Energy dissipation in computing devices

Luca Gammaitoni
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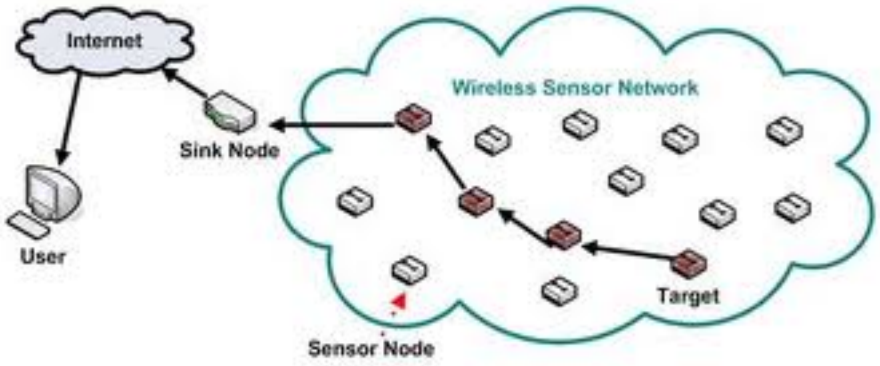
Energy consumption in computing has become a major issue for the future of ICT

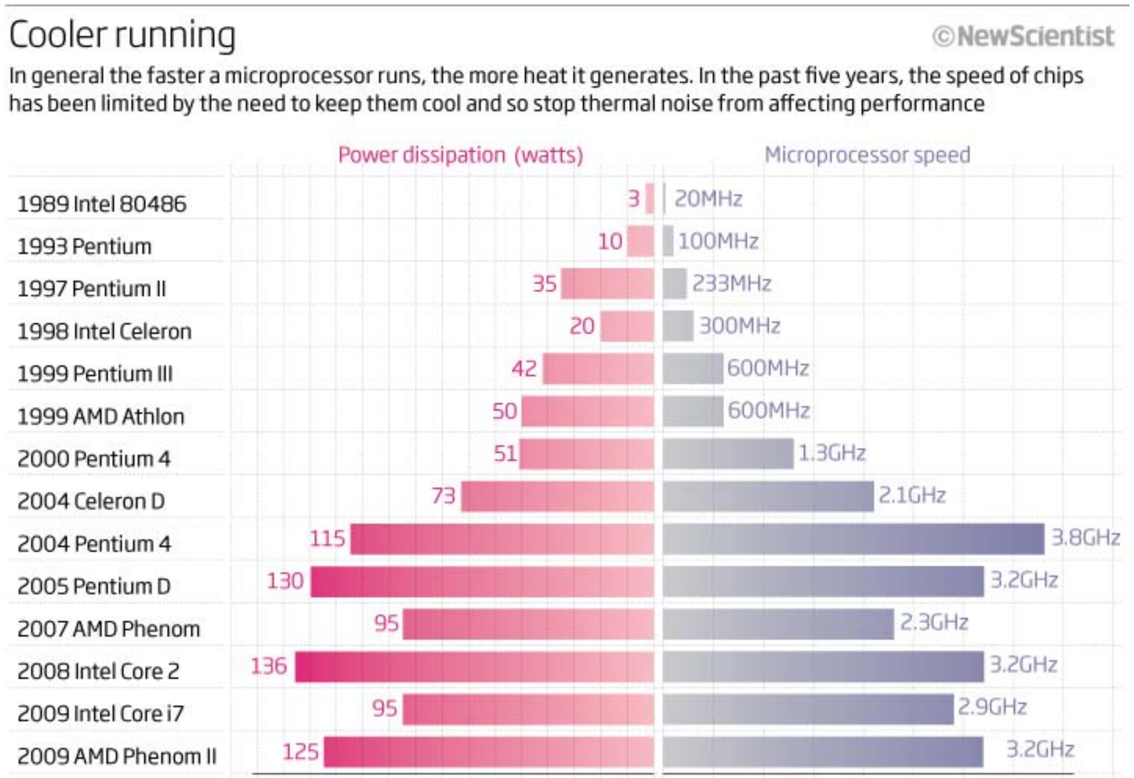
1) High performance computing systems

2) Wireless sensor networks



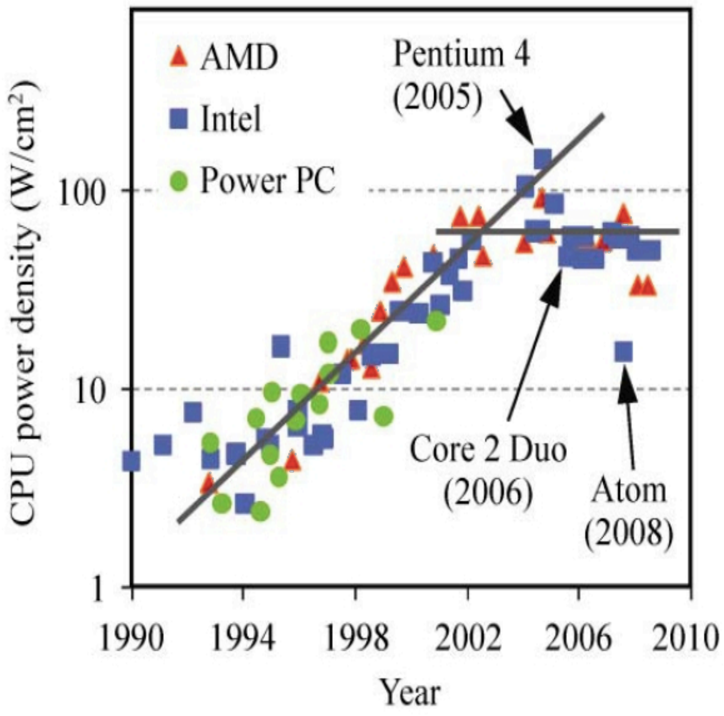
1) High performance computing systems

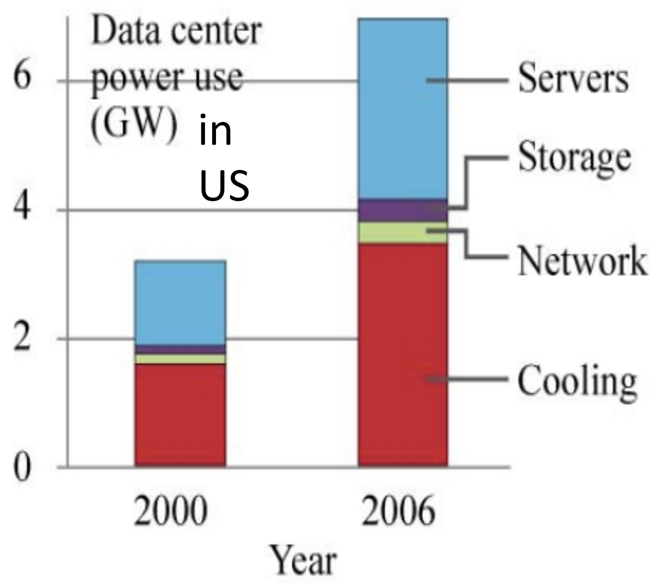
Energy consumption in computing systems has become a major issue for the future of ICT



ICT - Energy

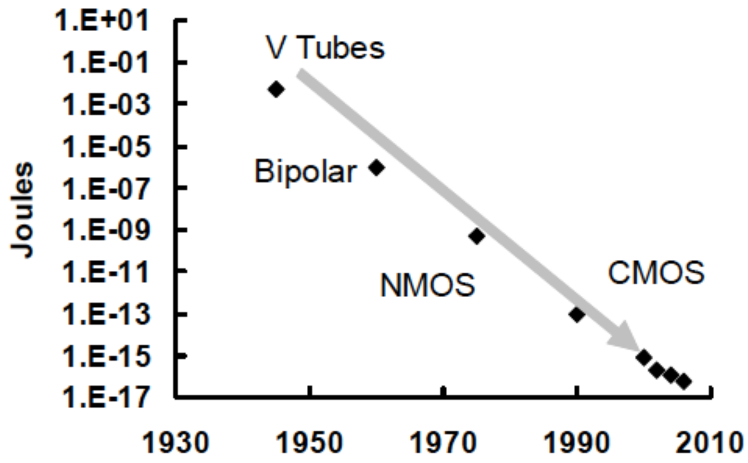
The binomial **ICT-Energy** has become the focus of future ICT research world wide





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

Energy required to operate microprocessors

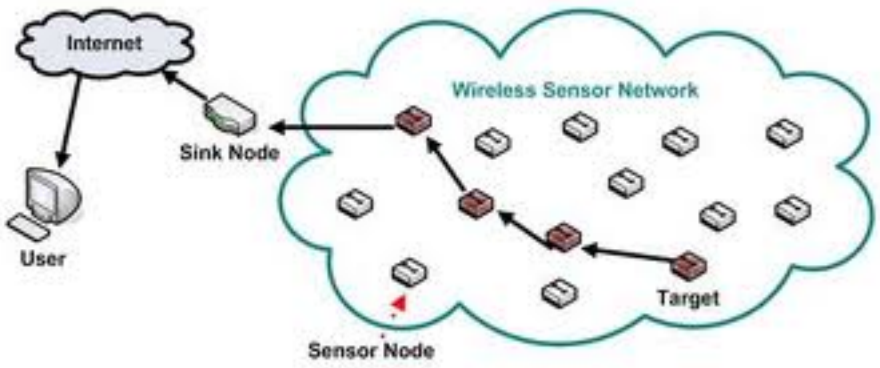


Shekhar Borkar, **Electronics Beyond Nano-scale CMOS,** Design Automation Conference, 2006 43rd ACM/IEEE

"…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.."

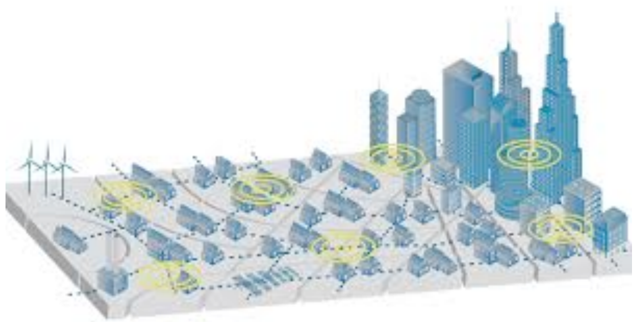
Jeffrey J. Welser
The Quest for the Next Information Processing Technology ,
2008

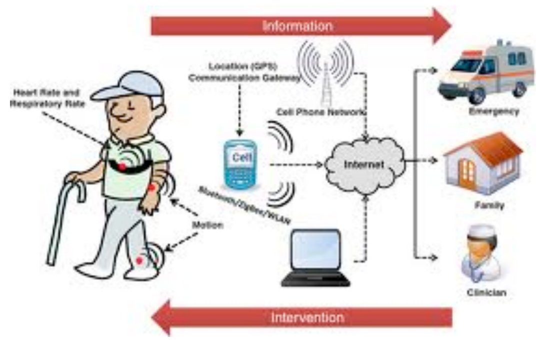
2) Wireless sensor networks



The promised land of ubiquitous computing

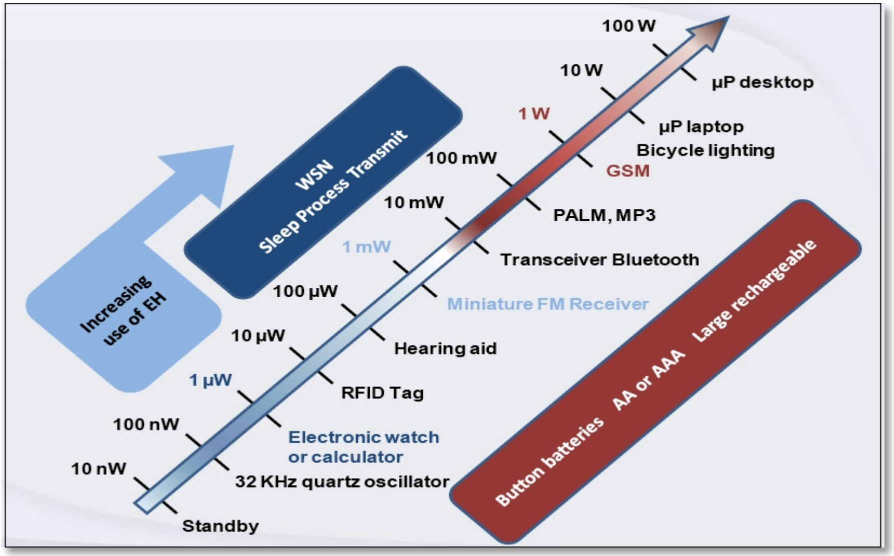
This is the land of wireless micro-sensors that continuously and ubiquitously measure, process and transmit data to improve our living.





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

Energy required to operate the portable devices



Energy available from portable sources (energy harvesting)

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

Energy required to operate the portable devices

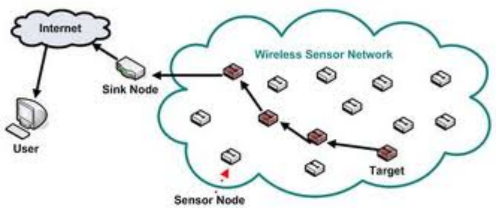
We need to bridge the gap by acting on both arrows

Energy available from portable sources

Energy required to operate computing devices

Why does it make sense to talk of a new field ICT-Energy ?

Energy available from the environment



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.

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

Heat-Work
relations

ICT Revolution
XX-XXI

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.

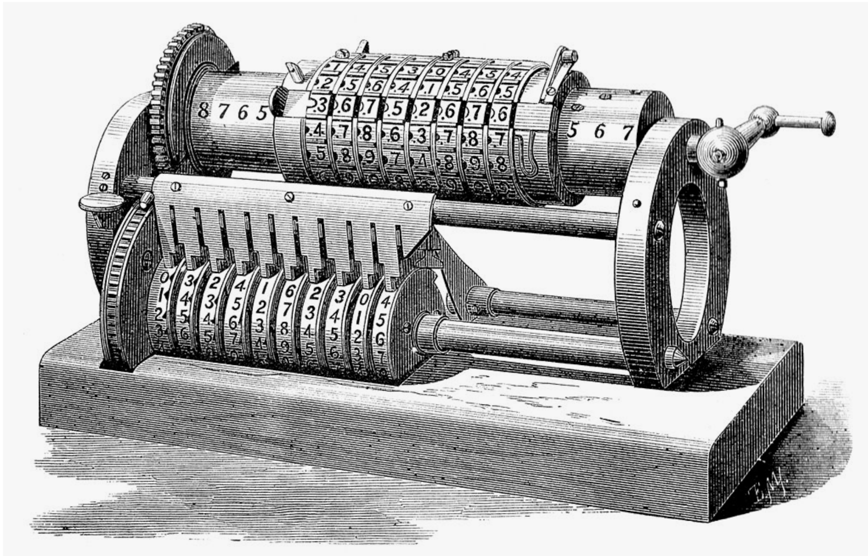
Toward zero power computing

Is it possible to operate a computing device with zero energy expenditure ?

YES

A computing device….
(slide rule)

YES



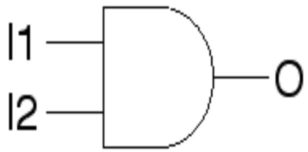
A computing device….

Is it possible to operate a binary (digital) computing device
with zero energy energy expenditure ?

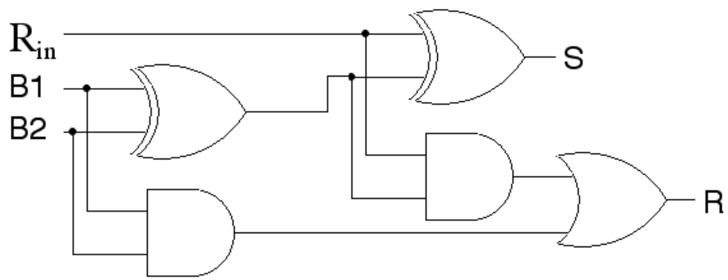
a binary (digital) computing device

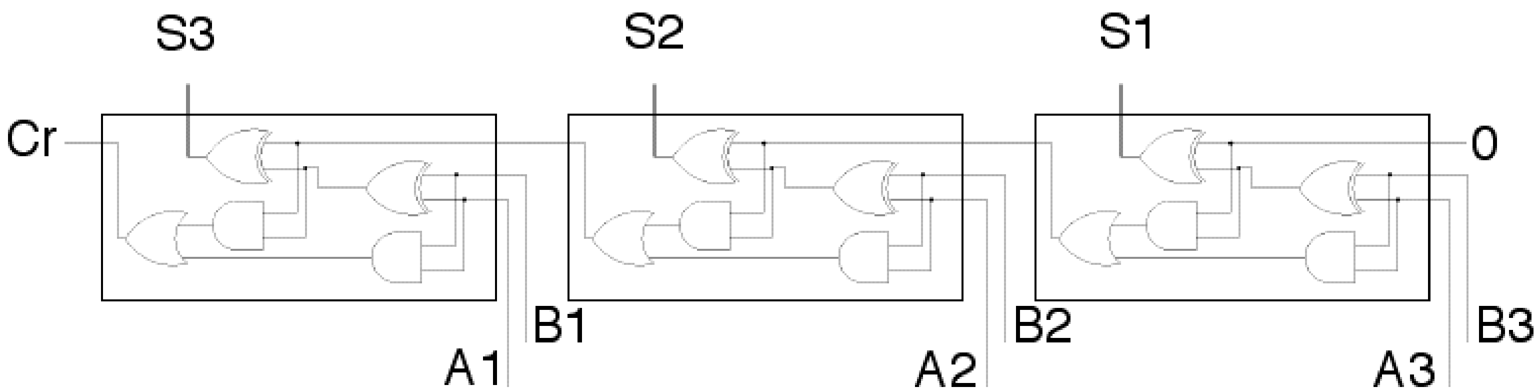
How does the binary (digital computation) work?

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



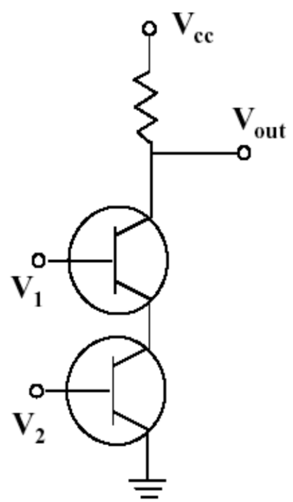


Logic gates and switches

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

Switches based on capacitors

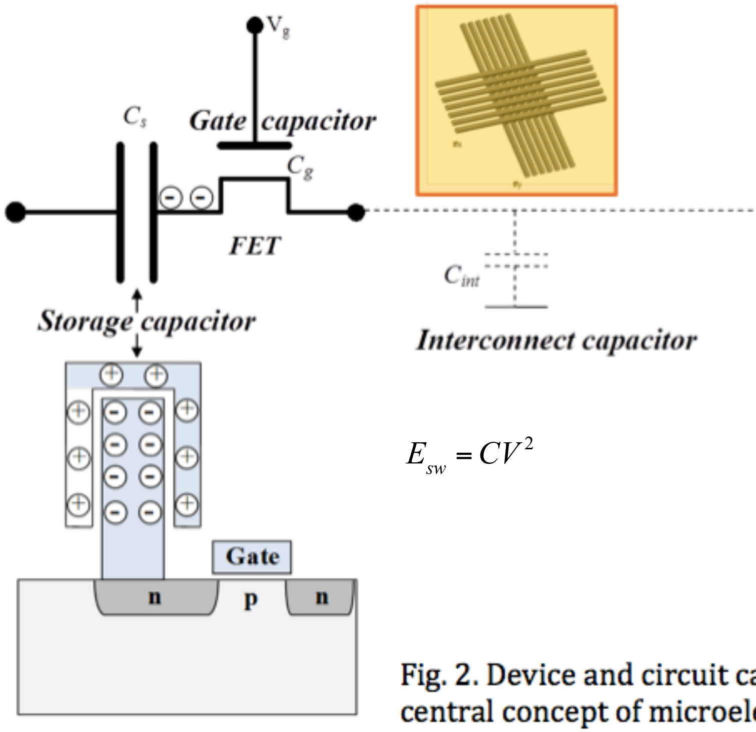


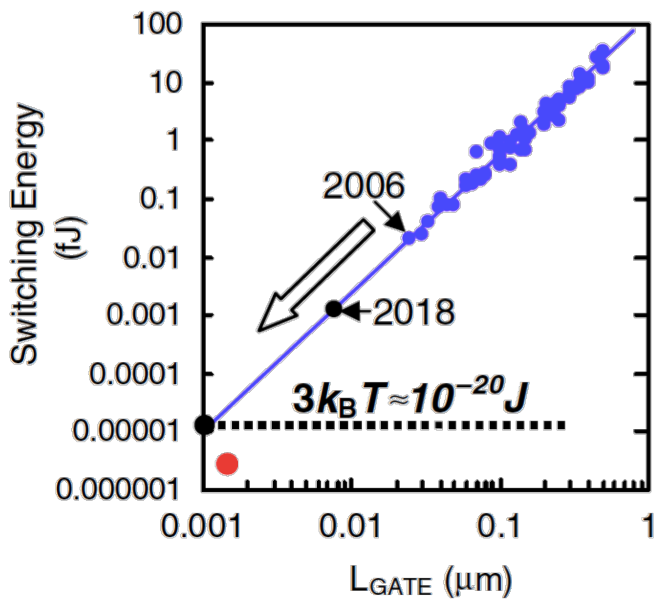
Fig. 2. Device and circuit capacitance as a central concept of microelectronics.

$$E_{sw} = CV^2 \qquad P = \alpha E_{sw} f = \alpha C V^2 f$$

Minimum Energy of Computing, Fundamental Considerations, L. Victor Zhirnov, Ralph Cavin and Luca Gammaitoni in the book "ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology" InTech, February 2, 2014

ICT - Energy

The present trend…



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

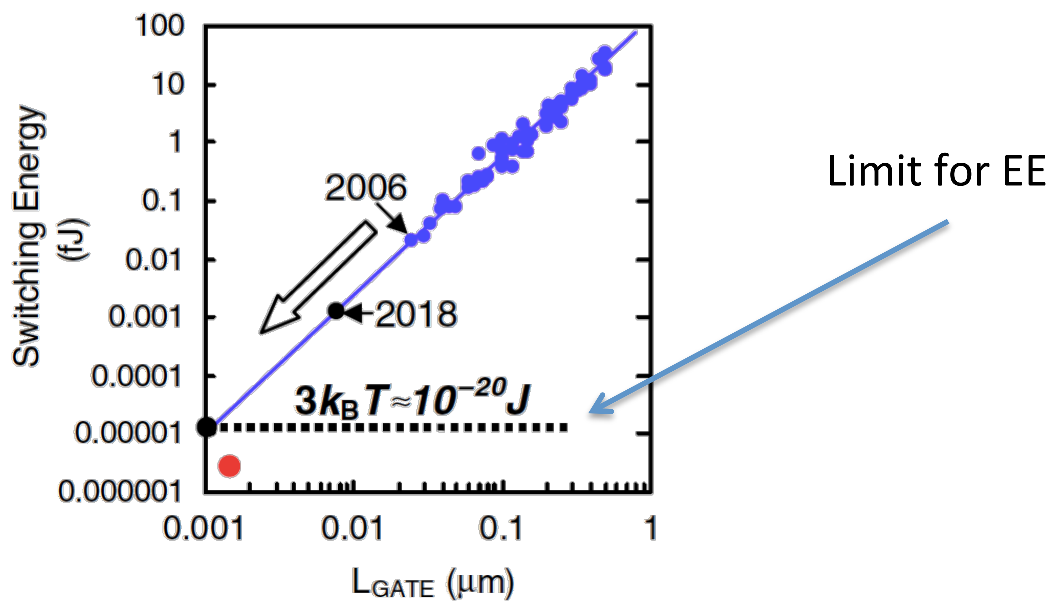
Thus, the search for alternative switches is presently very active.

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).

ICT - Energy

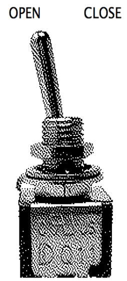
Question:

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

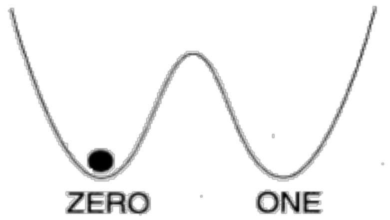


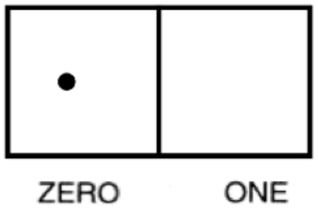
There is no general agreement on the answer… and present limits are associated with charge based computation.

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.





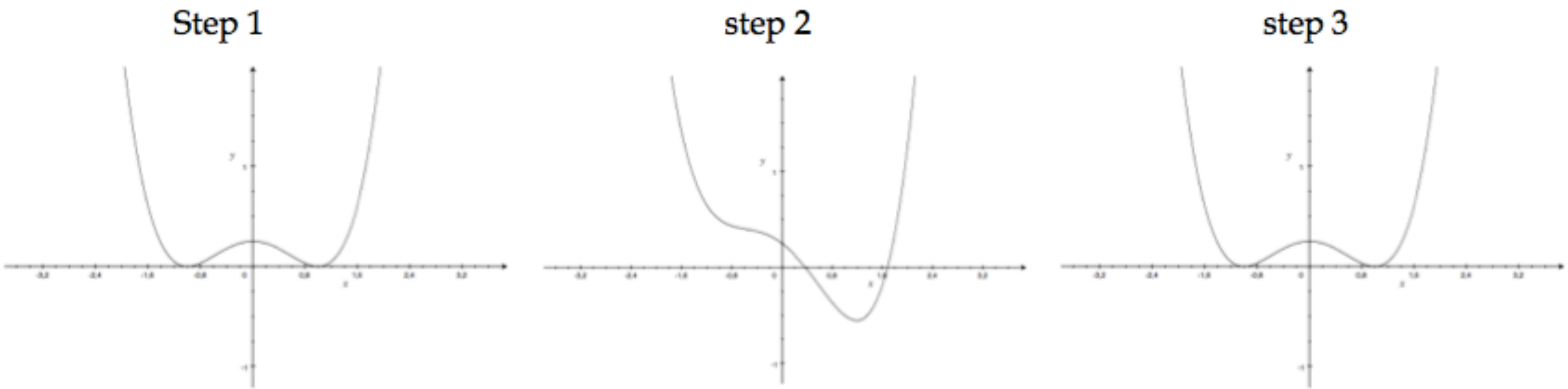
The two states, in order to be dynamically stable, are separated by some energy barrier that should be surpassed in order to perform the switch event.
This situation can be mathematically described by a second order differential equation like:

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

The Physics of switches

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 $F_0>0$



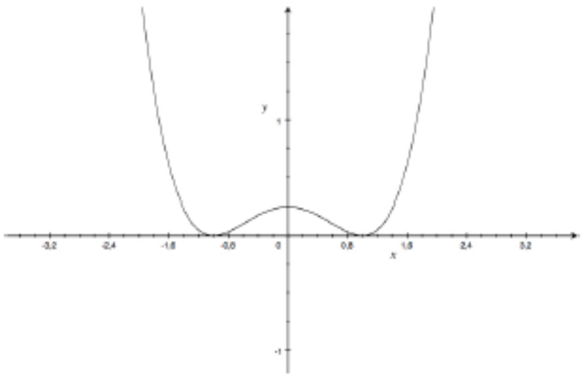
We can ask what is the minimum work that the force F has to perform in order to make the device switch from 0 to 1 (or equivalently from 1 to 0).
The work is computed as:

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

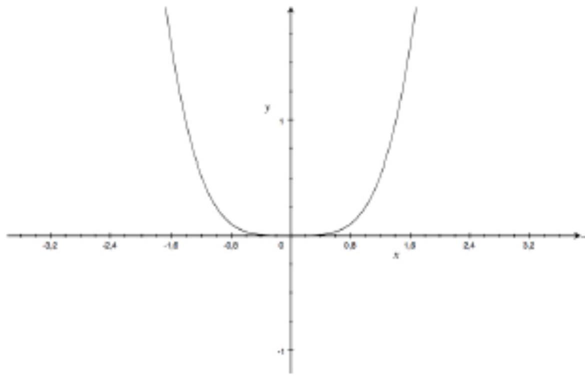
The Physics of switches

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

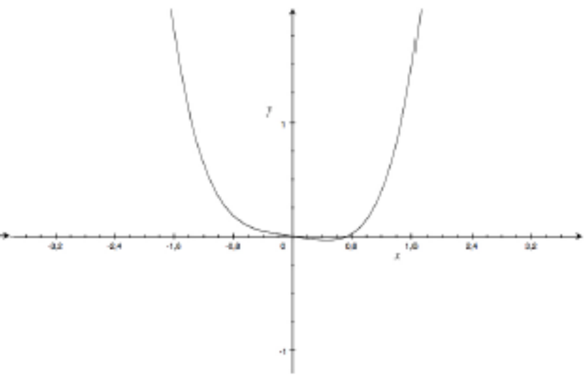
step 1



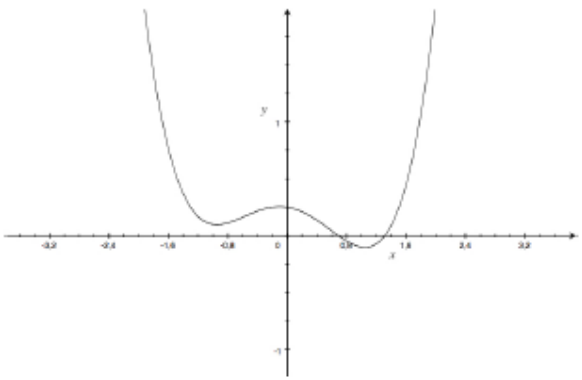
step 2



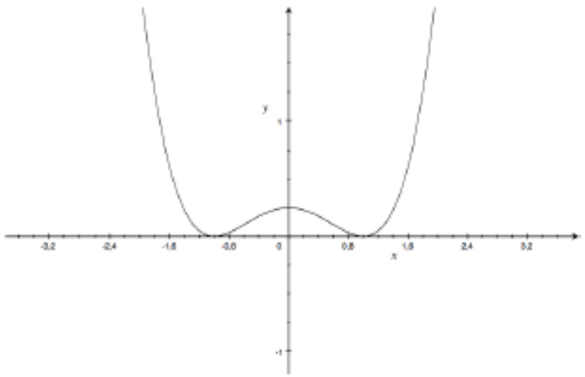
step 3



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 $F_1 \ll F_0$ we have $L_1 \ll L_0$

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:

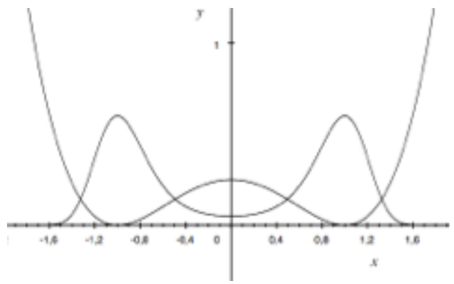
$$m\ddot{x} = -\frac{d}{dx}U(x) - m\gamma\dot{x} + \xi(t) + F$$

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

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

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:

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

and the final condition by:

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

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.

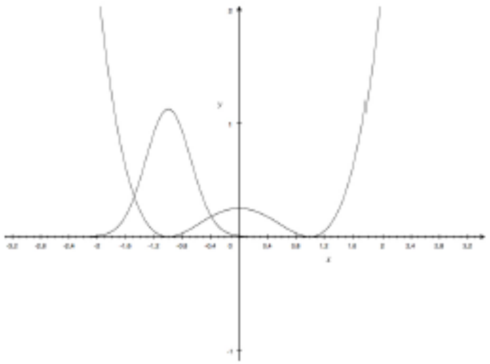
Entropy here is defined according to Gibbs: $S = -K_B \sum_i p_i \log p_i$

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

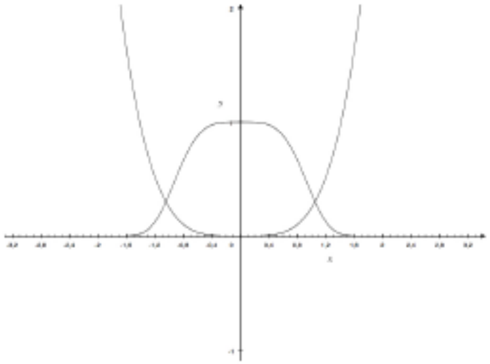
The Physics of realistic switches

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

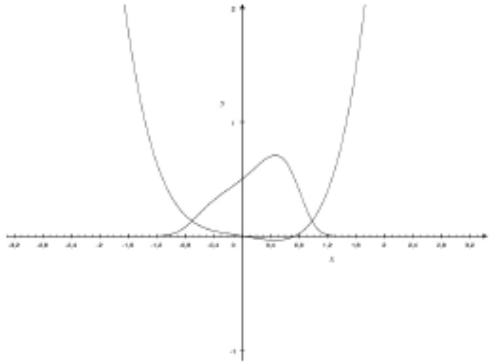
step 1



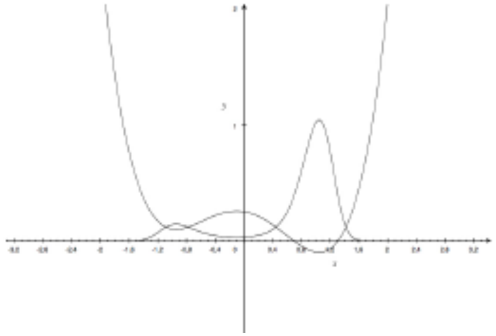
step 2



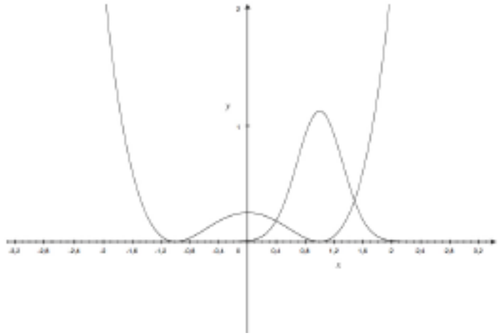
step 3



step 4



step 5



we observe a change in entropy:

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

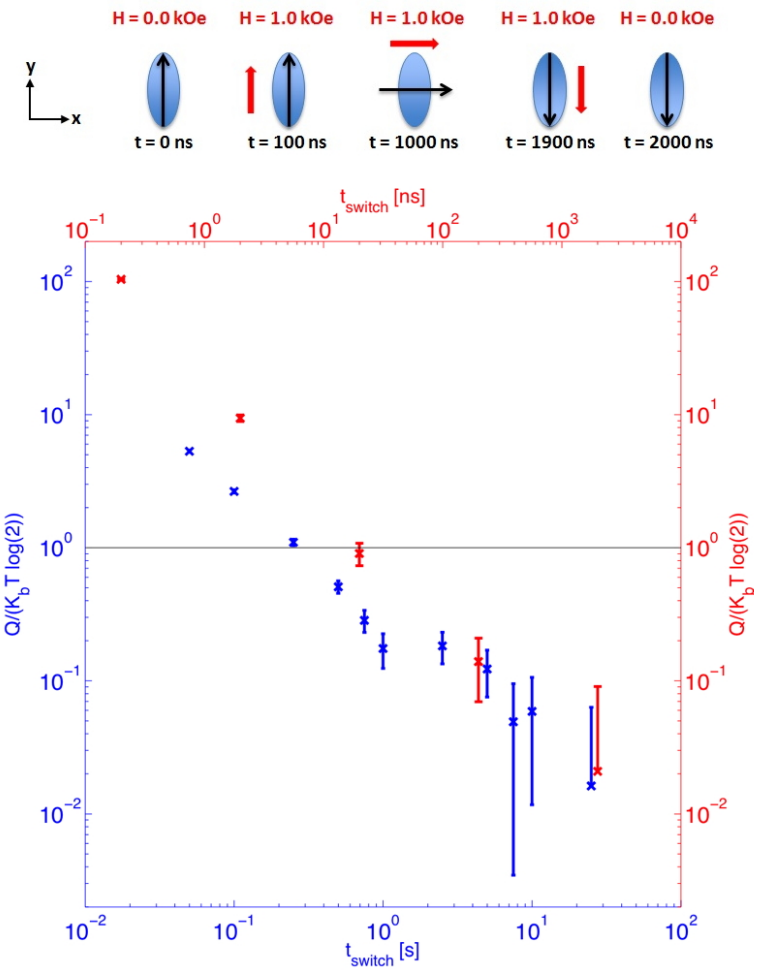
The Physics of realistic switches

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?

Yes… at least in principle…

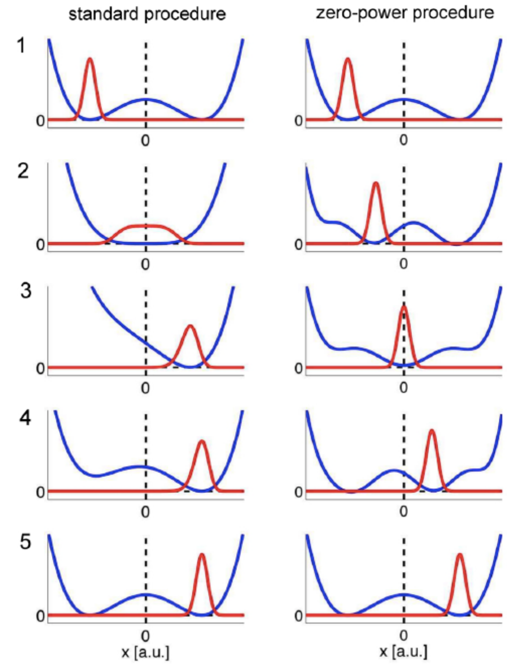


Magnetic nano dots

Single cylindrical element of permalloy (NiFe) with dimensions 50 x 50 x 5 nm³

Entropy changes

Entropy stays constant



More info available at www.landauer-project.eu