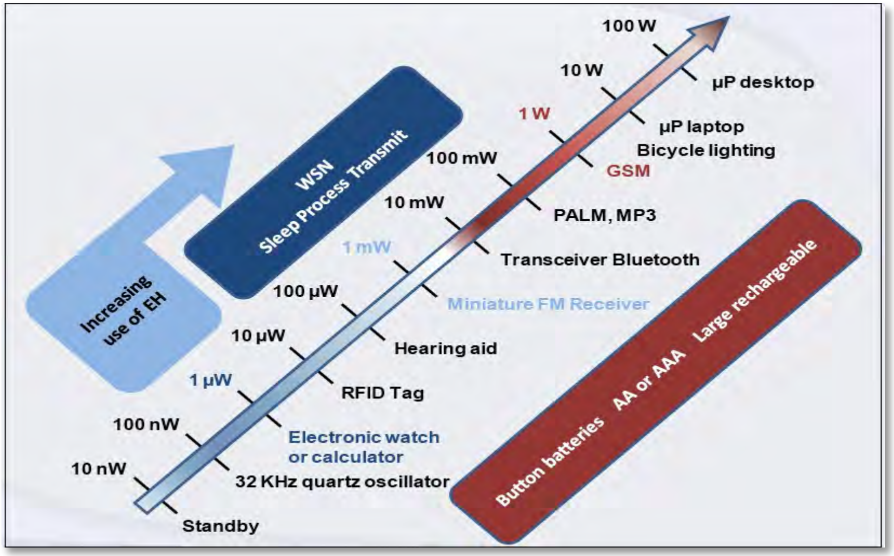
Why are we not there yet?

The promised land

Because, as in any promised land,…. There is a desert to cross

In our case the desert is the distance between the energy required and the energy available to power the portable electronics

Energy required to operate the portable devices



Energy available from portable sources

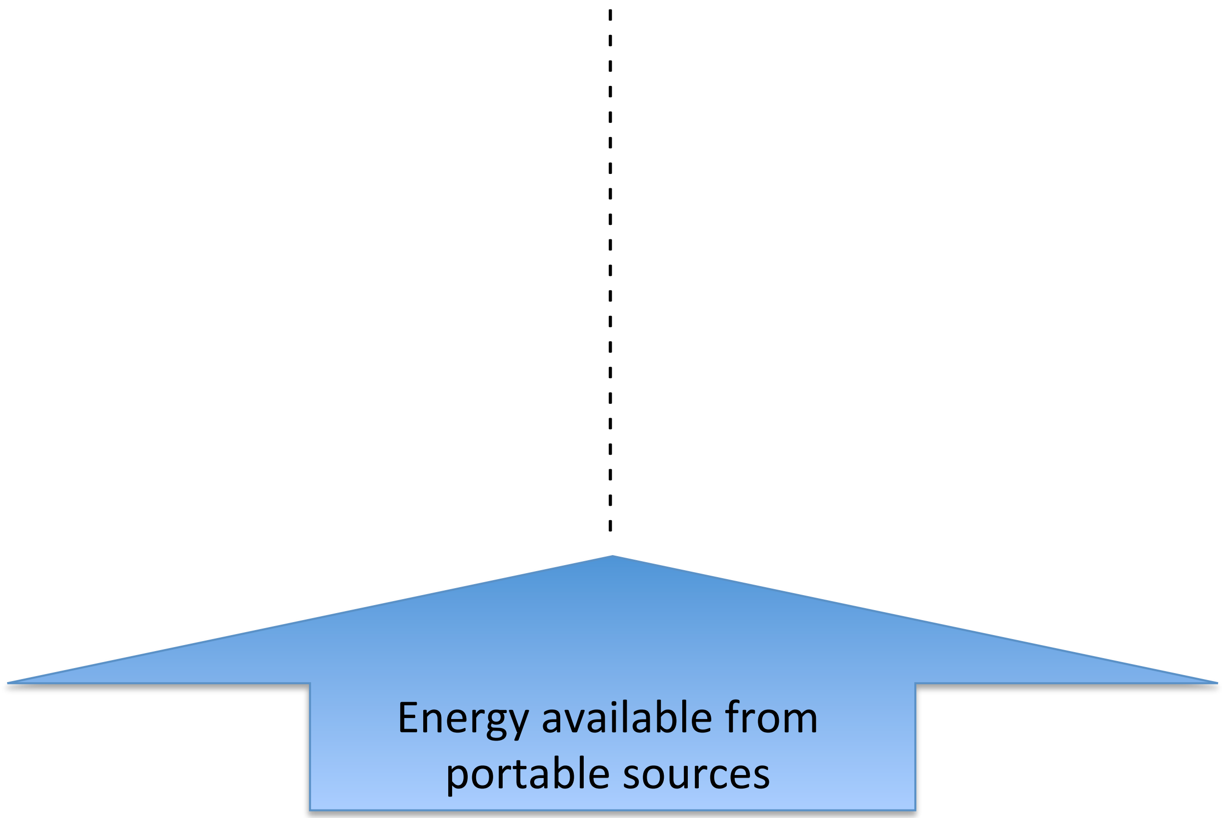
Source: *IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009. EH: Energy Harvesting; WSN: Wireless Sensors Network*

Energy required to operate the portable devices

We need to bridge the gap by acting on both arrows

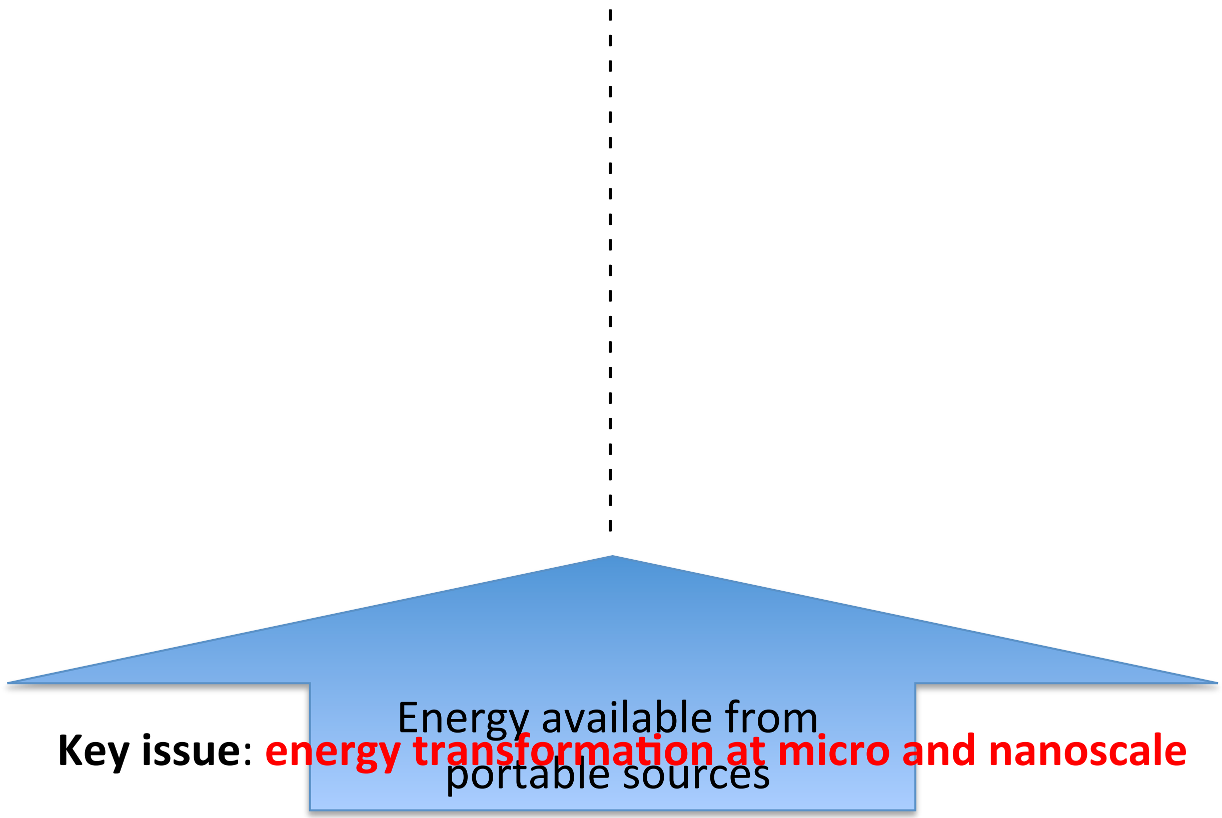
Energy available from portable sources

The bottom arrow:
Energy harvesting



Open questions:

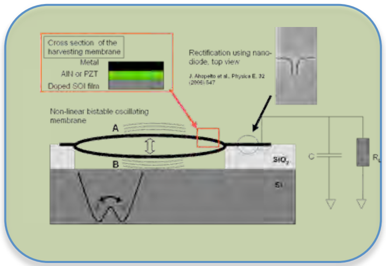
- What is the best technology for energy harvesting ?
- How can we improve efficiency in energy transformation ?
- How do the system scale when we go to micro and nano scale ?
- …



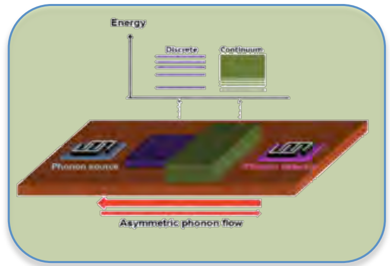
Key issue: **energy transformation at micro and nanoscale**

Energy harvesting NANOPOWER FET Proactive

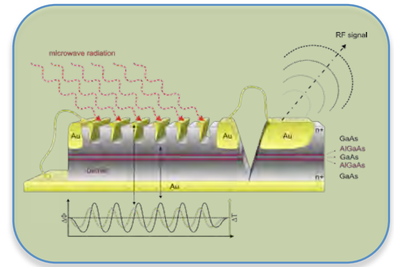
Three classes of potential nanoscale energy harvester devices have been studied.



Nonlinear nano oscillators



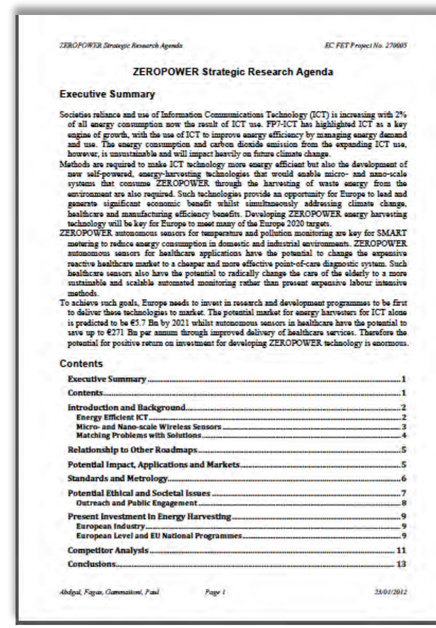
Heat rectification harvester



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.



ZEROPOWER Strategic Research Agenda — EC FET Project No. 270005

ZEROPOWER Strategic Research Agenda

Executive Summary

Societies reliance and use of Information Communications Technology (ICT) is increasing with 2% of all energy consumption now the result of ICT use. FP7-ICT has highlighted ICT as a key engine of growth, with the use of ICT to improve energy efficiency by managing energy demand and use. The energy consumption and carbon dioxide emission from the expanding ICT use, however, is unsustainable and will impact heavily on future climate change.

Methods are required to make ICT technology more energy efficient but also the development of new self-powered, energy-harvesting technologies that would enable micro- and nano-scale systems that consume ZEROPOWER through the harvesting of waste energy from the environment are also required. Such technologies provide an opportunity for Europe to lead and generate significant economic benefit whilst simultaneously addressing climate change, healthcare and manufacturing efficiency benefits. Developing ZEROPOWER energy harvesting technology will be key for Europe to meet many of the Europe 2020 targets.

ZEROPOWER autonomous sensors for temperature and pollution monitoring are key for SMART metering to reduce energy consumption in domestic and industrial environments. ZEROPOWER autonomous sensors for healthcare applications have the potential to change the expensive reactive healthcare market to a cheaper and more effective point-of-care diagnostic system. Such healthcare sensors also have the potential to radically change the care of the elderly to a more sustainable and scalable automated monitoring rather than present expensive labour intensive methods.

To achieve such goals, Europe needs to invest in research and development programmes to be first to deliver these technologies to market. The potential market for energy harvesters for ICT alone is predicted to be €5.7 Bn by 2021 whilst autonomous sensors in healthcare have the potential to save up to €271 Bn per annum through improved delivery of healthcare services. Therefore the potential for positive return on investment for developing ZEROPOWER technology is enormous.

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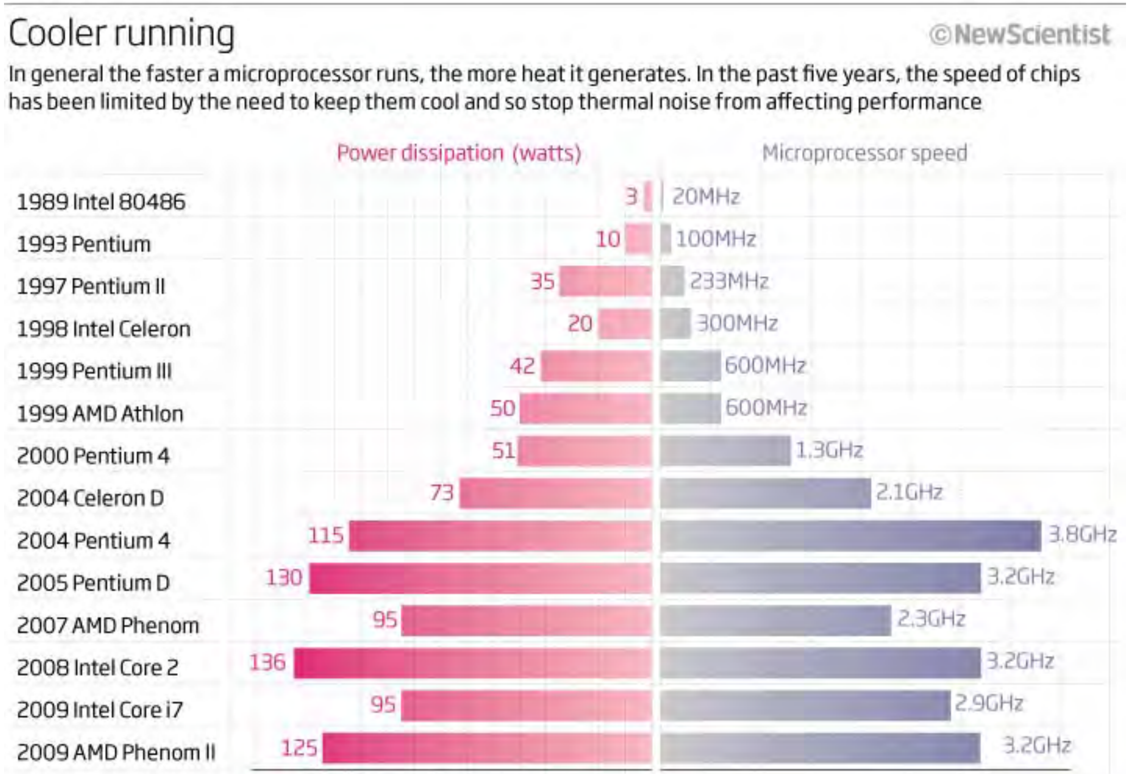
Abdgal, Fagas, Gammaitoni, Paul — Page 1 — 23/01/2012

Energy required to
operate the portable
devices

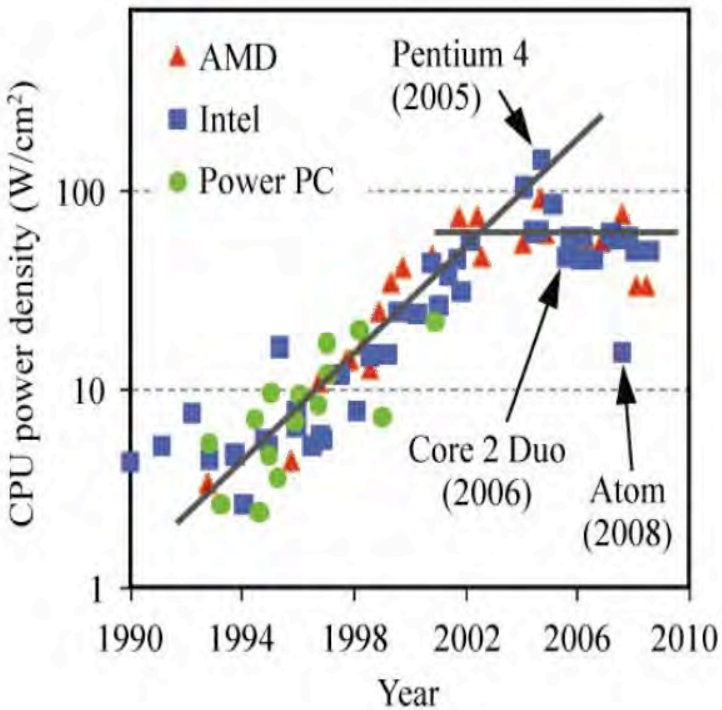
The problem with ENERGY EFFICIENCY in present ICT

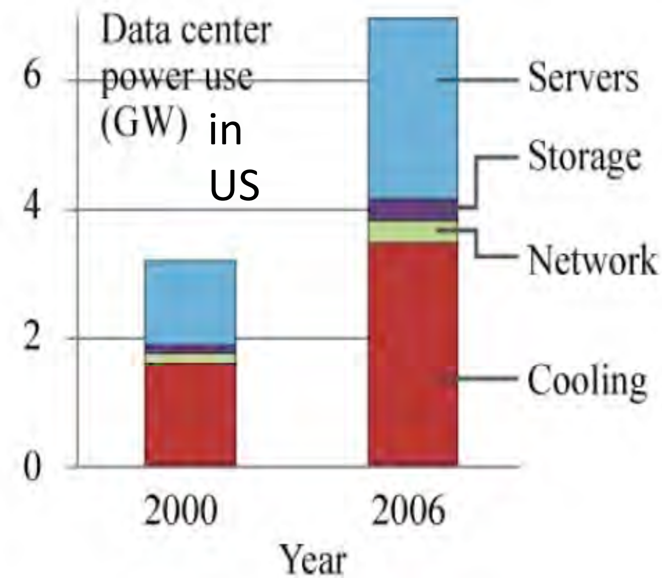
Energy efficiency in computing systems has become a major issue for the future of ICT



ICT - Energy

Energy efficiency in computing systems has become a major issue for the future of ICT





E. Pop, *Energy Dissipation and Transport in Nanoscale Devices*, Nano Res (2010) 3: 147–169

Energy required to operate the portable devices

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

Questions:

- How much can we decrease the energy consumption ?
- Is there any limit to the minimum energy required ?
- What is the future technology (beyond CMOS) ?
- …

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

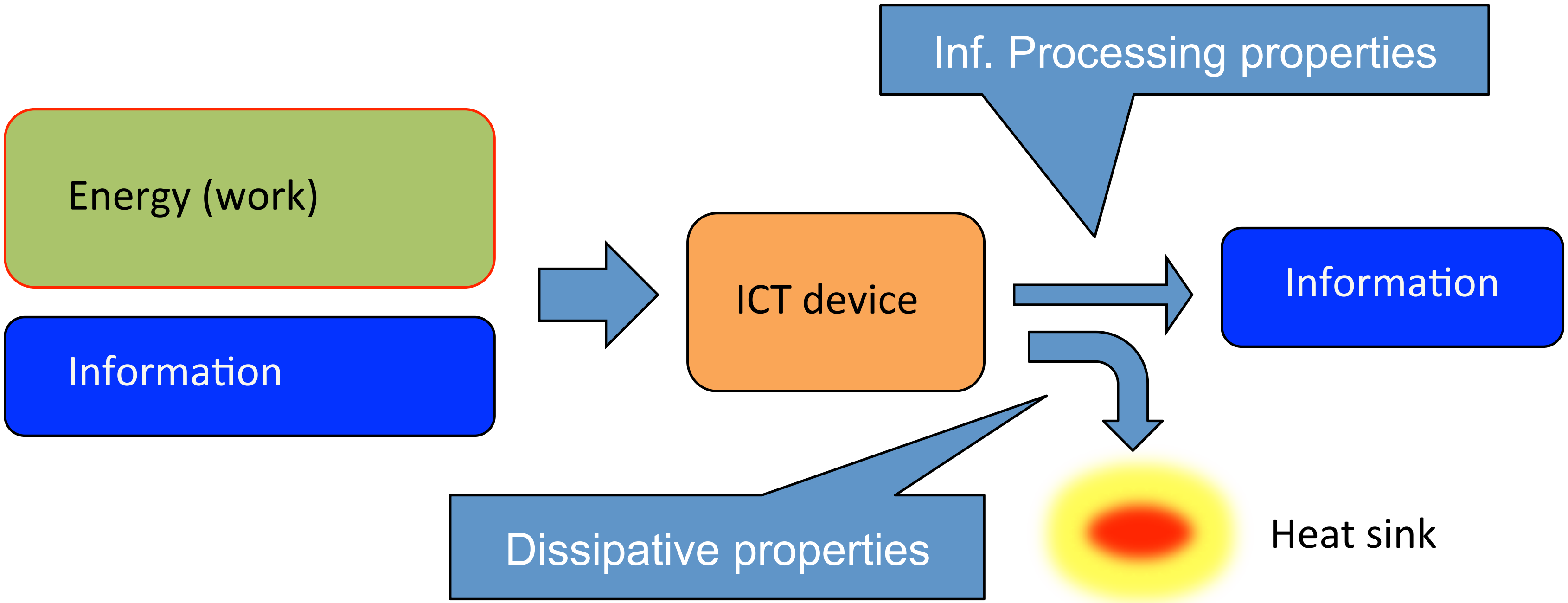
Questions like:

-How does electric energy get converted into heat at nanoscale
-How can we find an information transport solution that does not add to dissipation
-How can we harvest thermal vibrations to power nanoscale devices
-...

Could be asked and answered within this framwork.

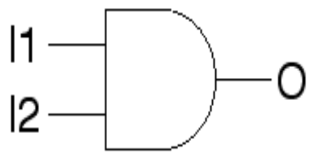
In order to better contestualize the issue let's focus on a scheme for ICT devices...

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).



Logic gates

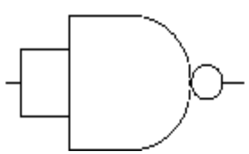
In modern computers the information is processed via networks of logic gates that perform all the mathematical operations through assemblies of basic Boolean functions. E.g. the NAND gate that due to its universal character can be widely employed to be networked in connected networks in order to perform any other logic functions.



I1	I2	O
0	0	0
0	1	0
1	0	0
1	1	1

We can distinguish the logic function in **logically reversible** logic gates and **logically irreversible** logic gates. "A logically reversible function is one whose inputs can be determined precisely from its outputs".

Es: the NOT gate



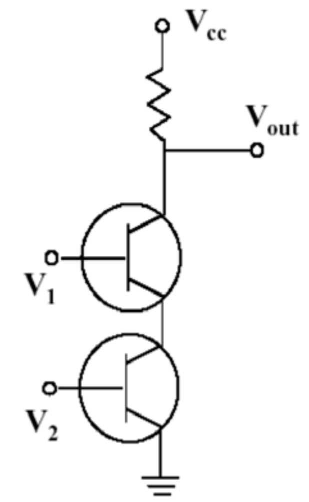
I	O
0	1
1	0

Logic gates and switches

In a -practical computer, the logic gate function is realized by some material device. The bit value is represented by some physical entity (signal) like electric current or voltage, light intensity, magnetic field,…etc.

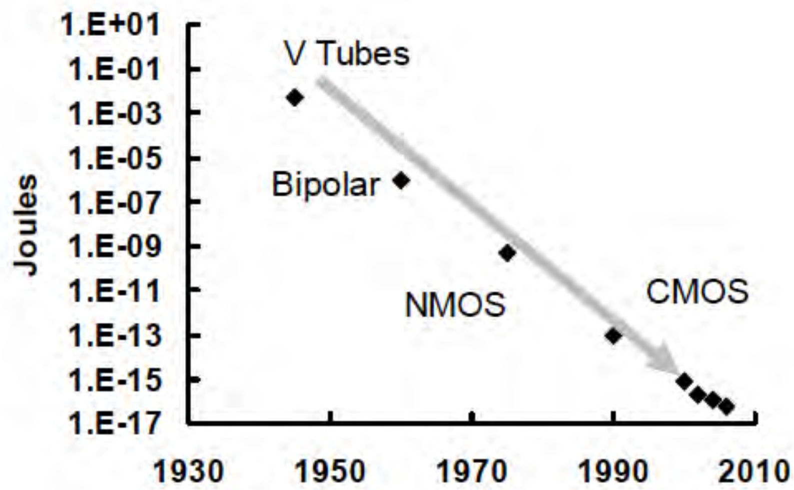
Modern logic gate devices are made by assembling more elementary units: i.e. the **transistors**.

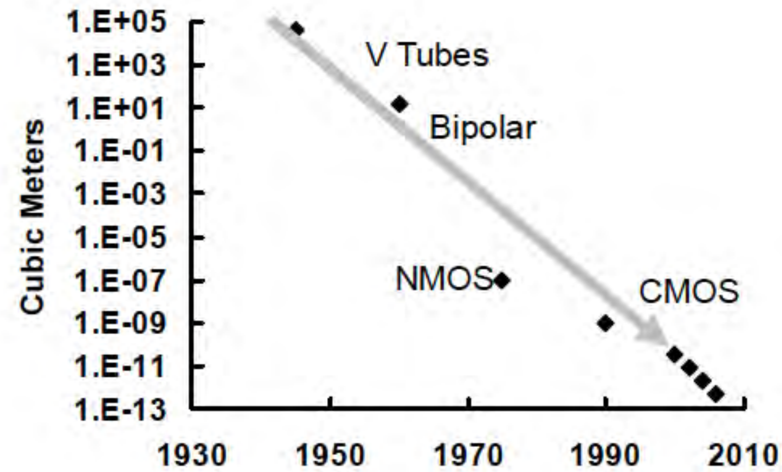
A transistor is an electronic device that here performs the role of a **switch** by letting or not-letting the electric current go pass through.



Es: the NAND gate with 2 transistor

Operating switches dissipates energy





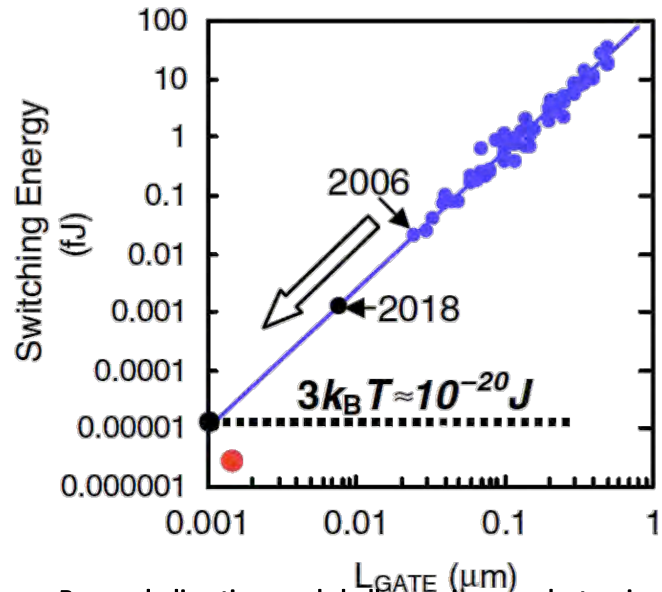
Shekhar Borkar, **Electronics Beyond Nano-scale CMOS,** Design Automation Conference, 2006 43rd ACM/IEEE

"...the resulting power density for these switches at maximum packing density would be on the order of 1MW/cm^2 – orders of magnitude higher than the practical air-cooling limit.."

Jeffrey J. Welser
The Quest for the Next Information Processing Technology , 2008

ICT - Energy

The future does not look good either…



Research directions and challenges in nanoelectronics
R. K. Cavin1, V. V. Zhirnov, D. J. C. Herr1, Alba Avila and J. Hutchby, 2006

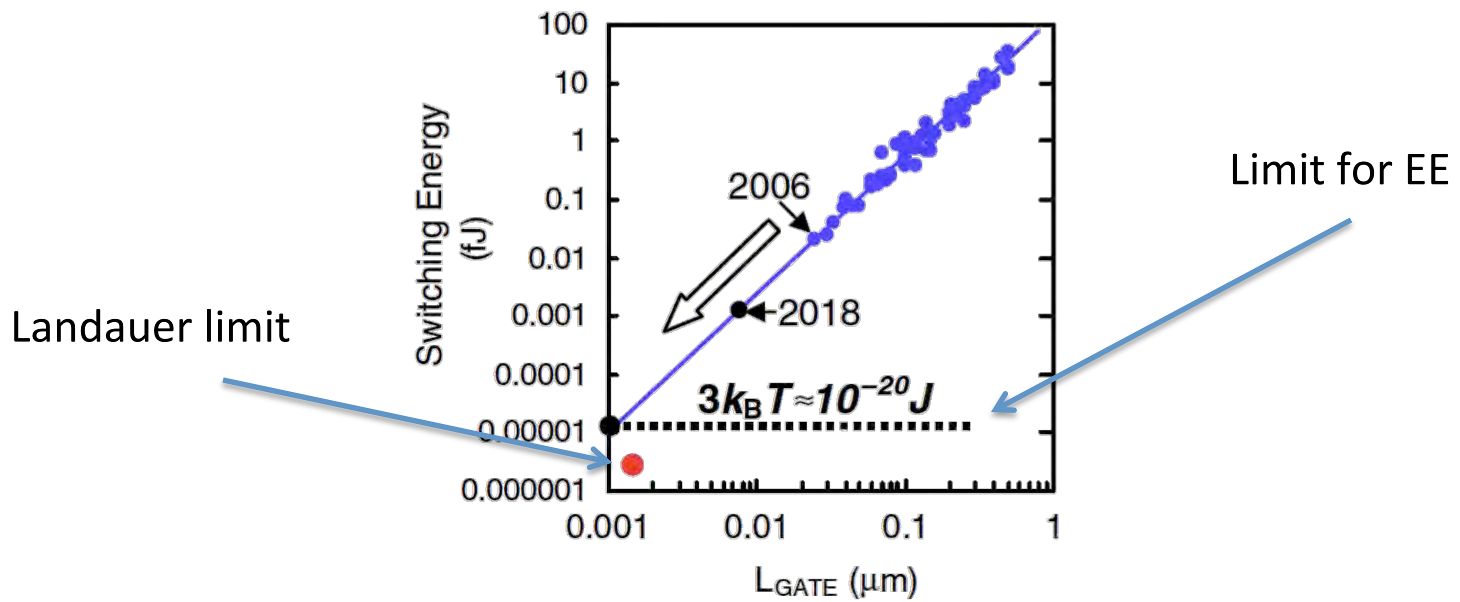
Thus, the search for alternative switches is presently very active.

To take on this grand challenge, the Nanoelectronics Research Initiative (NRI) (nri.src.org) was formed in 2004 as a consortium of Semiconductor Industry Association (SIA) (www.sia-online.org) companies to manage a university-based research program as part of the Semiconductor Research Corporation (SRC) (www.src.org). The NRI was founded by six U.S. semiconductor companies (AMD, Freescale, IBM, Intel, Micron, and TI), and partners with the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST), and state governments, sponsoring research currently at 35 U.S. universities in 20 states.

ICT - Energy

Question:

Is there a fundamental physical limit to the minimum energy needed to switch?



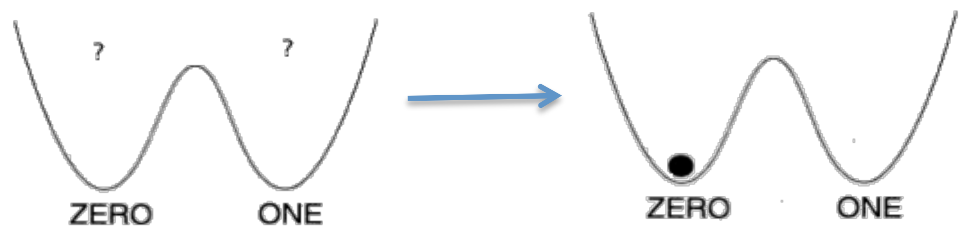
There is no general agreement on the answer and.... some misconceptions do not help.

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:



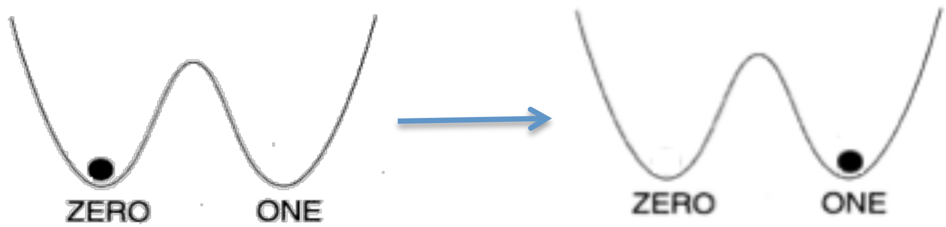
Number of possible config. 2   Number of possible config. 1

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)

THE LANDAUER LIMIT

But… this is not the case of a switch event:



Number of possible config. 1

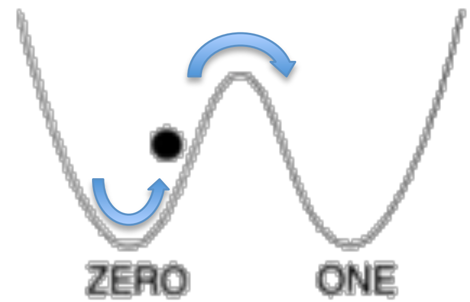
Number of possible config. 1

$$\Delta S = 0$$

So …is there a minimum energy requirement for switching?

THE EE LIMIT (i.e. the role of fluctuations)

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.

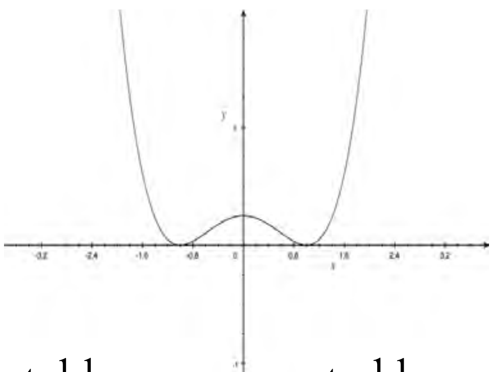
This idea is based on a naïve argument and is biased by the technology employed to build switches: CMOS tech.
In fact in a CMOS based system the switch is realized by charging a capacitor and this is technologically a lossy operation. There is no fundamental reason in this argument.

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

The Physics of 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.
We assume that the switch dynamics can be described by a single dof that we identify with x.

x is a continuous variable (e.g. the position of a cursor or the value of a magnetic field) that can assume two identifiable stable states: e.g. $x<0$ (logic state OPEN or logic value "0"), $x>0$ (logic state CLOSE or logic value "1").



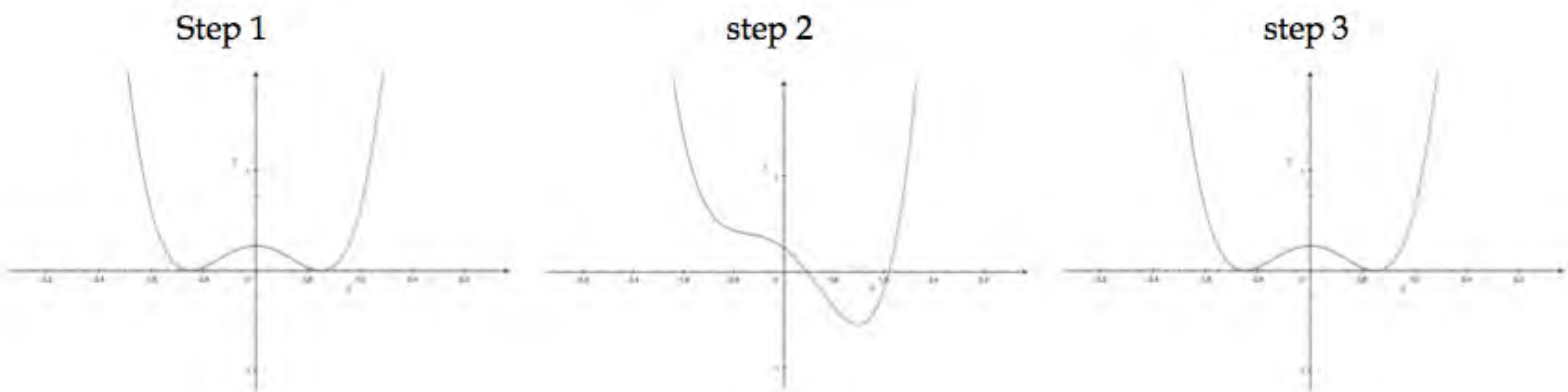
The two states, in order to be dynamically stable, are separated by some energy barrier that should be surpassed in order to perform the switch event.
This situation can be mathematically described by a second order differential equation like:

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

The Physics of switches

According to this model if we want 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:

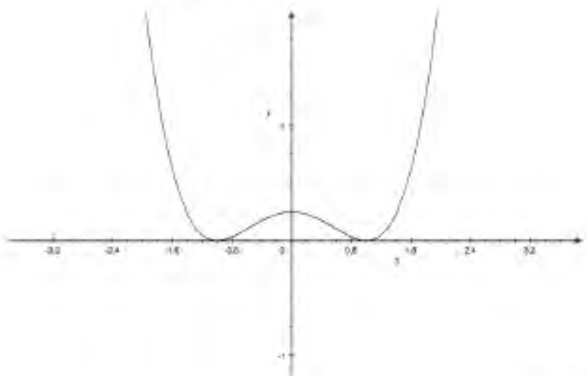
$$L = \int_{x_1}^{x_2} F(x)\,dx$$

Thus $L = 2\ F_0$

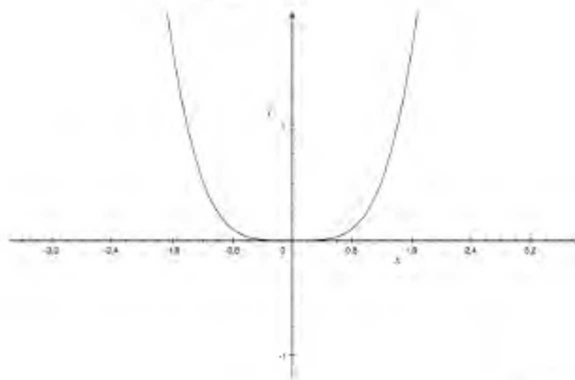
The Physics of switches

Is this the minimum work?
Let's look at this other procedure (**second procedure**):

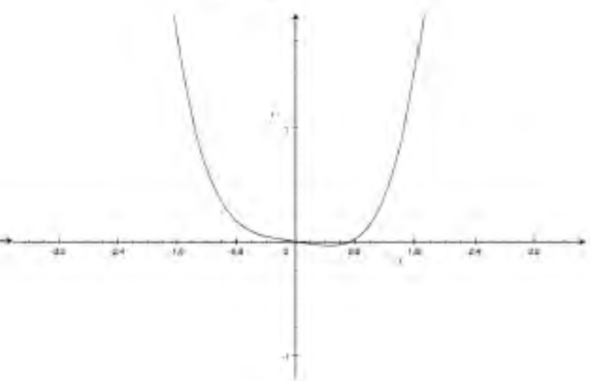
step 1



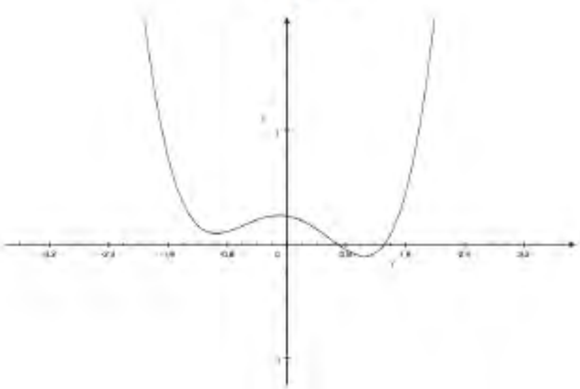
step 2



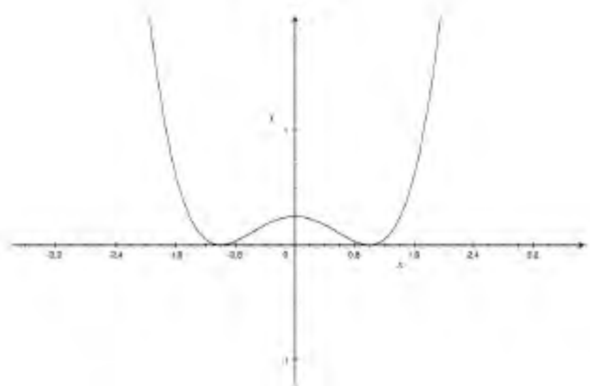
step 3



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 $F_1 << F_0$ we have $L_1 << L_0$

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:

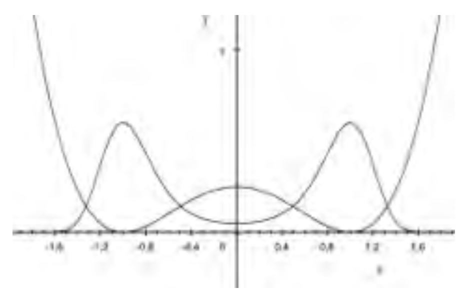
$$m\ddot{x} = -\frac{d}{dx}U(x) - m\gamma\dot{x} + \xi(t) + F$$

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

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

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

Based on these considerations we now define the switch event as the transition from an initial condition toward a final condition, where the initial condition is defined as $<x> < 0$ and the final condition is defined as $<x> > 0$. With the initial condition characterized by:

$$p_0(t) = \int_{-\infty}^{0} \boldsymbol{P(x,t)}dx \cong 1 \quad and \quad p_1(t) = \int_{0}^{+\infty} \boldsymbol{P(x,t)}dx \cong 0$$

and the final condition by:

$$p_0(t) = \int_{-\infty}^{0} \boldsymbol{P(x,t)}dx \cong 0 \quad and \quad p_1(t) = \int_{0}^{+\infty} \boldsymbol{P(x,t)}dx \cong 1$$

In order to produce the switch event we proceed as follows: we set our initial position at any value $x < 0$ and wait a time t_a, with $\tau_1 << t_a << \tau_2$, then we apply an external force F for a time t_b in order to produce a change in the $<x>$ value from $<x> < 0$ to $<x> > 0$. Then we remove the force. In practice we need to wait a time t_a after the force removal in order to verify that the switch event has occurred, i.e. that $<x> > 0$. The total time spent has to satisfy the condition $2\, t_a + t_b << \tau_2$.

Now that we have defined the switch event in this new framework, we can go back to our question: what is the minimum energy required to produce a switch event?

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:

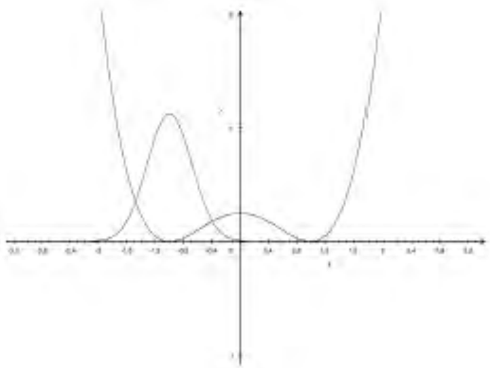
$$S = -K_B \sum_i p_i \log p_i$$

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

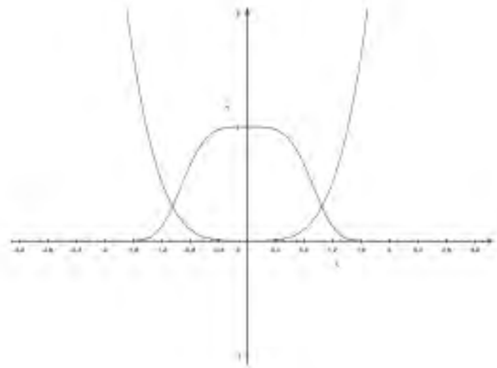
The Physics of realistic switches

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

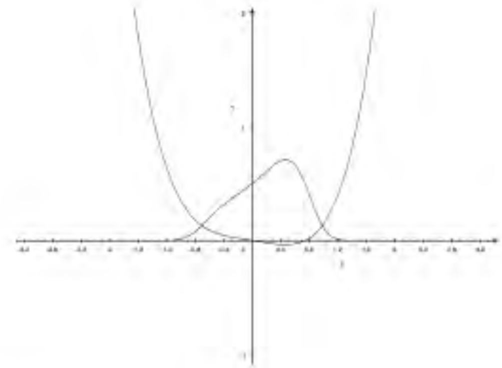
step 1



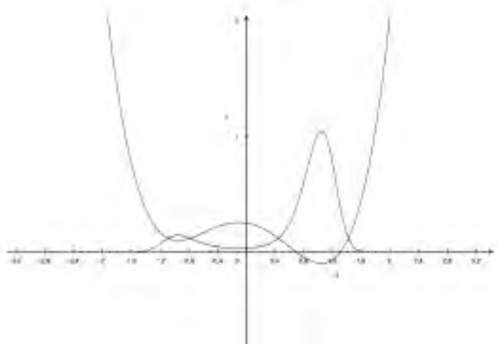
step 2



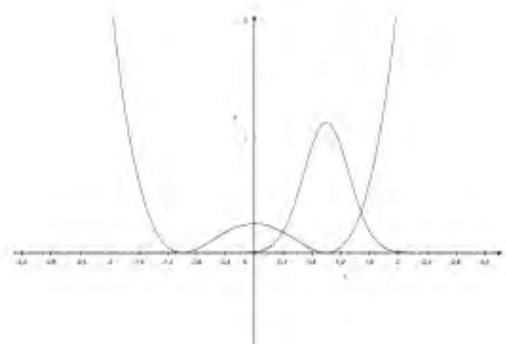
step 3



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

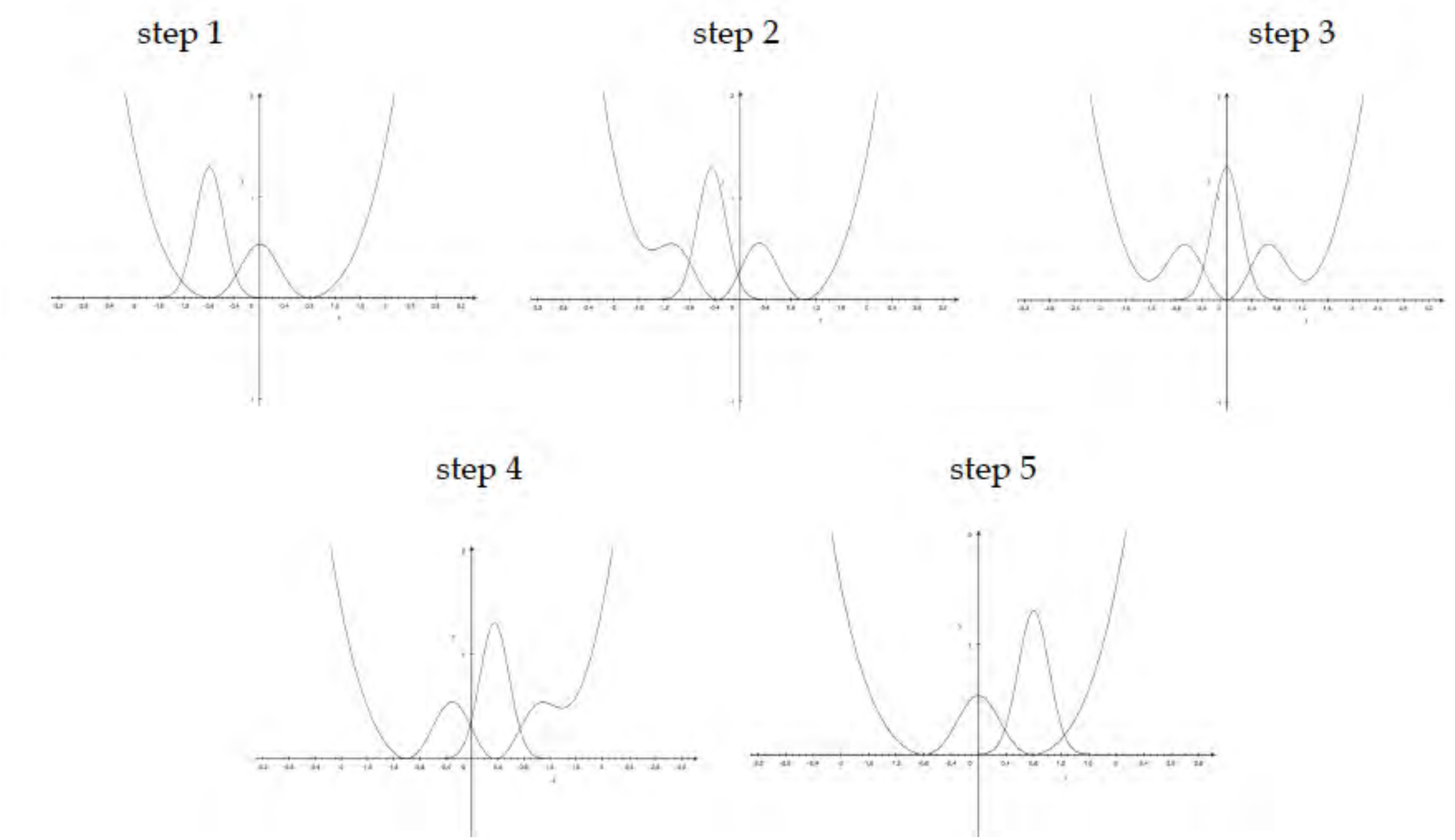
Based on these considerations we can now reformulate conditions required in order to perform the switch by spending zero energy:

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…

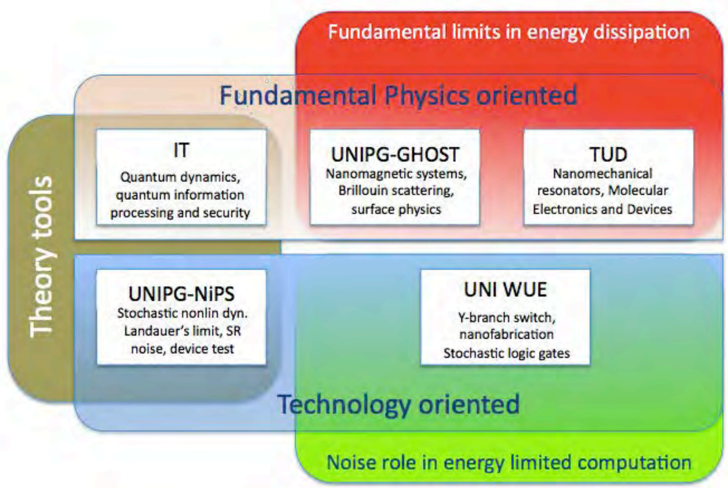
The MINECC initiative

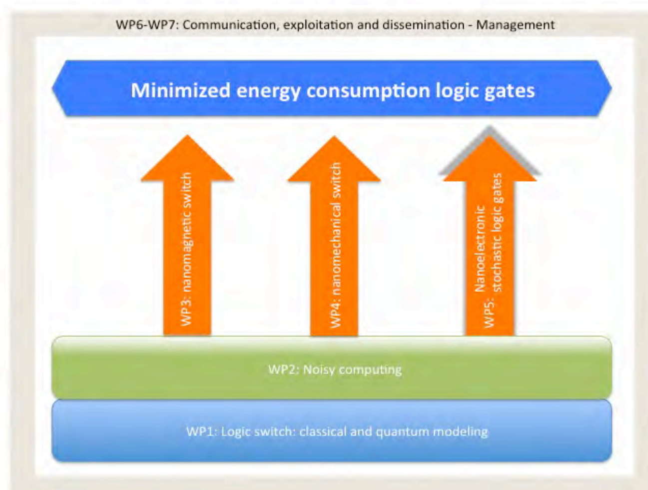
Minimizing Energy Consumption of Computing to the limit - FET Proactive

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

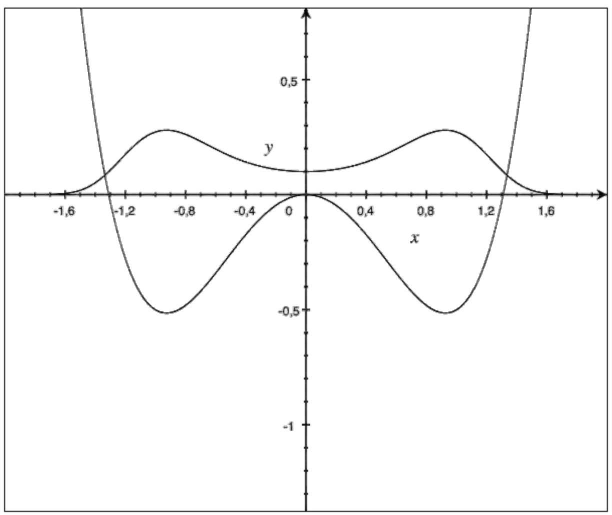


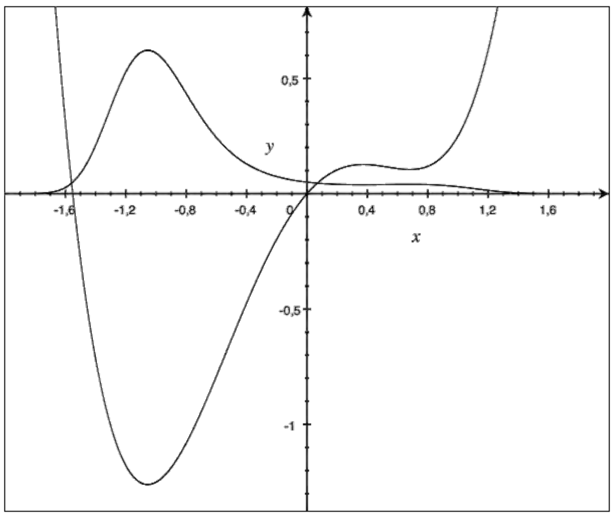


More info available at www.landauer-project.eu

Remarks on the Landauer principle

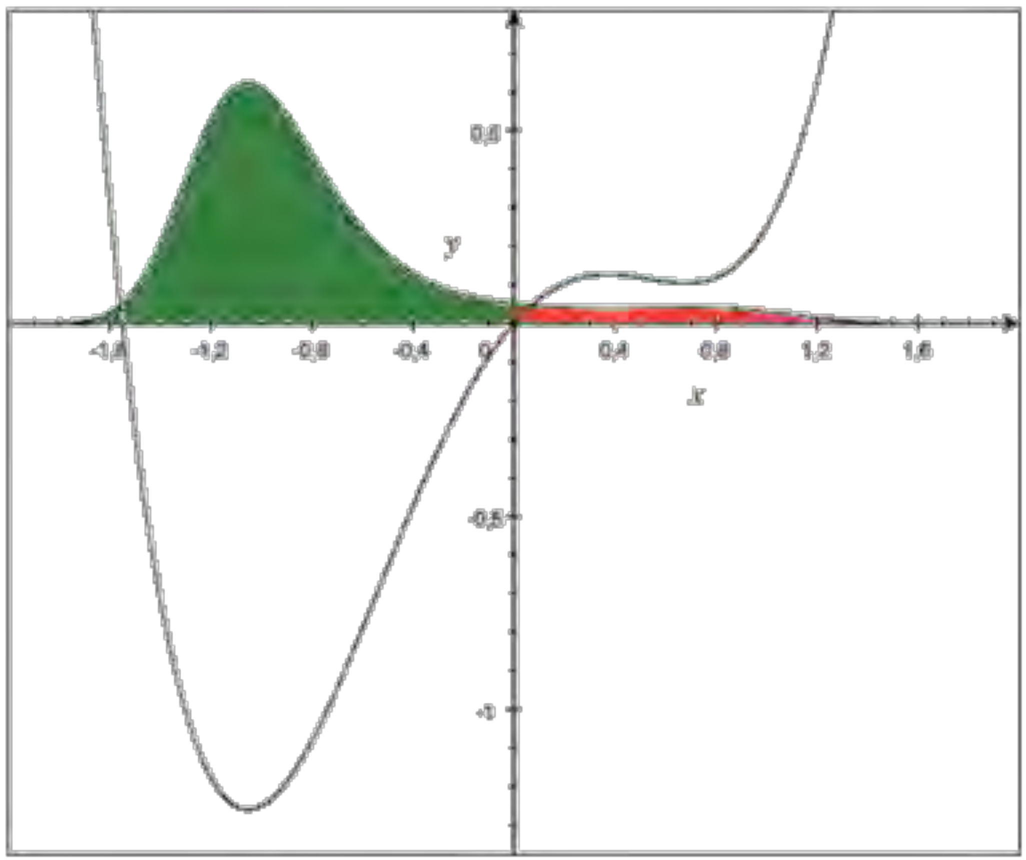
Let's consider a resetting operation:





Probabilities

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



Probabilities

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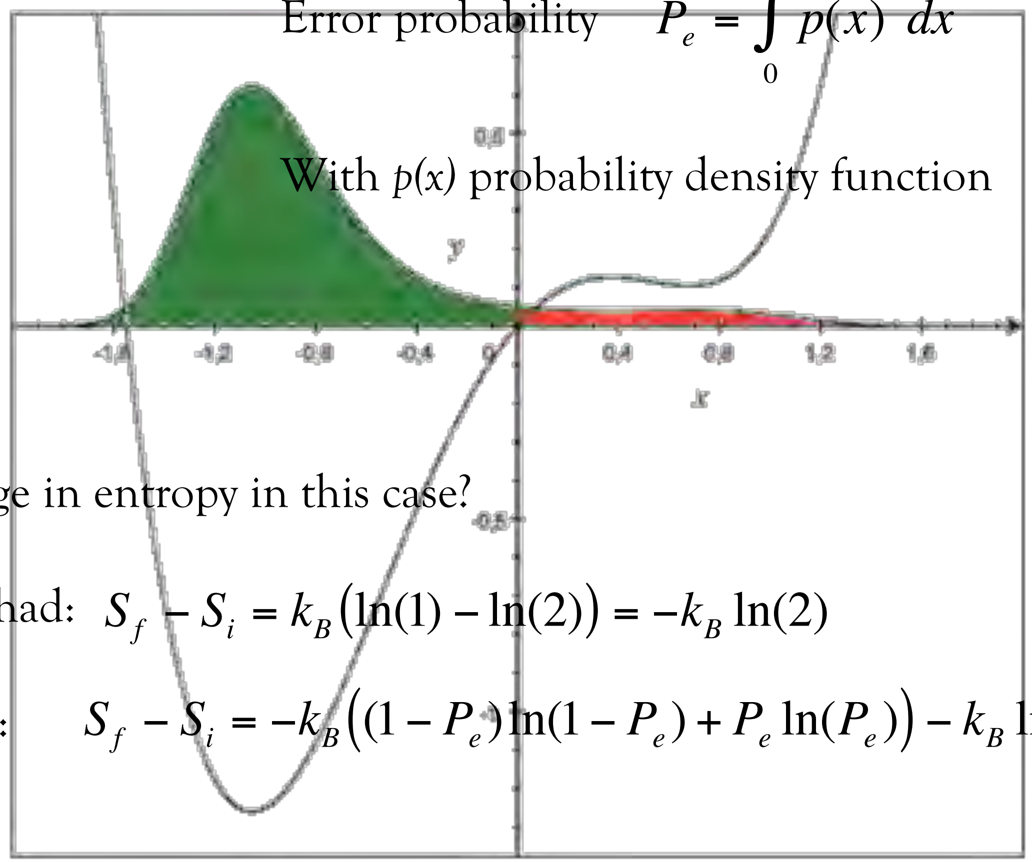


Error probability $P_e = \int_0^{\infty} p(x)\ dx$

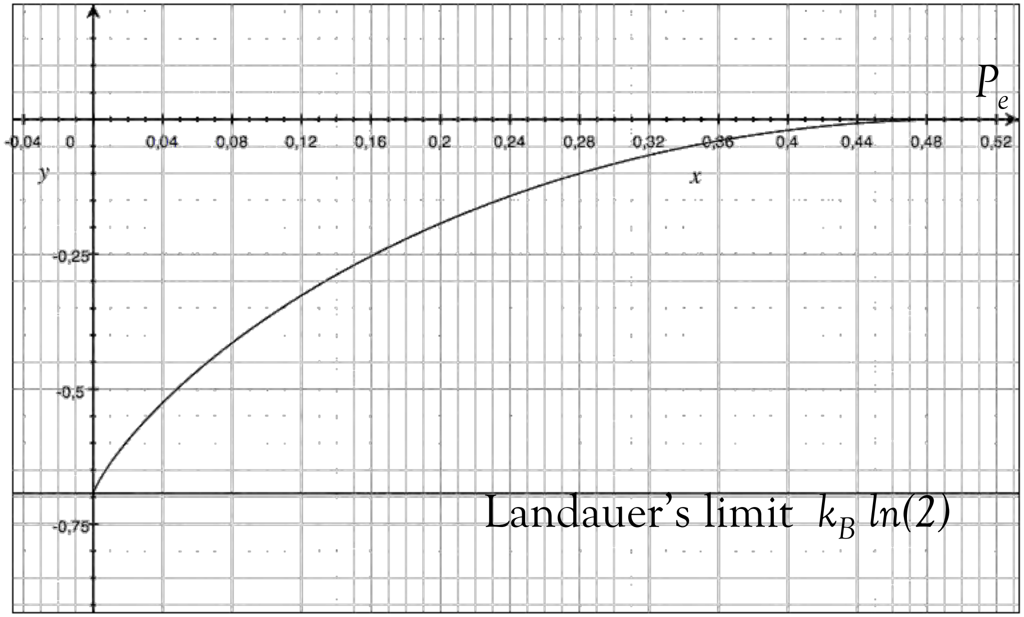
With $p(x)$ probability density function

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 P_e



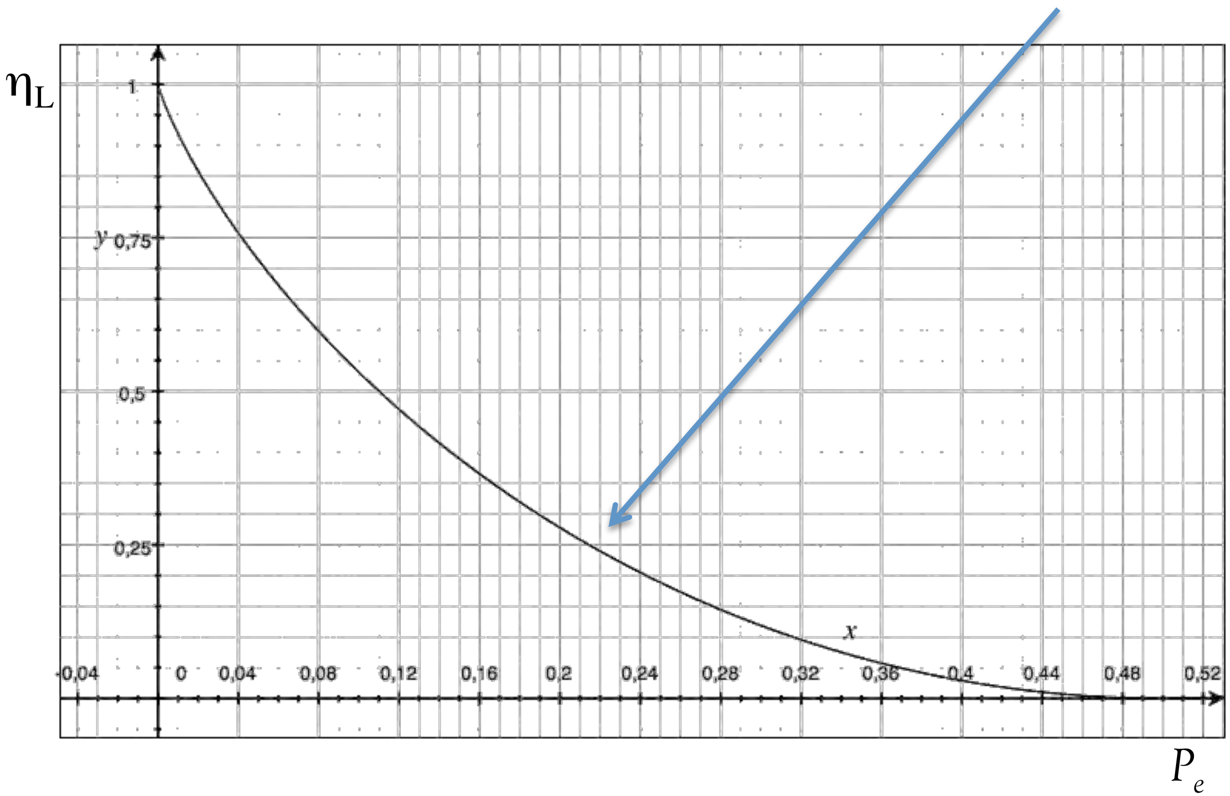
The more increases the probability of error
The more decreases the entropy difference
…and thus the dissipated energy.

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

Minimum energy ratio for reset operation*

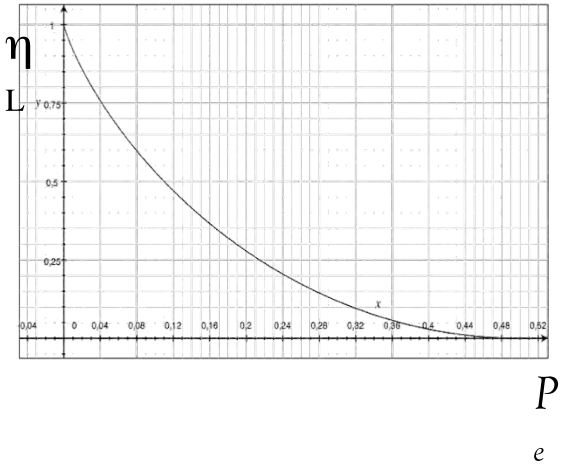
$$\eta_L(P_e) = \frac{Q(P_e)}{Q} = 1 + \frac{(1-P_e)\ln(1-P_e) + P_e\ln(P_e)}{\ln(2)}$$

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*



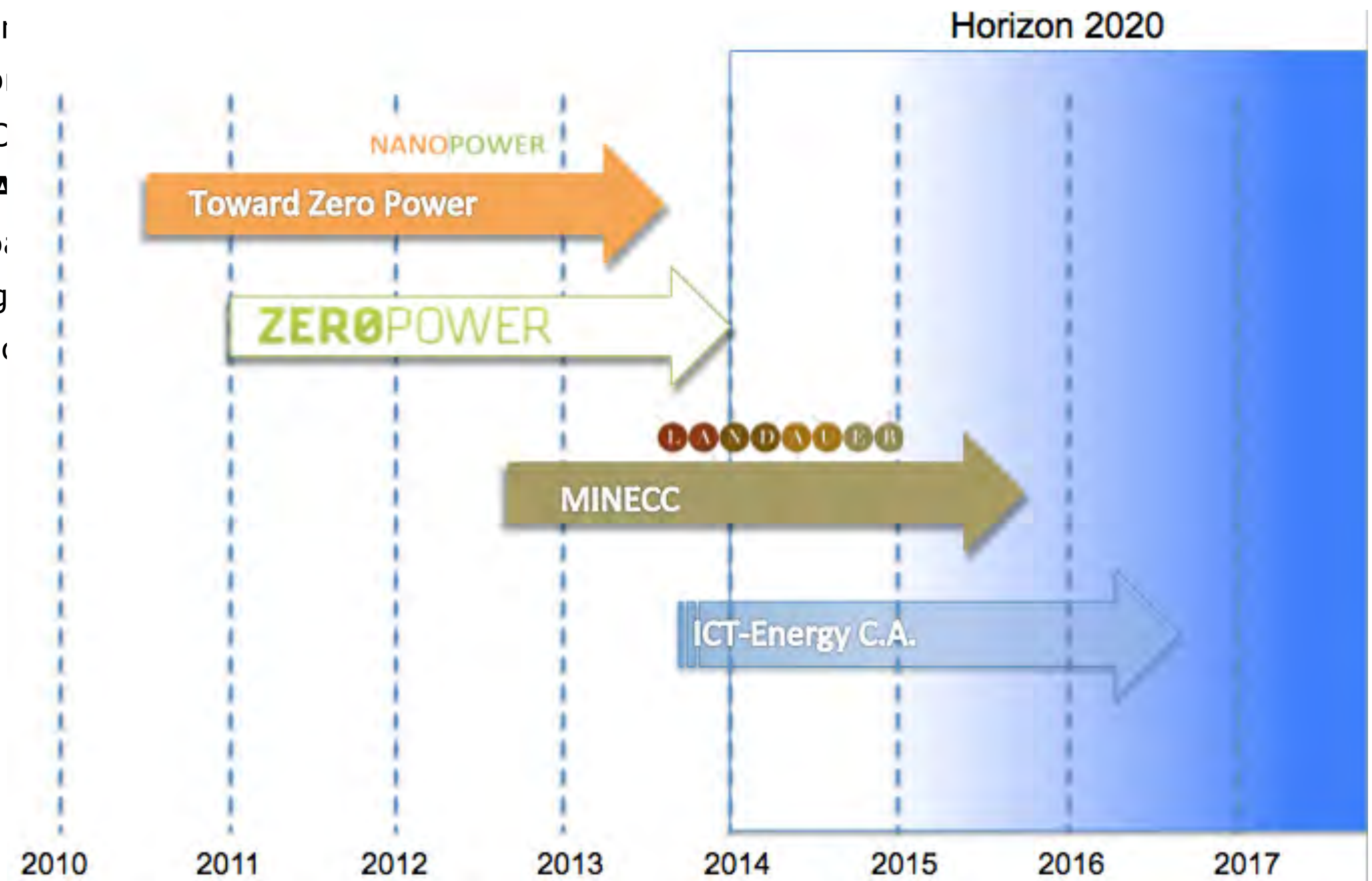
In general it is possible to build a resetting procedure that accepts a significant resetting error in exchange for Some energy savings…

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..

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 Co
- 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



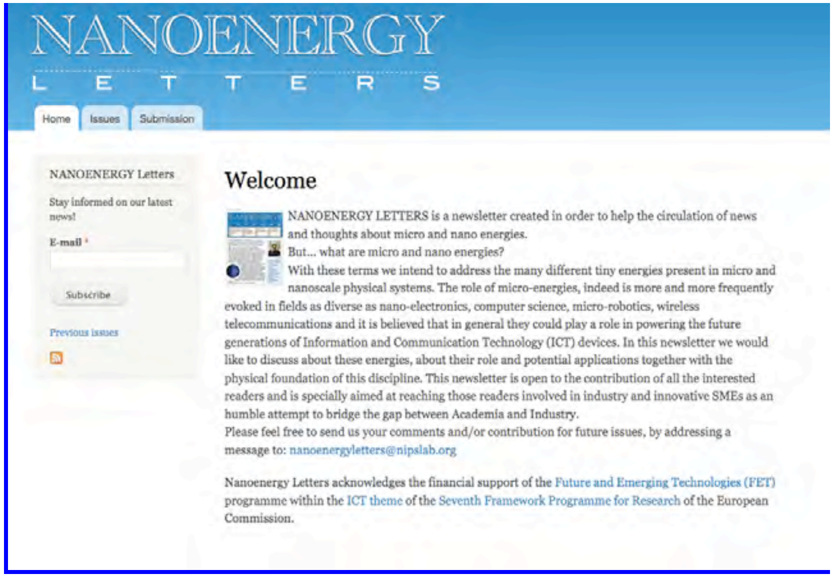
ICT-Energy consortium/community

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
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www.nanoenergy2013.eu

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