4

ICT Devices

Luca Gammaitoni

ICT-Energy Summer school 2015, Fiuggi (IT)

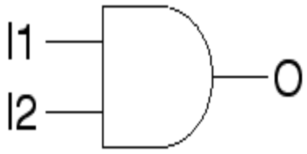
NiPS Laboratory
Noise in Physical Systems

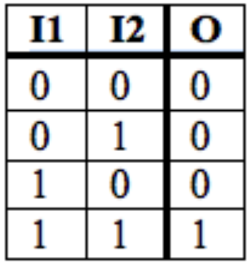
Content

How does a computer work ?

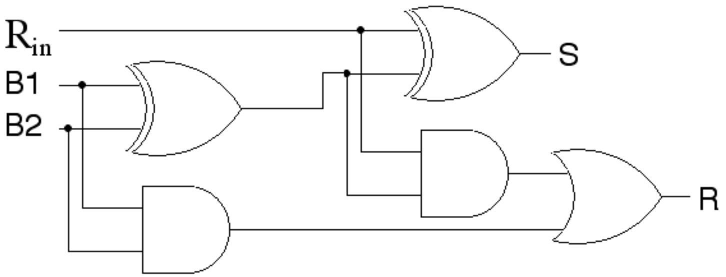
How does the binary (digital computation) work?

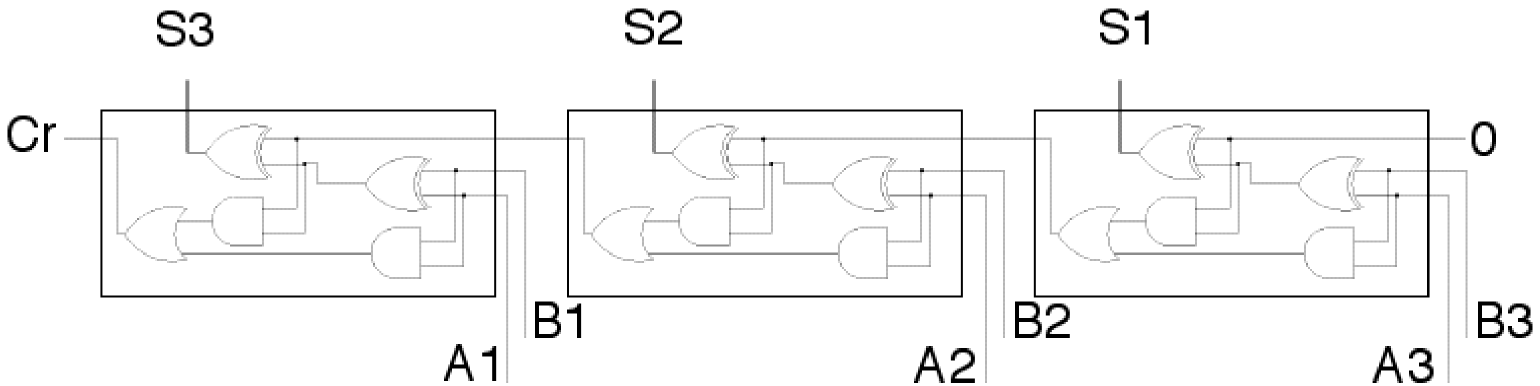
In modern computers the information is processed via networks of logic gates that perform all the mathematical operations through assemblies of basic Boolean functions. E.g. the NAND gate that due to its universal character can be widely employed to be networked in connected networks in order to perform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





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



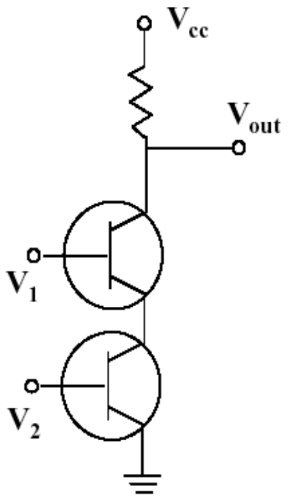


Logic gates and switches

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

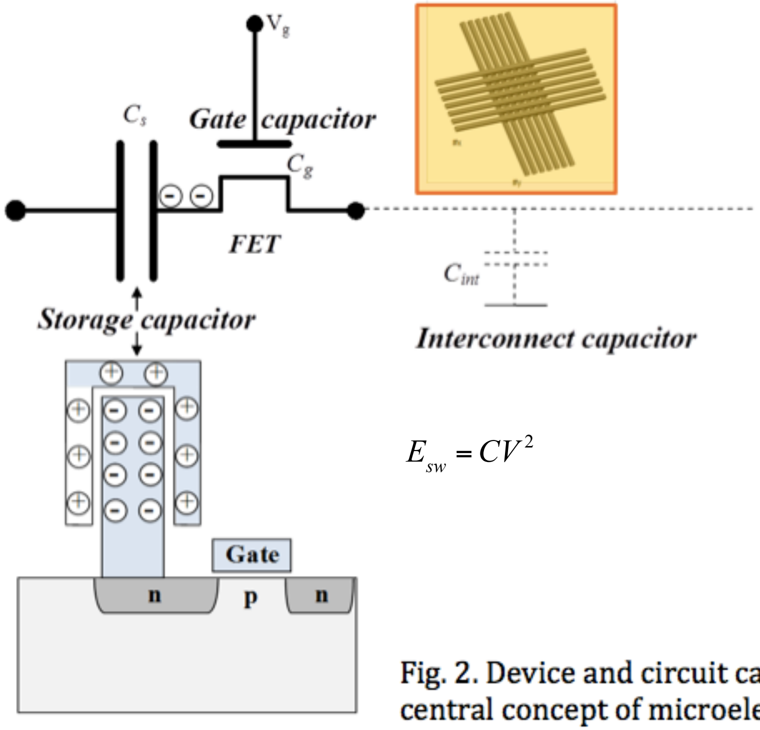


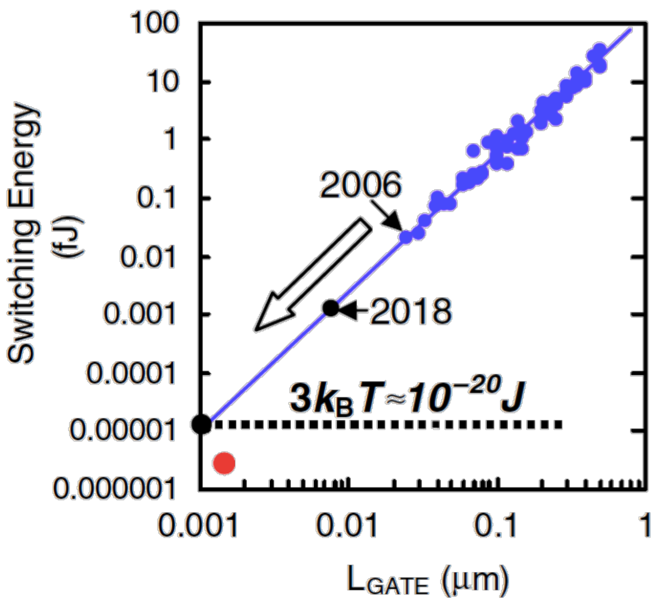
Fig. 2. Device and circuit capacitance as a central concept of microelectronics.

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

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

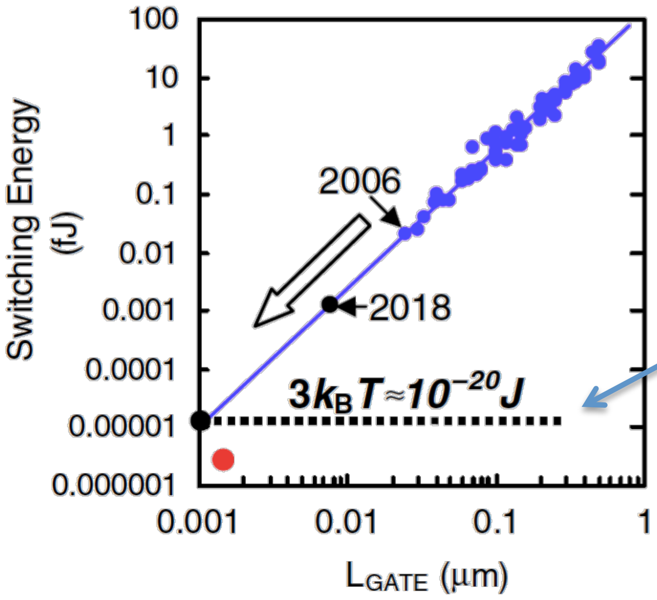
Thus, the search for alternative switches is presently very active.

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?



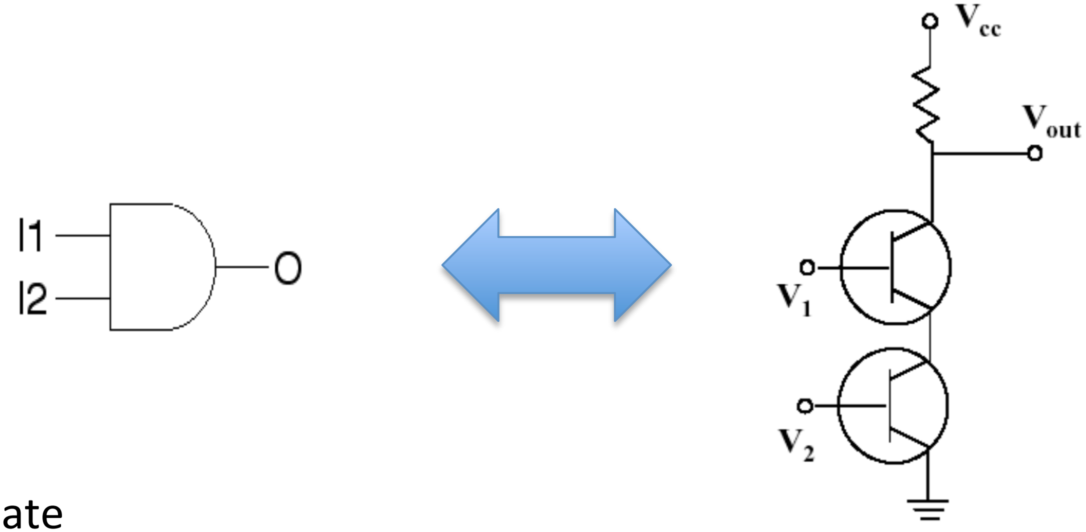
Limit for EE

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

The switch

Logic gates are made by switches (presently transistors) and also memory cells can be represented in terms of switches.

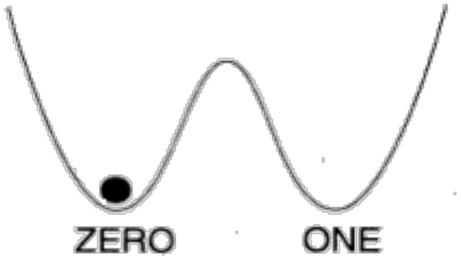
I1	I2	O
0	0	0
0	1	0
1	0	0
1	1	1



NAND gate

The switch

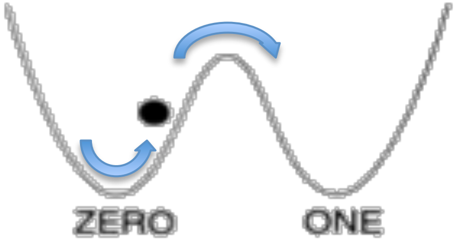
A simple switch can be represented by a physical dynamical model based on a bistable potential



We need a potential barrier in order to allow for physical distinguishability of the two states

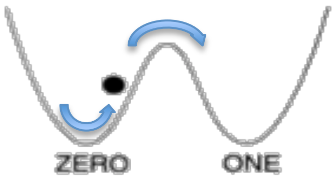
The switch

A simple switch can be represented by a physical dynamical model based on a bistable potential

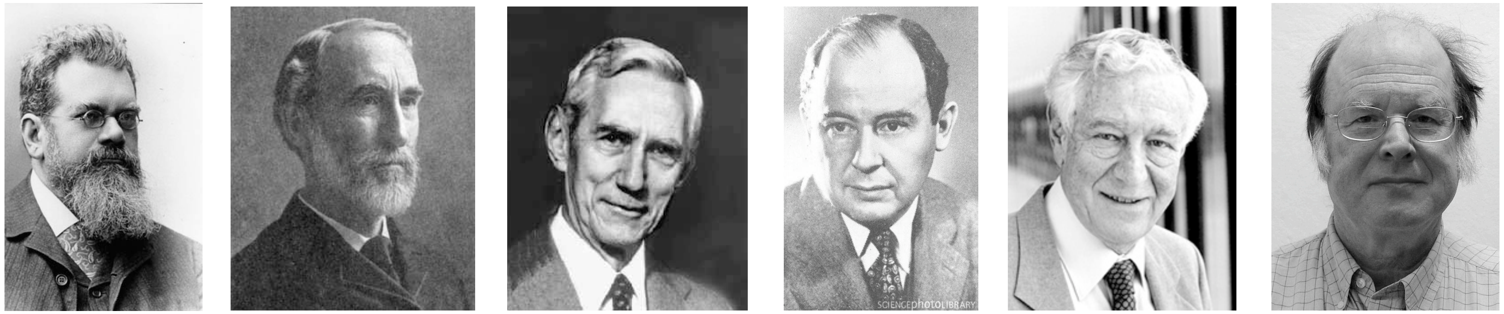


Switch event

Questions

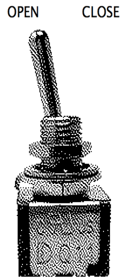


- What is the minimum energy we have to spend if we want to produce a switch event ?
- Does this energy depends on the technology of the switch ?
- Does this energy depends on the instruction that we give to the switch ?
- ….

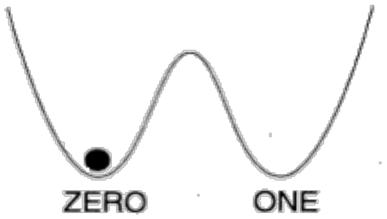


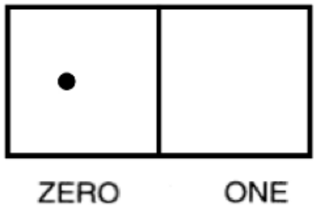
Some answers are still controversial…

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.





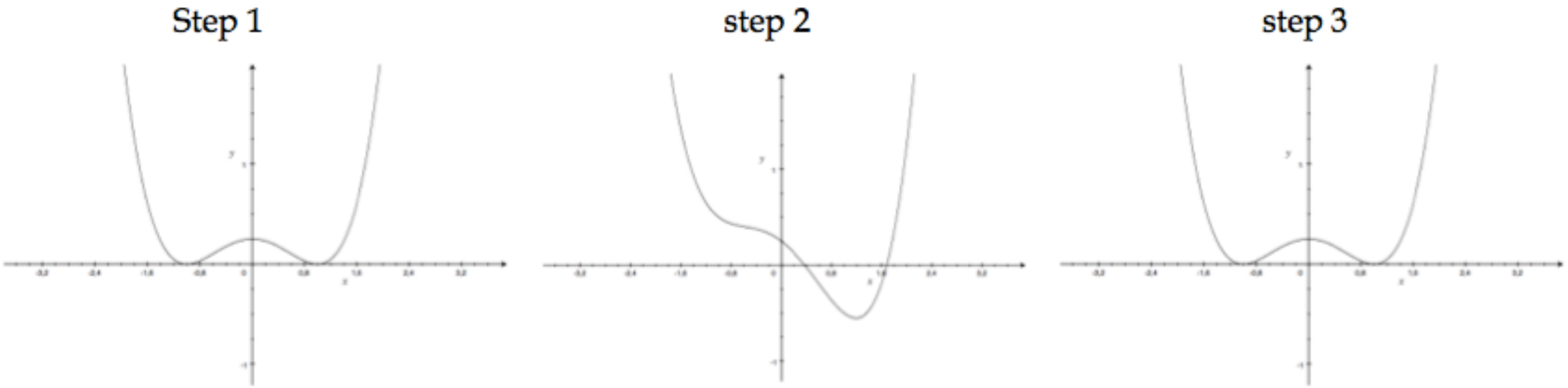
The two states, in order to be dynamically stable, are separated by some energy barrier that should be surpassed in order to perform the switch event.
This situation can be mathematically described by a second order differential equation like:

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

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 $F_0 > 0$



Step 1 step 2 step 3

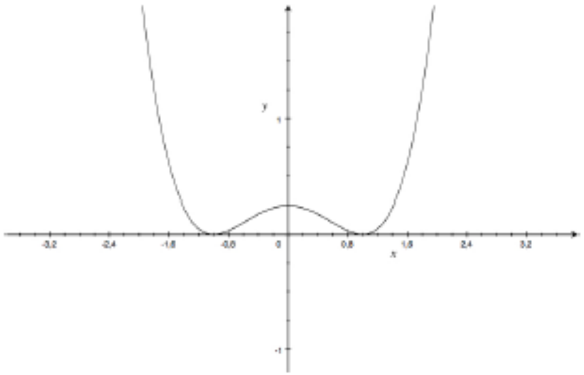
We can ask what is the minimum work that the force F has to perform in order to make the device switch from 0 to 1 (or equivalently from 1 to 0).
The work is computed as:

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

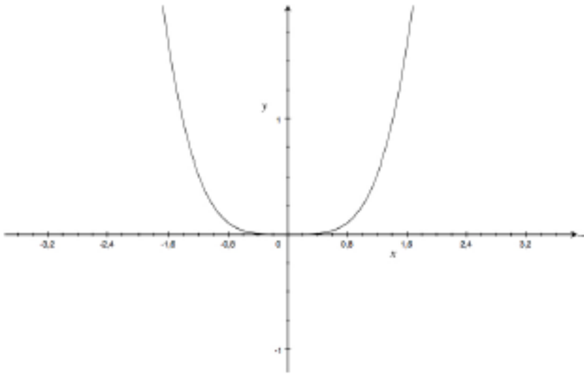
The Physics of switches

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

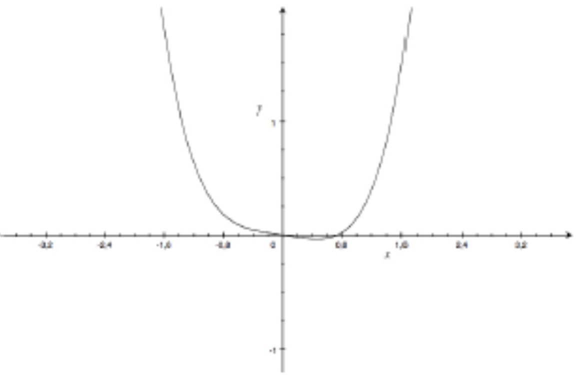
step 1



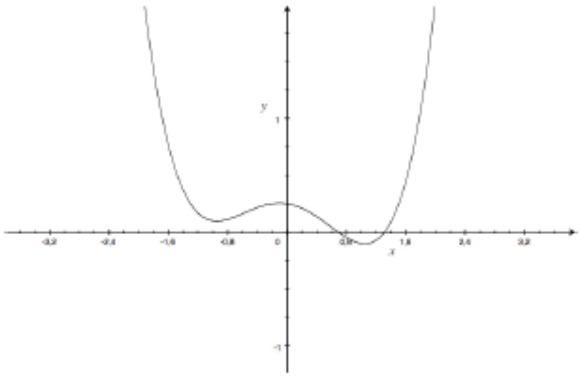
step 2



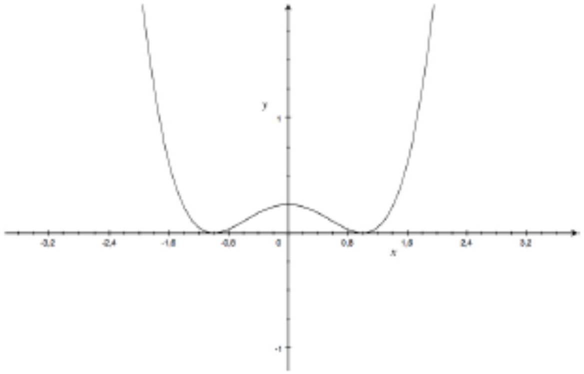
step 3



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 $F_1 << F_0$ 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 can be made arbitrarily small.

IS THIS TRUE?

$$\Delta U = L - Q$$

$$\Delta U = 0 \quad \longrightarrow \quad L = Q$$

The second principle of thermodynamics requires that: $Q \geq T\Delta S$

$$Q = T\,\Delta S + \mathit{friction}$$

We might be able to make friction = 0 but…what about entropy?

The Physics of realistic switches

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

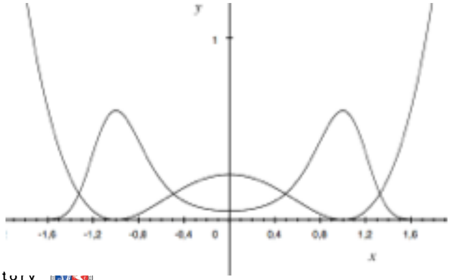
$$m\ddot{x} = -\frac{d}{dx}U(x) - m\gamma\dot{x} + \xi(t) + F$$

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:

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

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:

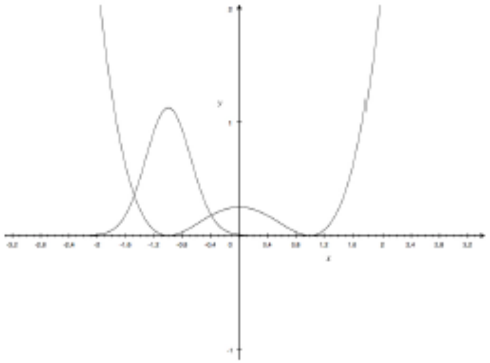
$$S = -K_B \sum_i p_i \log p_i$$

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

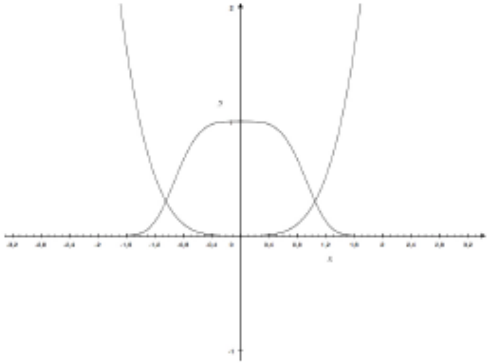
The Physics of realistic switches

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

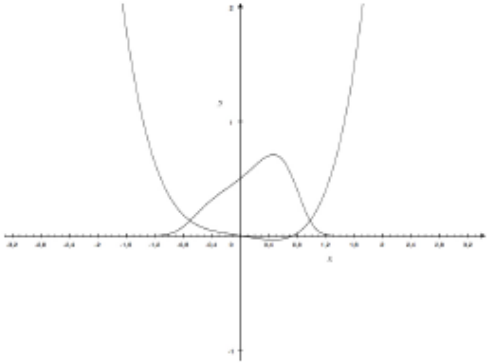
step 1



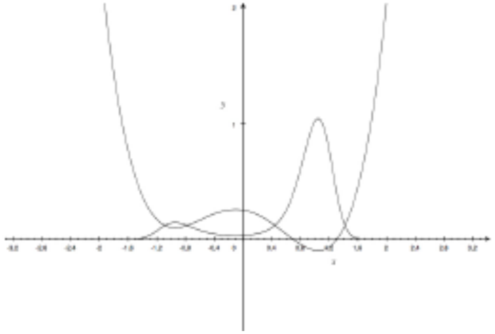
step 2



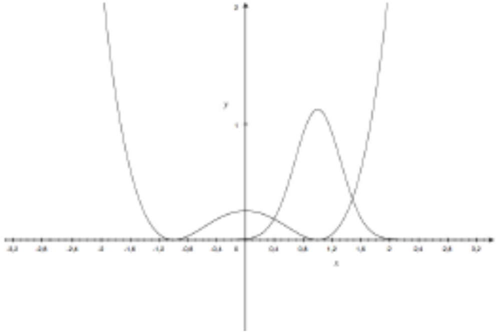
step 3



step 4



step 5



we observe a change in entropy:

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

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:

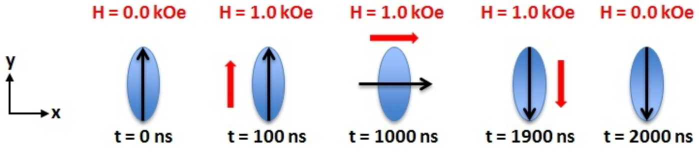
1) The total work performed on the system by the external force has to be zero.
2) The switch event has to proceed with a speed arbitrarily small in order to have arbitrarily small losses due to friction.
3) The system entropy never decreases during the switch event.

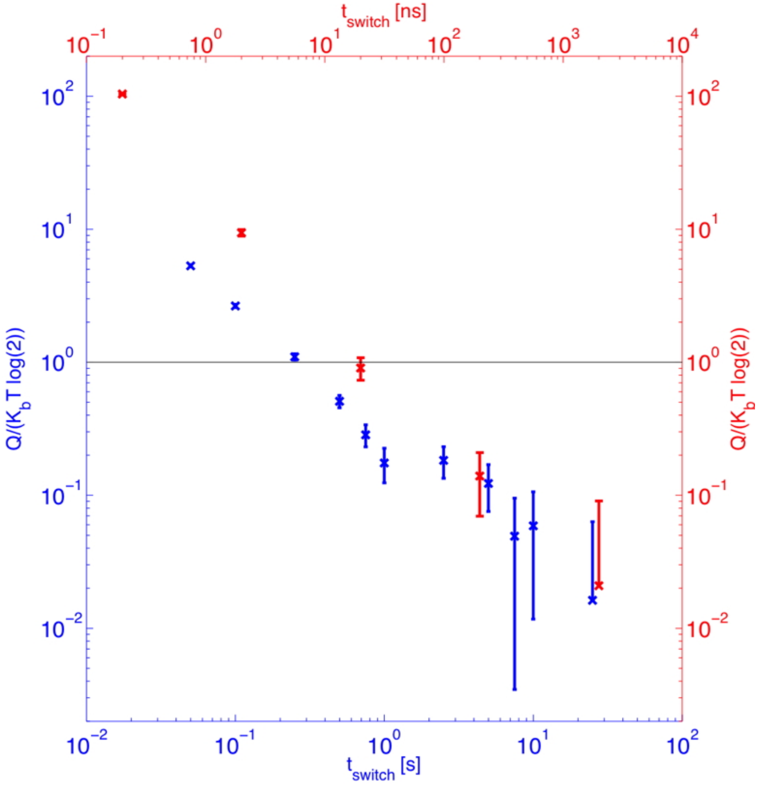
Is it possible?   For a switch operation yes… at least in principle…

LANDAUER

FUTURE & EMERGING TECHNOLOGIES

Operating ICT basic switches below the Landauer limit





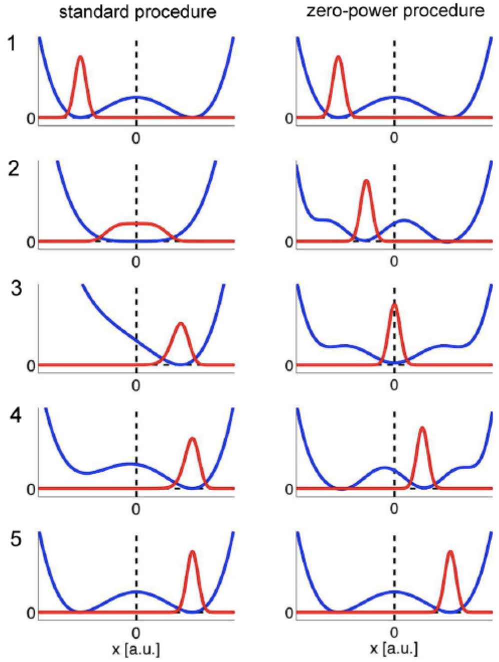
More info available at www.landauer-project.eu

Magnetic nano dots

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

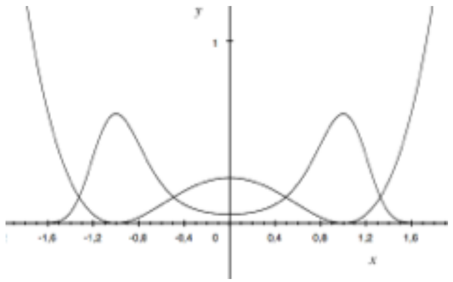
Entropy changes

Entropy stays constant

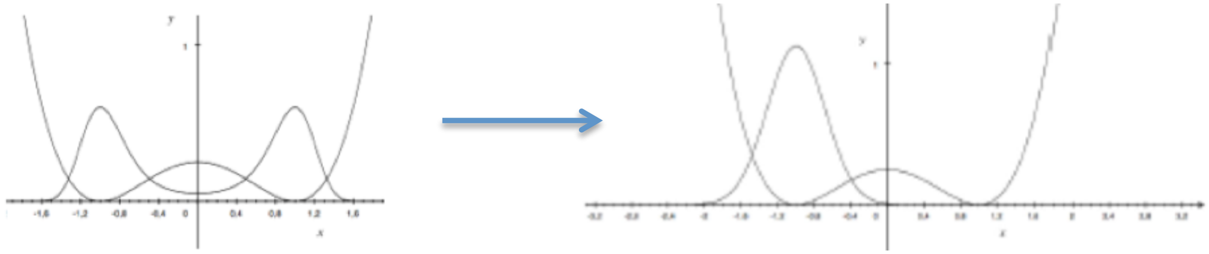


The Physics of realistic switches: the reset

But… let’s suppose we start from an equilibrium condition



In this case if we want to use the switch we need to operate a reset operation



Is there a minimal cost for this operation?

THE VON NEUMANN-LANDAUER BOUND

The Landauer's principle (1) 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.

Please note: this is the **minimum** energy required.

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

Can we design computers that are operated without spending any energy?

Can we design computers that are operated without spending any energy?

YES !

(provided we do not decrease information **IN** the computing device)

REVERSIBLE COMPUTING

C. H. Bennett, "Logical reversibility of computation," IBM Journal of Research and Development, vol. 17, no. 6, pp. 525-532, 1973.

I_{in} Information in

Computing device

I_{out} Information out

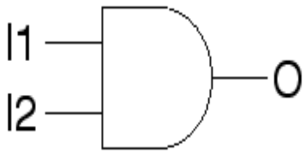
Logical reversibility: $I_{out} = I_{in}$

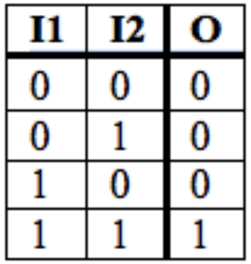
REVERSIBLE COMPUTING

I_{in} Information in

Computing device

I_{out} Information out

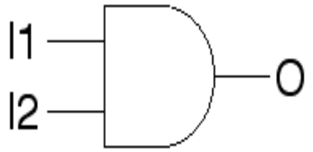




I1	I2	O
0	0	0
0	1	0
1	0	0
1	1	1

Logically irreversible: $I_{out} < I_{in}$

REVERSIBLE COMPUTING



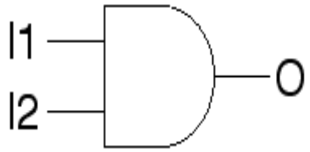
Logically irreversible: $I_{out} < I_{in}$

Can we design computers that are operated without spending any energy?

YES, provided we do not decrease information **IN** the computing device

Thus what is relevant is NOT the information balance between input and output but the change in entropy IN the device.

ZERO-POWER COMPUTING



Logically irreversible: $I_{out} < I_{in,}$ **BUT PHYSICALLY REVERSIBLE**

This is realized by building logic gates with switches that allow for zero energy expenditure, during the switch process.

Candidates ?

To know more

- www.nipslab.org, www.ict-energy.eu

- Review article: Towards zero-power ICT, L Gammaitoni, D Chiuchiú, M Madami, G Carlotti
  Nanotechnology 26 (22), 222001 (2015)

- Book: *ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology*, InTech, February 2, 2014.