Computing below the expected energy limits

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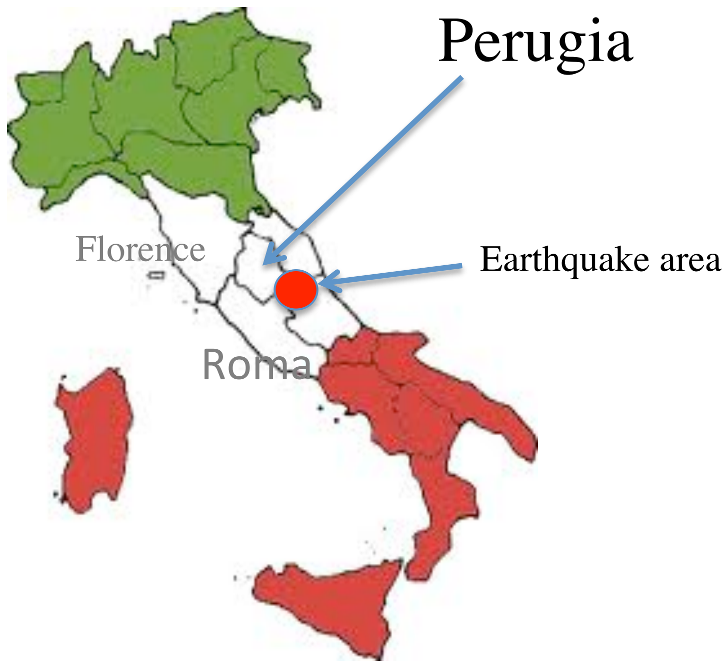
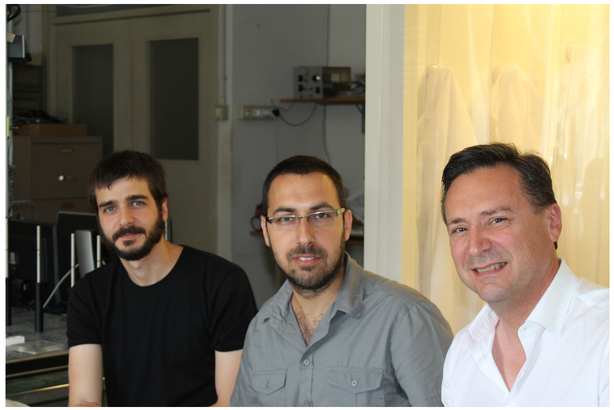


E.C. FET Proactive GA Landauer 318287
ONRG grant N00014-11-1-0695

NiPS Laboratory
Noise in Physical Systems

2016 (13 FT, 1 PT)



M. Lopez-Suarez, I. Neri, L.G.

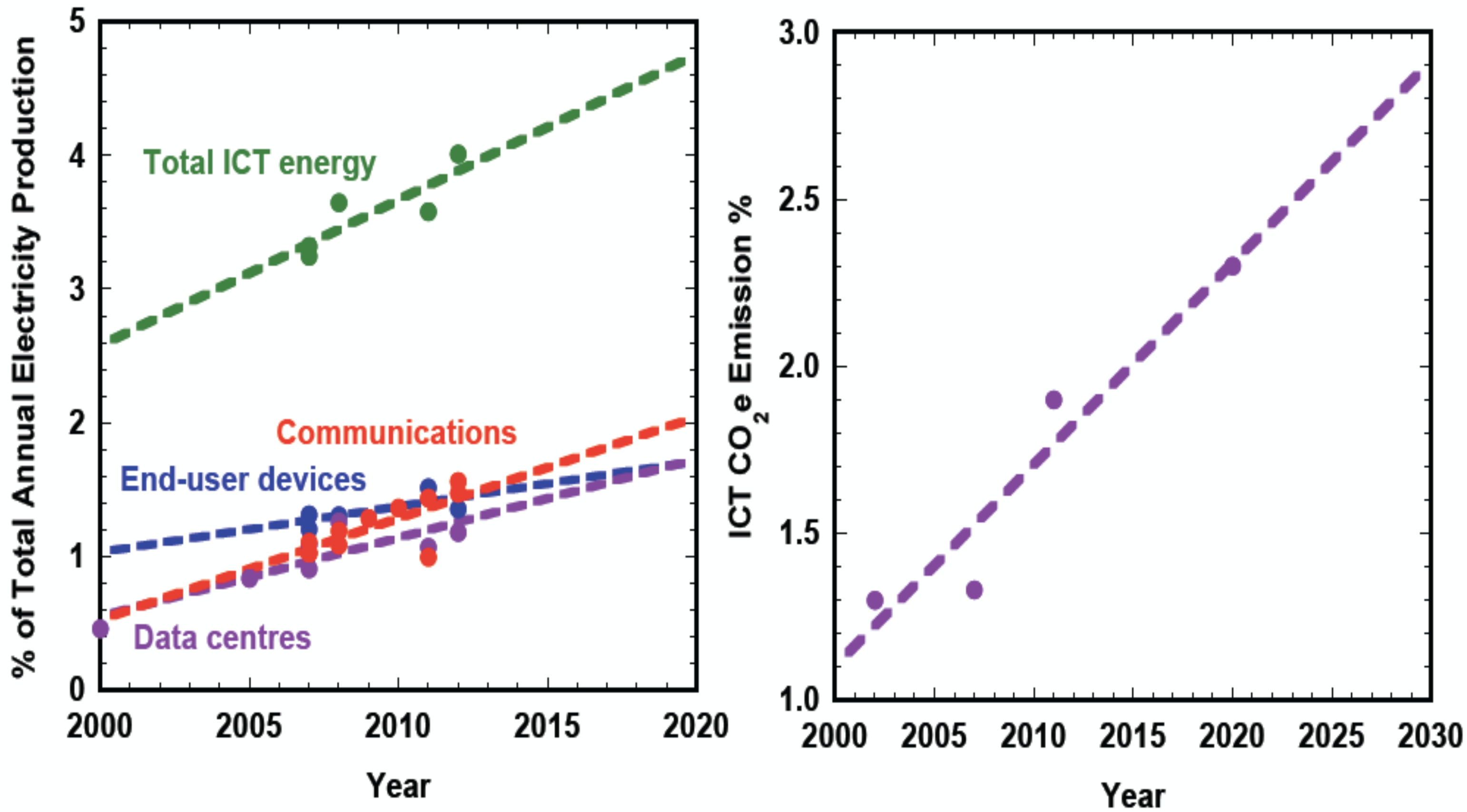
WISEPOWER

Present computers are energy hungry

April 4, 2005

March 13, 2013

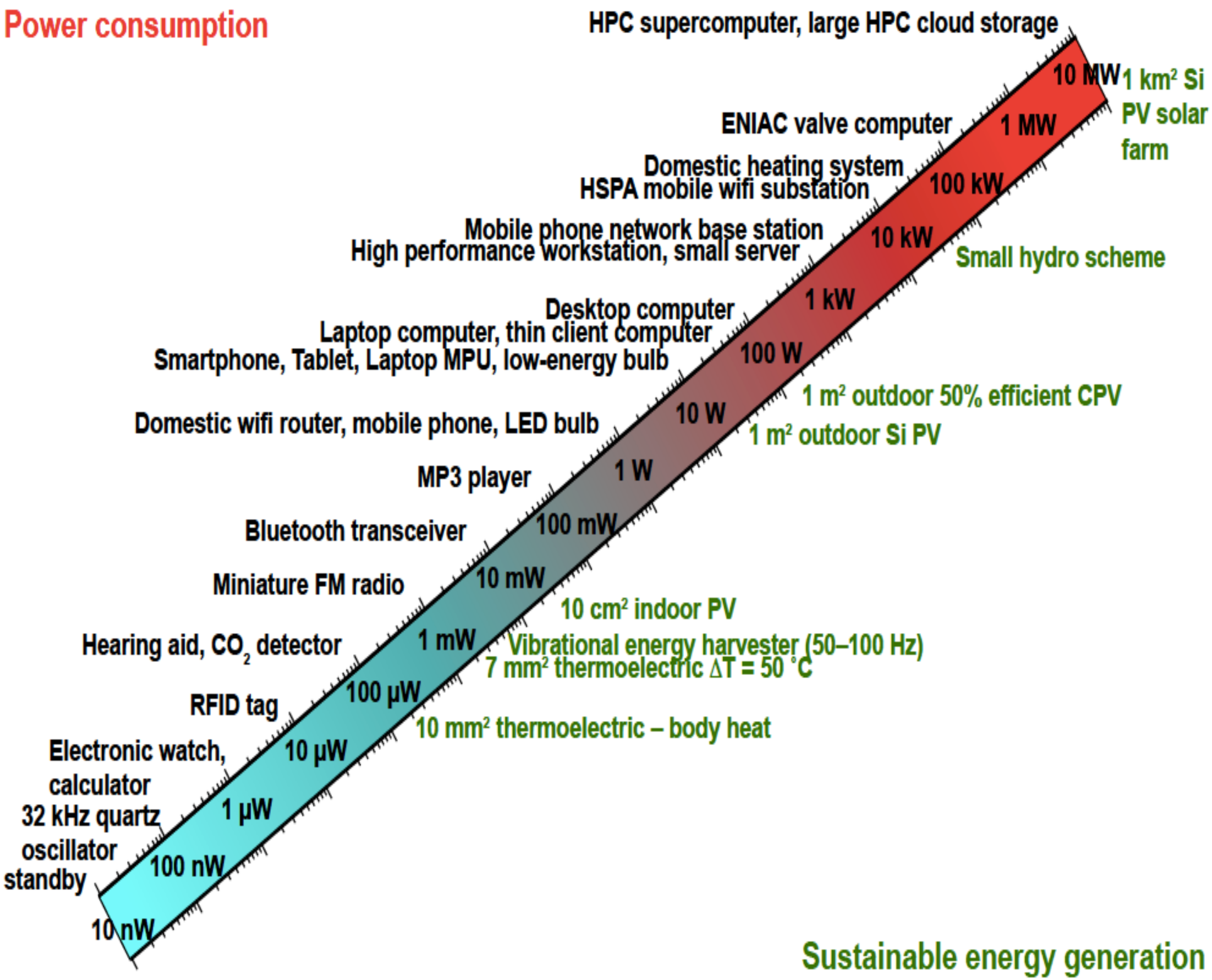
ICT global energy consumption



- **This excludes TV, media, publishing, games, power switches, domestic & industrial ICT devices**

Source: D. Paul, ICT-Energy Research Agenda, 2015

ICT energy requirements

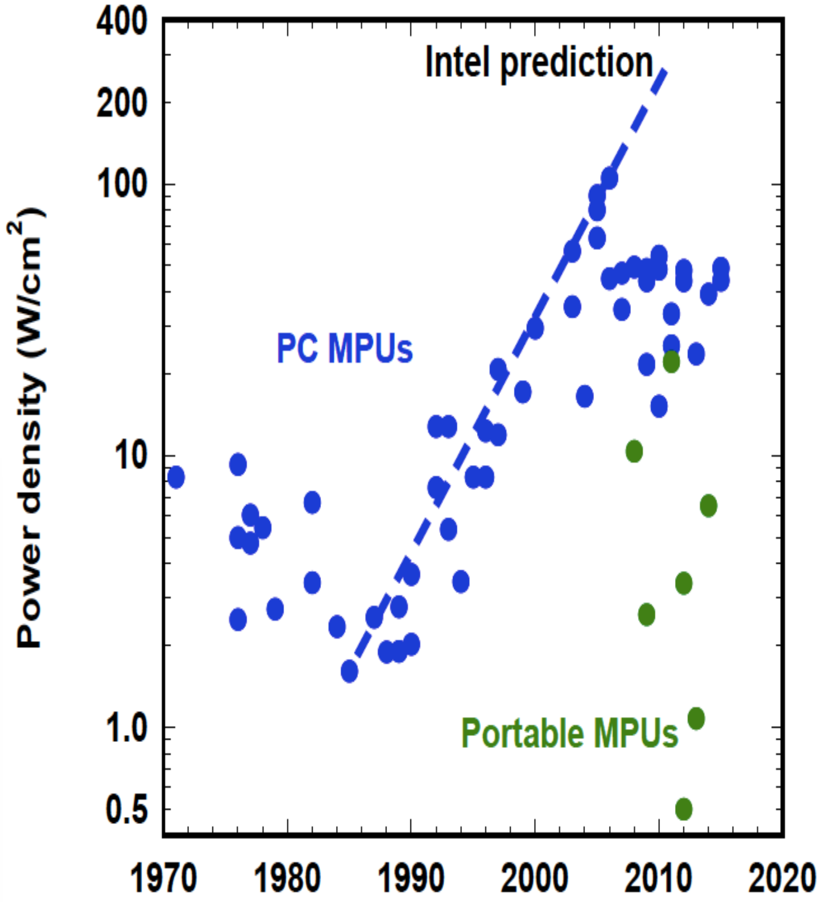


Source: D. Paul, ICT-Energy Research Agenda, 2015

Reducing energy is strategic

If we want more powerful supercomputers

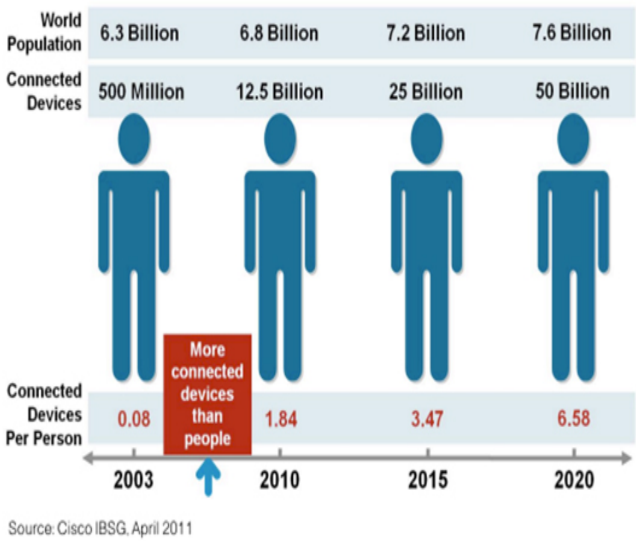
...to avoid microprocessor burning



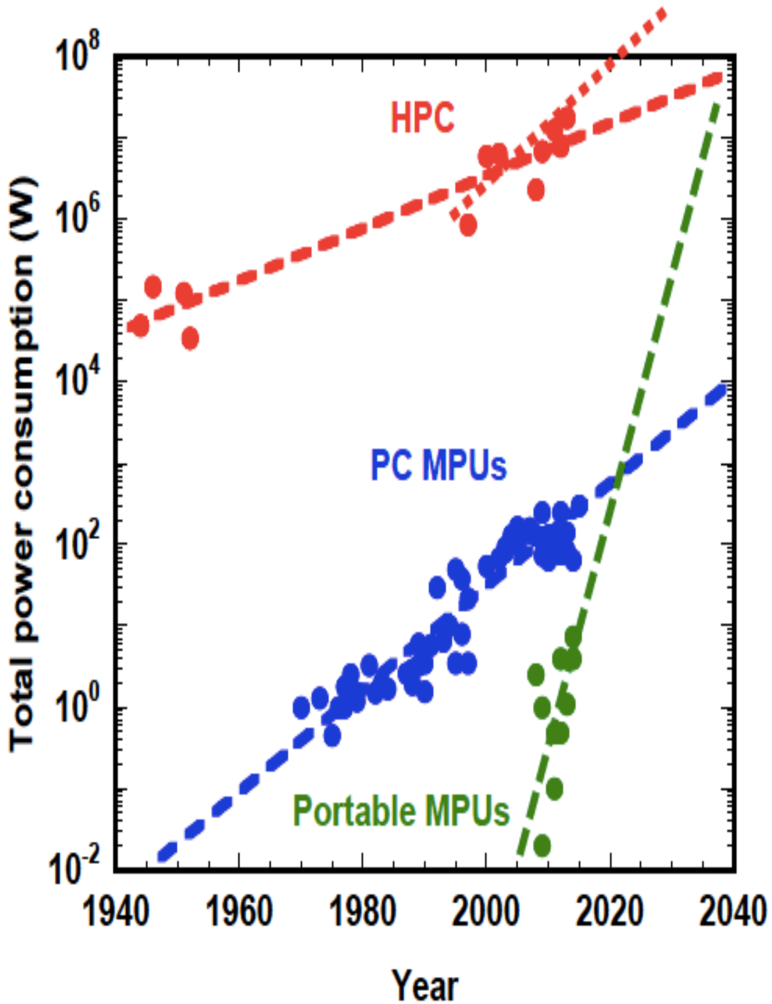
Source: D. Paul, ICT-Energy Research Agenda, 2015

Reducing energy is strategic

If we want the **Internet of Things** to happen



…to avoid lacking autonomous power



Source: D. Paul, ICT-Energy Research Agenda, 2015

What can we do?

If I could build any machine for doing computing, what is going to be the minimum energy required to do computation with it?

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

Computers are physical systems that process information while changing work into heat

By the moment that information processing/computing can be associated with the change of bits, in order to perform this activity we need two very important ingredients:

a) a physical system capable of assuming two different physical states: S_0 and S_1

b) a set of forces that induce state changes in this physical system:

F_{01} produces the change $S_0 \rightarrow S_1$

F_{10} produces the change $S_1 \rightarrow S_0$.

A simple system to perform computation

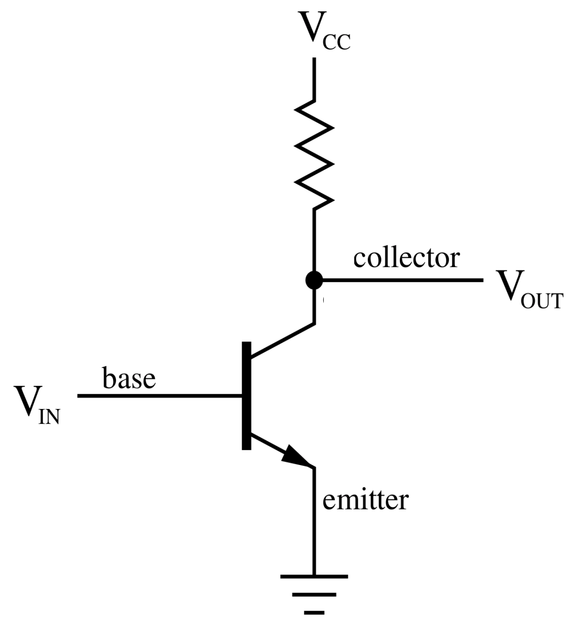
the physical system, made by a pebble* and two bowls.

a) The two states are represented by the measurable quantity “position of the pebble”: state “0” = pebble in left bowl; state “1” = pebble in right bowl;
b) the way to induce state changes represented by a force that brings around the pebble.

* “Calculus” is the Latin word for pebble

Devices that obeys the rules a) and b) are called *binary switches*.

In modern computers binary switches are made with transistors. These are electronic devices that satisfy the two conditions required:



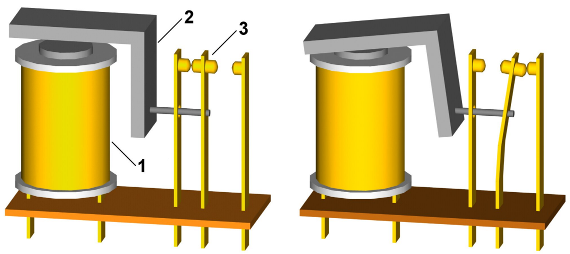
a) The two states are represented by the measurable quantity “electric voltage” at point V_{OUT}. As an example state “0” = $V_{OUT} < V_T$; state “1” = $V_{OUT} > V_T$; with V_T a given reference voltage.

b) The way to induce state changes represented by an electromotive force applied at point V_{IN}.

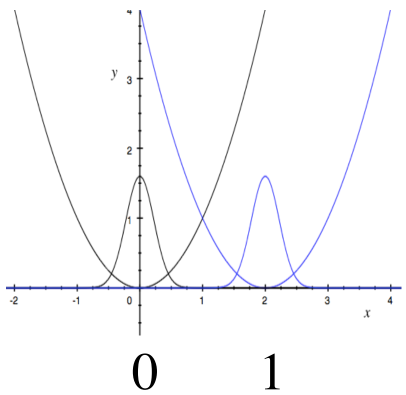
Minimum Energy of Computing, Fundamental Considerations, Victor Zhirnov, Ralph Cavin and Luca Gammaitoni
in the book "ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology”, InTech, 2014

Binary switches

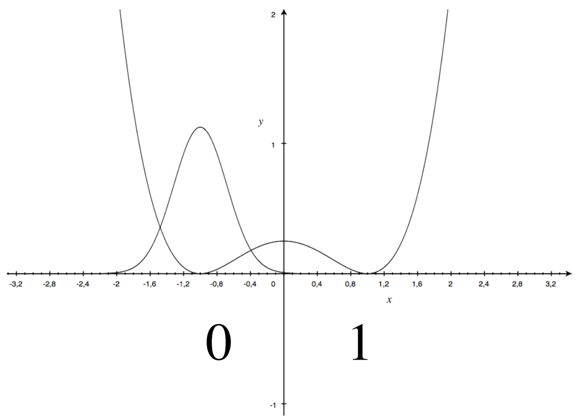
There exist at least two classes of devices that can satisfy the rules a) and b).
We call them ***combinational*** and ***sequential*** devices.



Conbinational:
in the absence of any external force, under equilibrium conditions, they are in the state S_0. When an external force F_{01} is applied, they switch to the state S_1 and remain in that state as long as the force is present. Once the force is removed they go back to the state S_0.

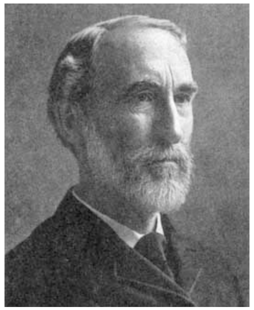
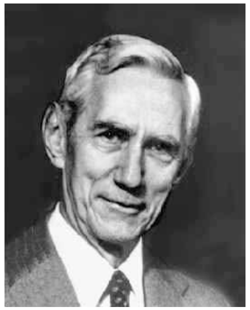


Sequential:
They can be changed from S_0 to S_1 by applying an external force F_{01}. Once they are in the state S_1 they remain in this state even when the force is removed. They go from S_1 to S_0 by applying a new force F_{10}. Once they are in S_0 they remain in this state even when the force is removed.



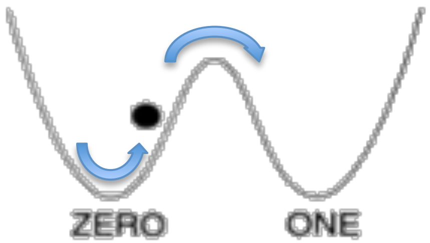
Questions

- 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 ?
- ….

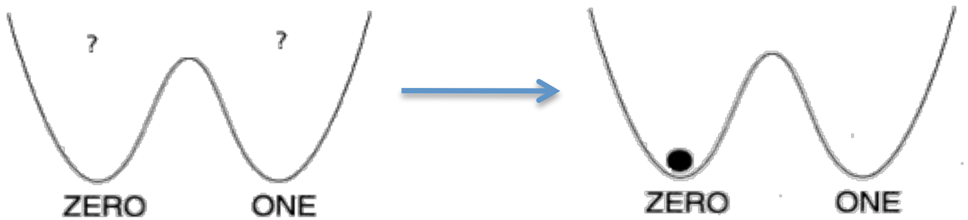
     

There are two basic operations we can do with a sequential switch

The switch operation (i.e. the change of state)

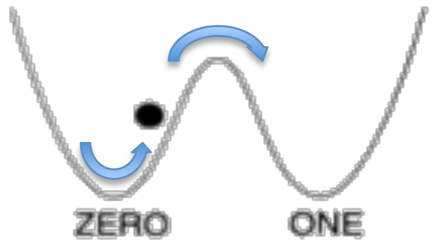


The reset operation (i.e. the set of a given state starting from an unknown state)



Let's look at this, with a reasoning introduced in 1961 by R. Landauer

The single switch operation



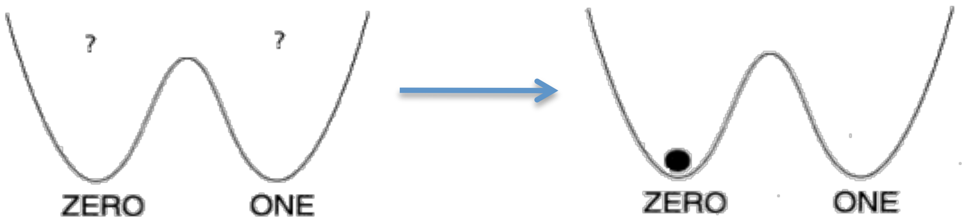
0 → 1

Before the switch = 1 logic state
After the switch = 1 logic state

Change in entropy = $S_f - S_i = K_B \log(1) - K_B \log(1) = 0$

No net decrease in entropy ---> no minimum energy required

The reset operation



$? \longrightarrow 0$

Before the reset = 2 possible logic states
After the reset = 1 logic state

Change in entropy = $S_f - S_i = K_B \log(1) - K_B \log(2) = - K_B \log(2)$

Net decrease in entropy ---> **energy expenditure required**

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.

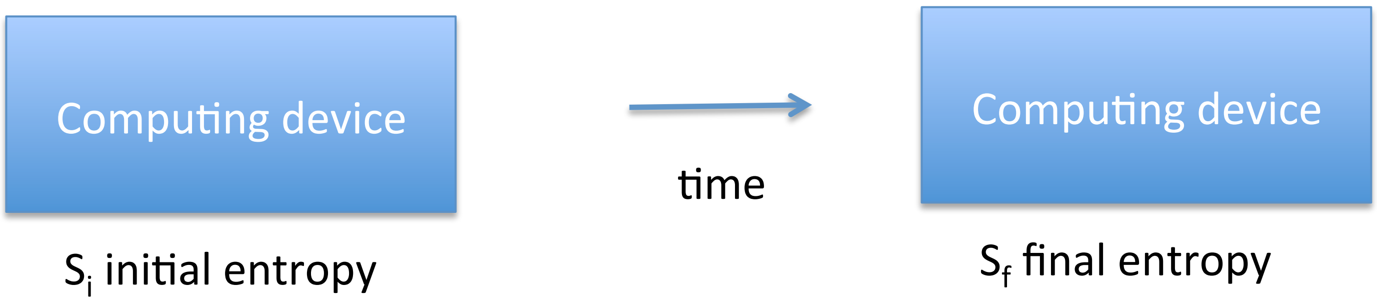
(1) R. Landauer, "Dissipation and Heat Generation in the Computing Process" *IBM J. Research and Develop. 5,* 183-191 (1961),

LOGICAL REVERSIBILITY

In the same paper Landauer generalized this result associated with the reset operation to the cases where there was a decrease of information between the input and the output of a computing system.
Landauer wrote:

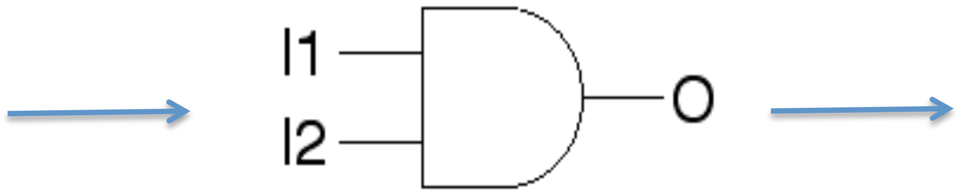
*We shall call a device logically irreversible if the output of a device does not uniquely define the inputs. We believe that devices exhibiting logical irreversibility are essential to computing. Logical irreversibility, we believe, in turn **implies** physical irreversibility, and the latter is accompanied by **dissipative effects**.*

Change of paradigm: the Boltzmann thermodynamics was:



TRADITIONAL COMPUTING

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



I_{in} Information in

I_{out} Information out

Logically reversible COMPUTING ($I_{out} = I_{in}$)

Bennet wrote:

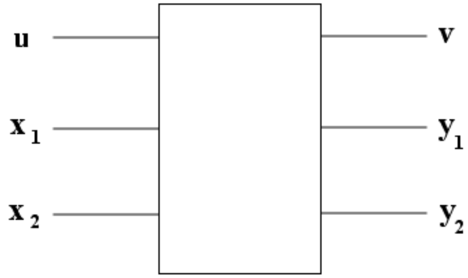
Landauer has posed the question of whether logical irreversibility is an unavoidable feature of useful computers, arguing that it is, and has demonstrated the physical and philosophical importance of this question by showing that whenever a physical computer throws away information about its previous state it must generate a corresponding amount of entropy.

Therefore, a computer ***must dissipate*** *at least $k_B T \ln \mathbf{2}$ of energy (about* ***3*** *X* ***10^{-21}*** *Joule at room temperature) for each bit of information it erases or otherwise throws away.*

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

LOGICALLY REVERSIBLE GATES

E. Fredkin



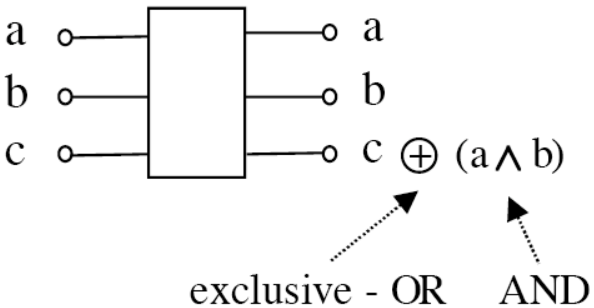
$v = u$

$y_1 = u\,x_1 + u'\,x_2$

$y_2 = u'\,x_1 + u x_2$

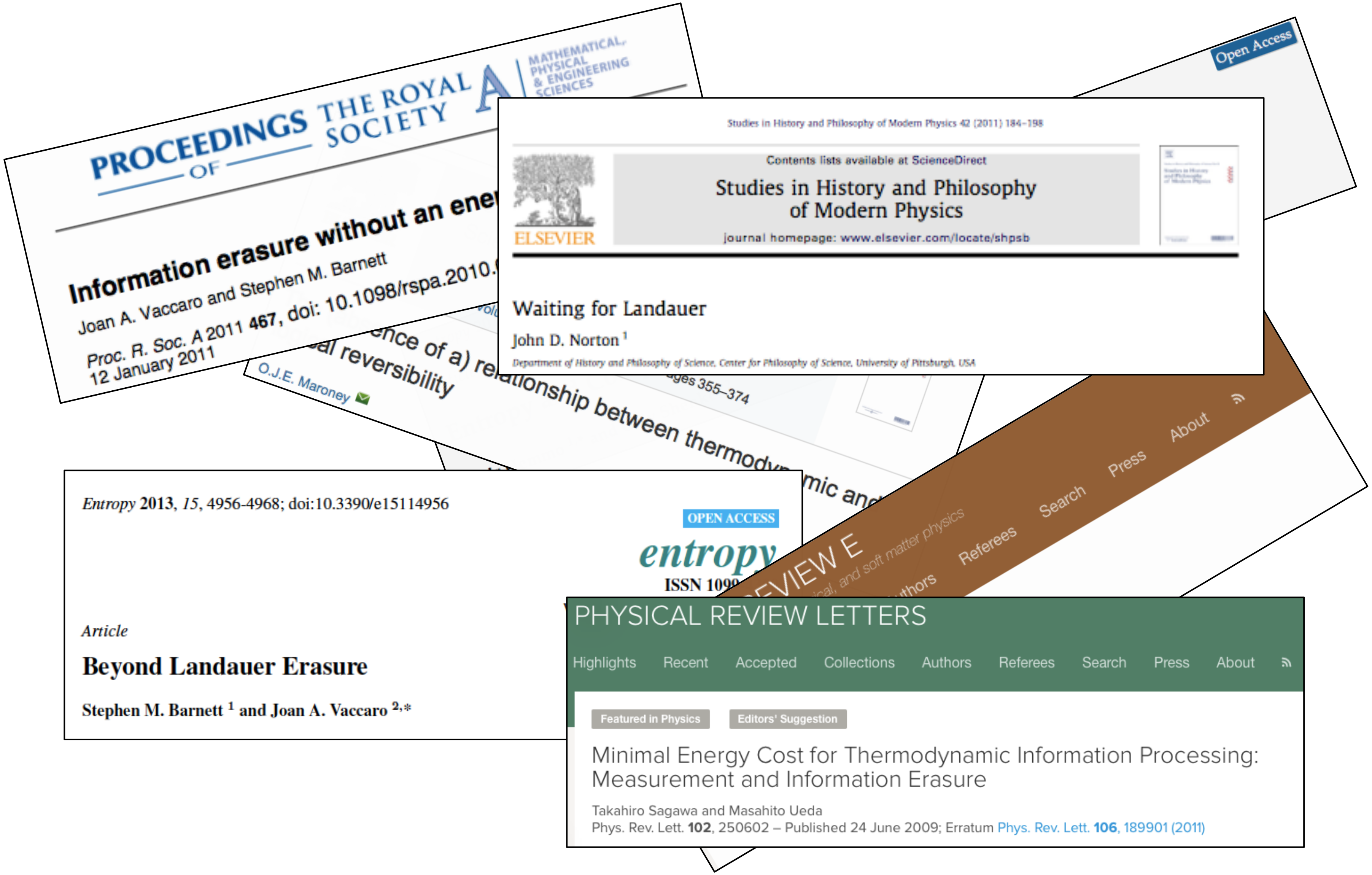
B. Toffoli

Toffoli gate



When and only when *a* and *b* are *1's*, *c* is inverted.

CONTROVERSIAL RESULT



EXPERIMENTS

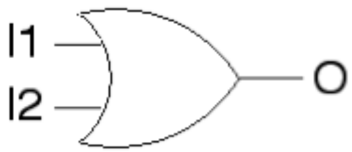
Testing the logical irreversibility limit

I_{in} Information in

I_{out} Information out

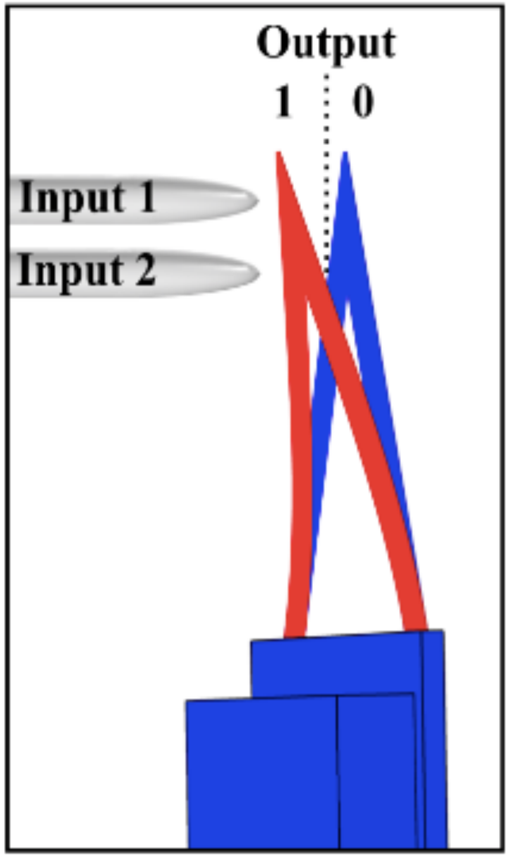
Logical irreversibility: $I_{out} < I_{in}$

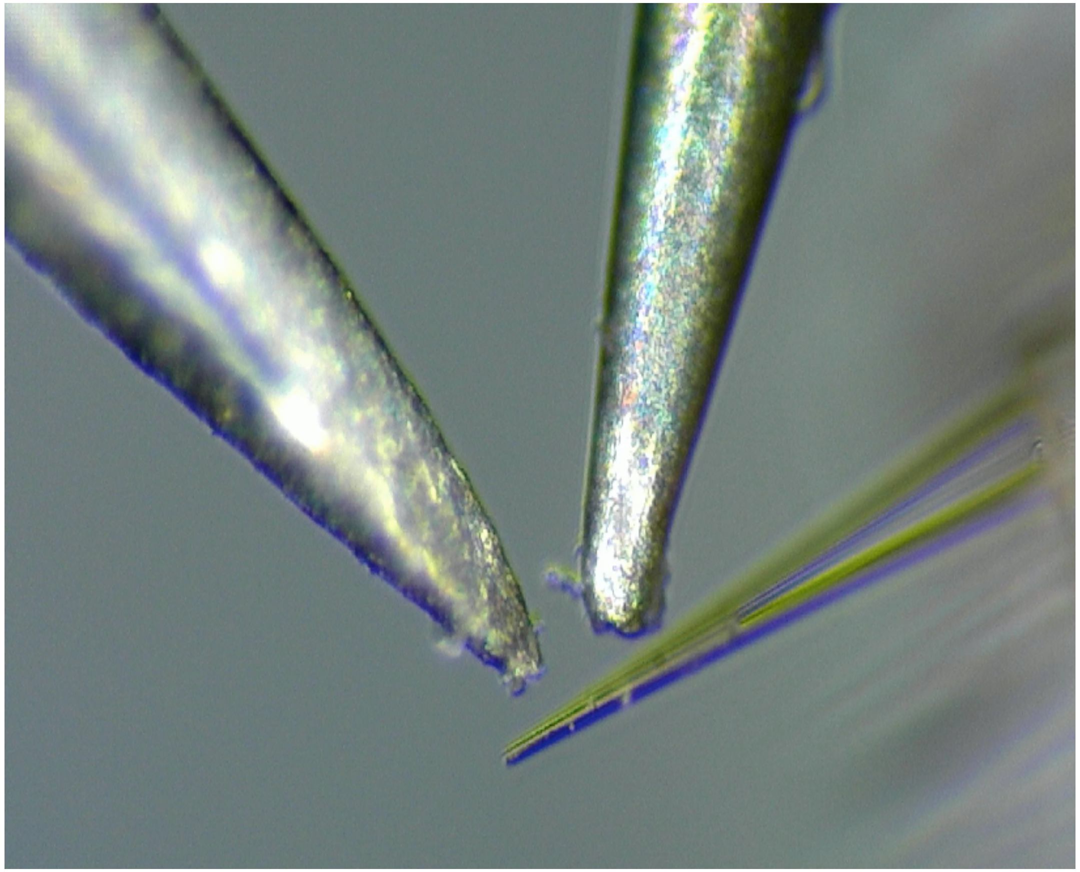
OR



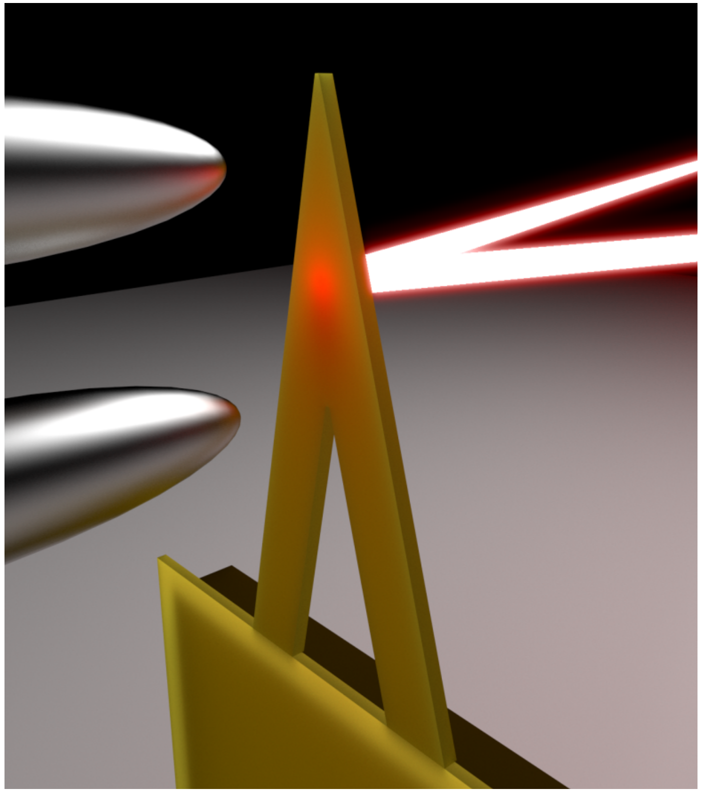
I1	I2	O
0	**0**	**0**
0	**1**	**1**
1	**0**	**1**
1	**1**	**1**

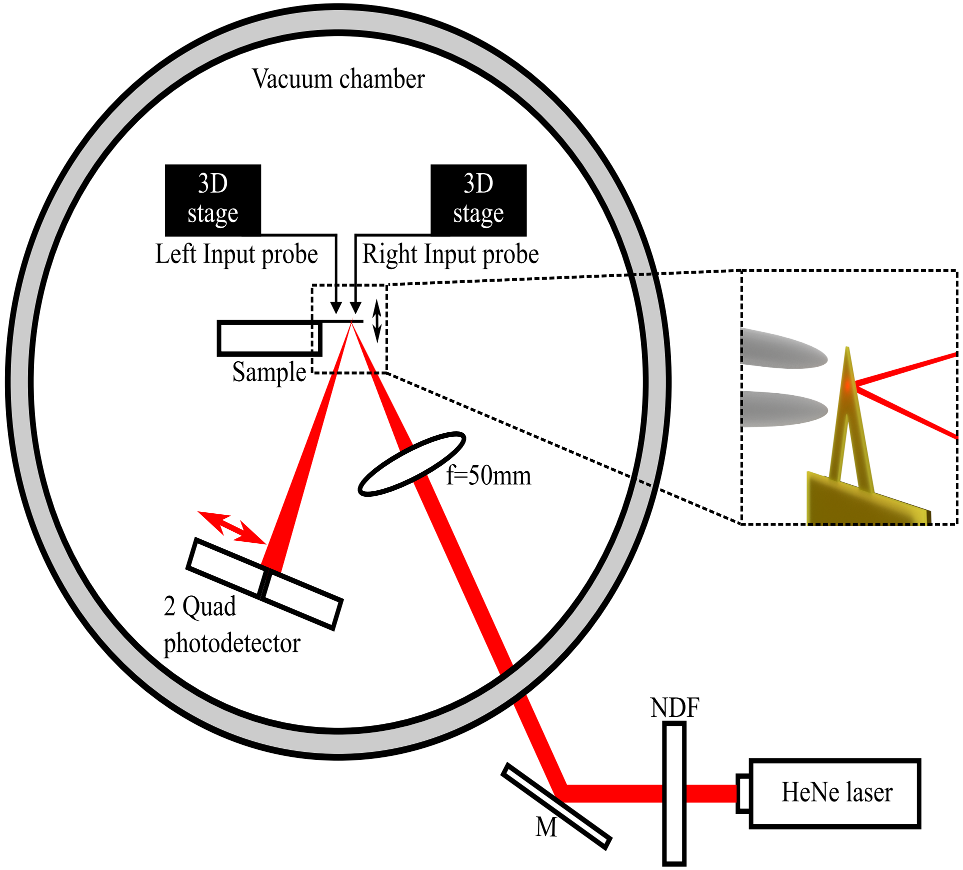
Micro electro-mechanical Logic gate

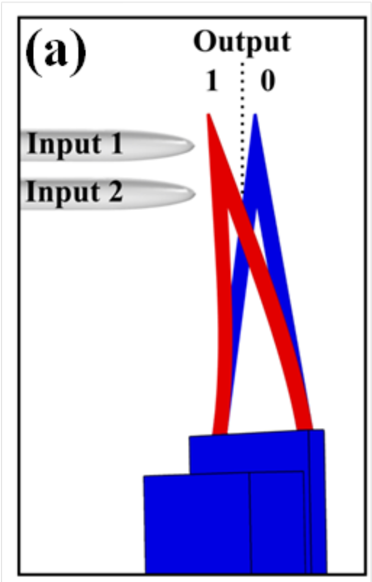


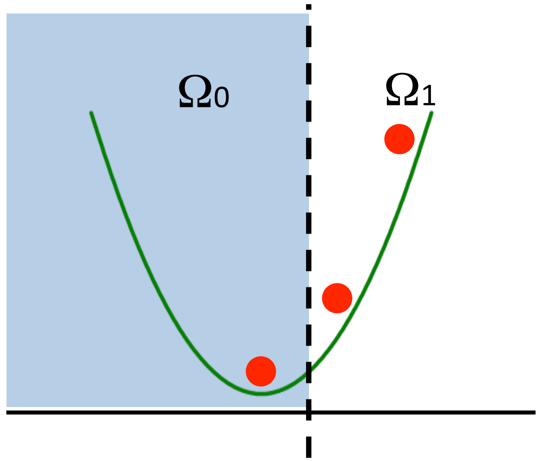


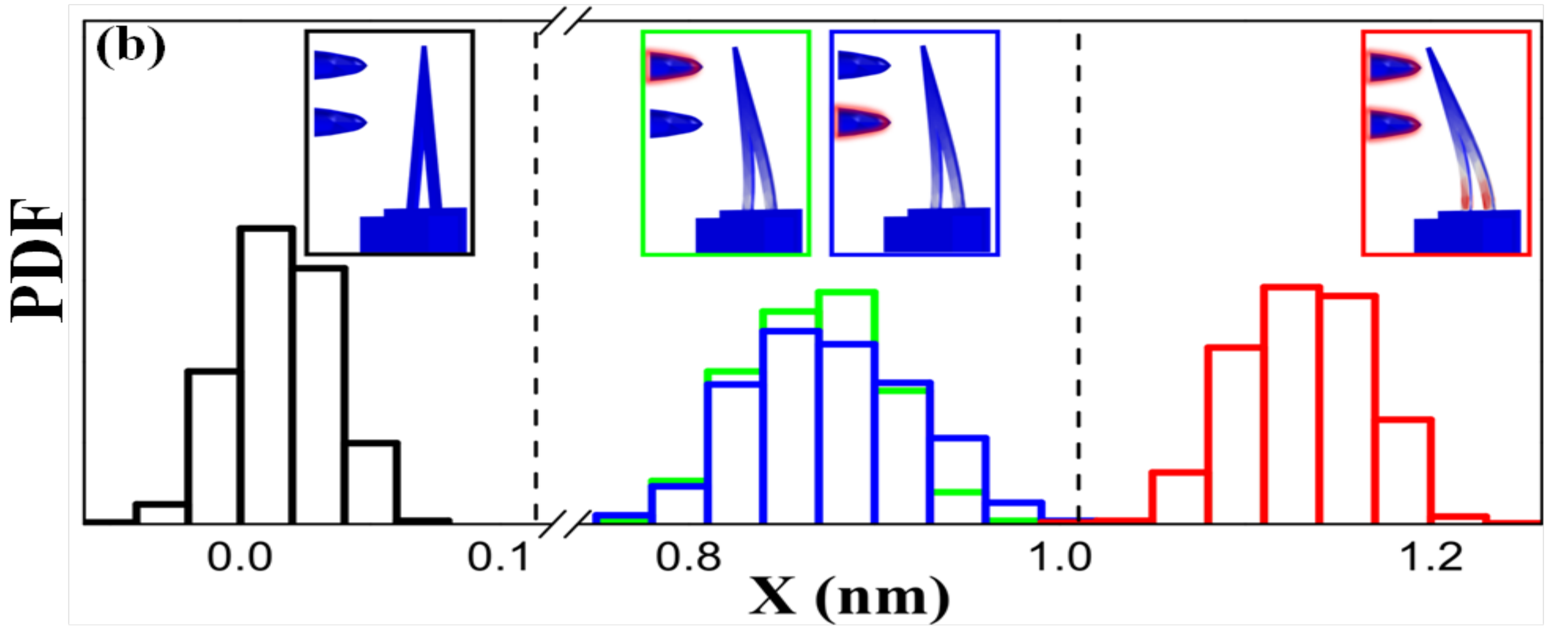
Micro electro-mechanical Logic gate



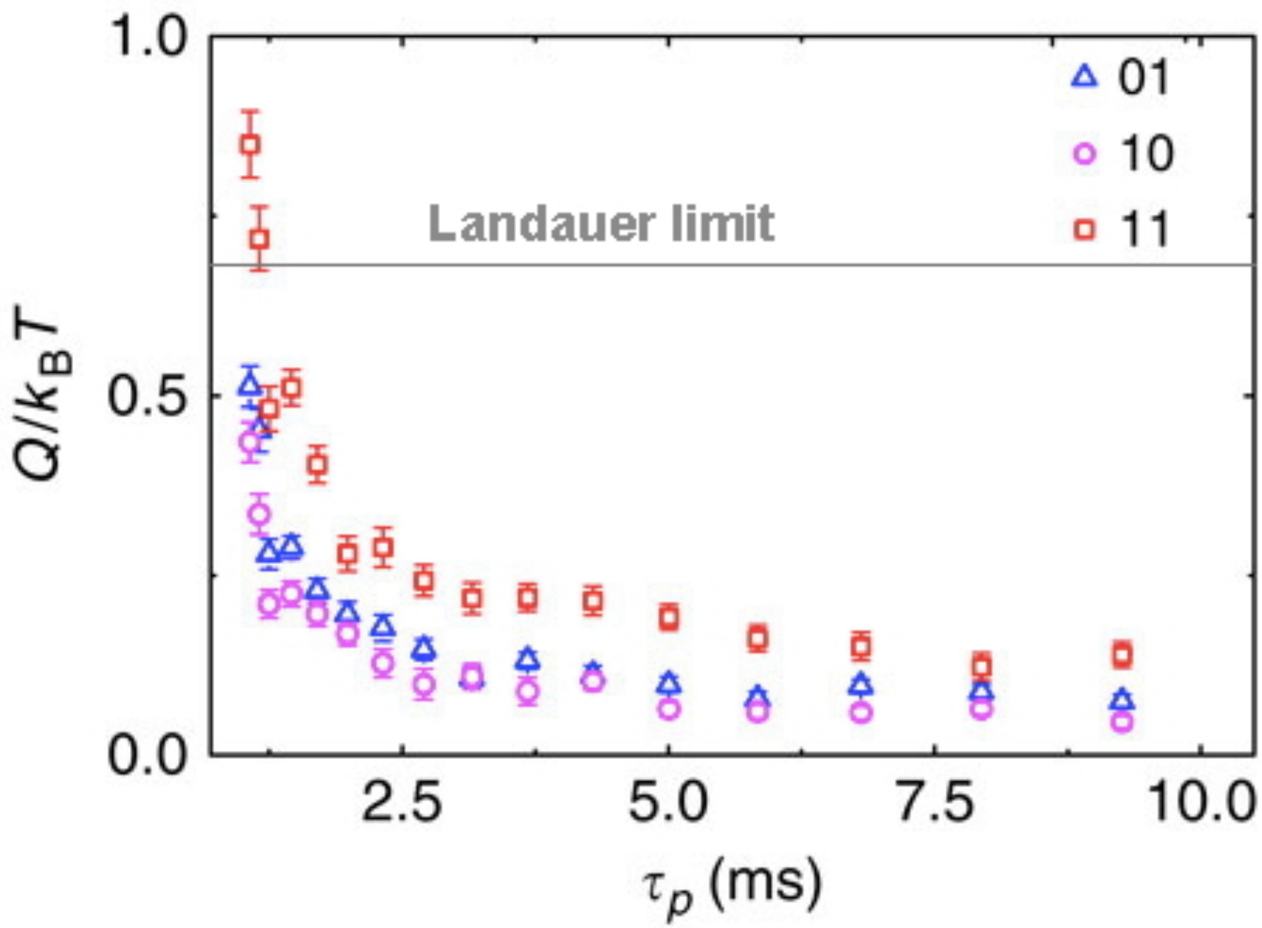



(a)
Output
1
0
Input 1
Input 2


Ω_0
Ω_1

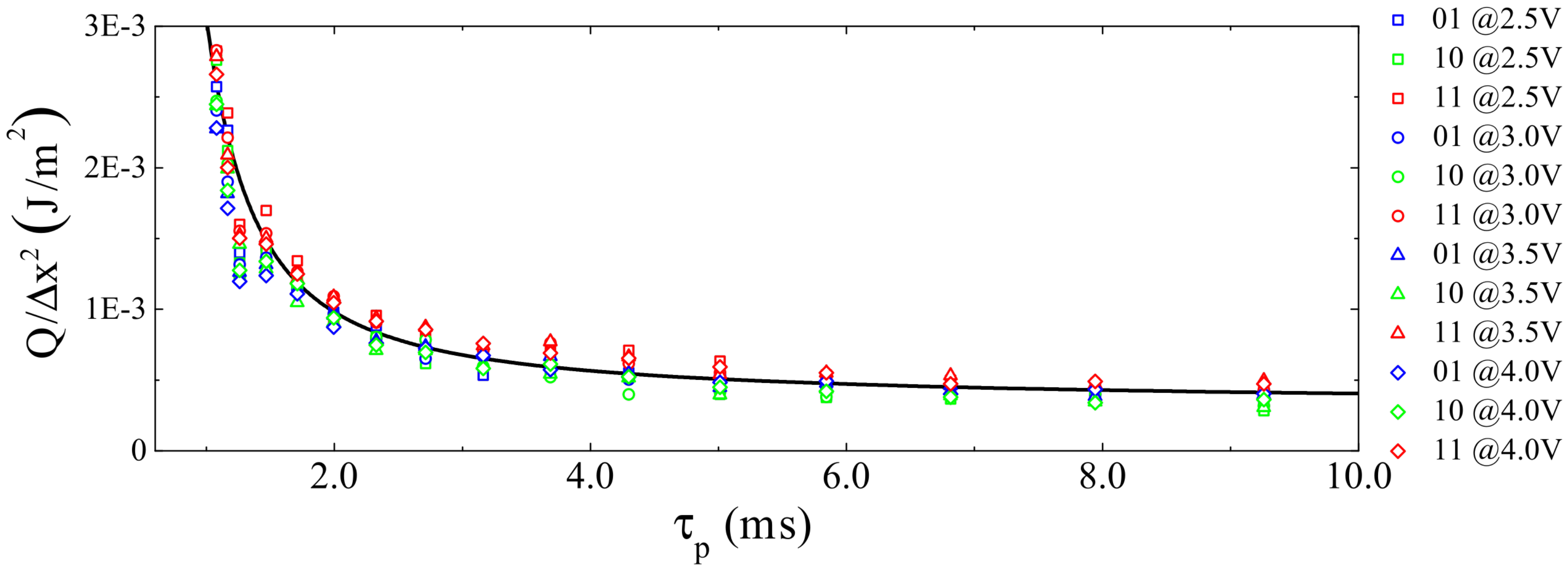

(b)
PDF
0.0
0.1
0.8
1.0
1.2
X (nm)

Measure of the energy dissipated during information processing with OR logic gate



Sub-kBT micro-electromechanical irreversible logic gate,
M. López-Suárez, I. Neri, L. Gammaitoni.
Nature Communications 7, Article number: 12068 (2016)

Dissipation model



Zener theory $-k(1+i\phi)$

$$\phi(\nu) = \phi_{\mathrm{str}} + \phi_{\mathrm{th-el}} + \phi_{\mathrm{vis}} + \phi_{\mathrm{clamp}}$$

LOGICAL REVERSIBILITY

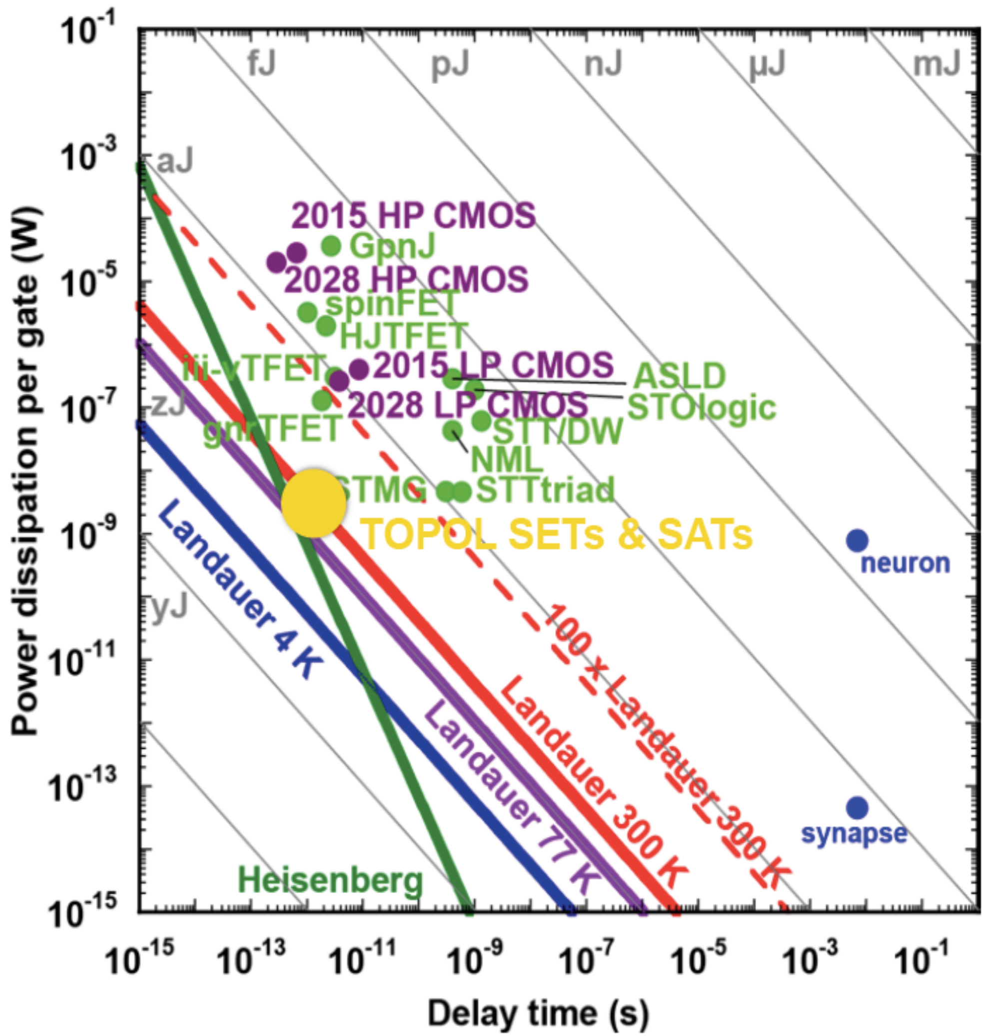
In the same paper Landauer generalized this result associated with the reset operation to the cases where there was a decrease of information between the input and the output of a computing system.

Landauer wrote:

We shall call a device logically irreversible if the output of a device does not uniquely define the inputs. We believe that devices exhibiting logical irreversibility are essential to computing. ***Logical irreversibility, we believe, in turn implies physical irreversibility, and the latter is accompanied by dissipative effects****.*

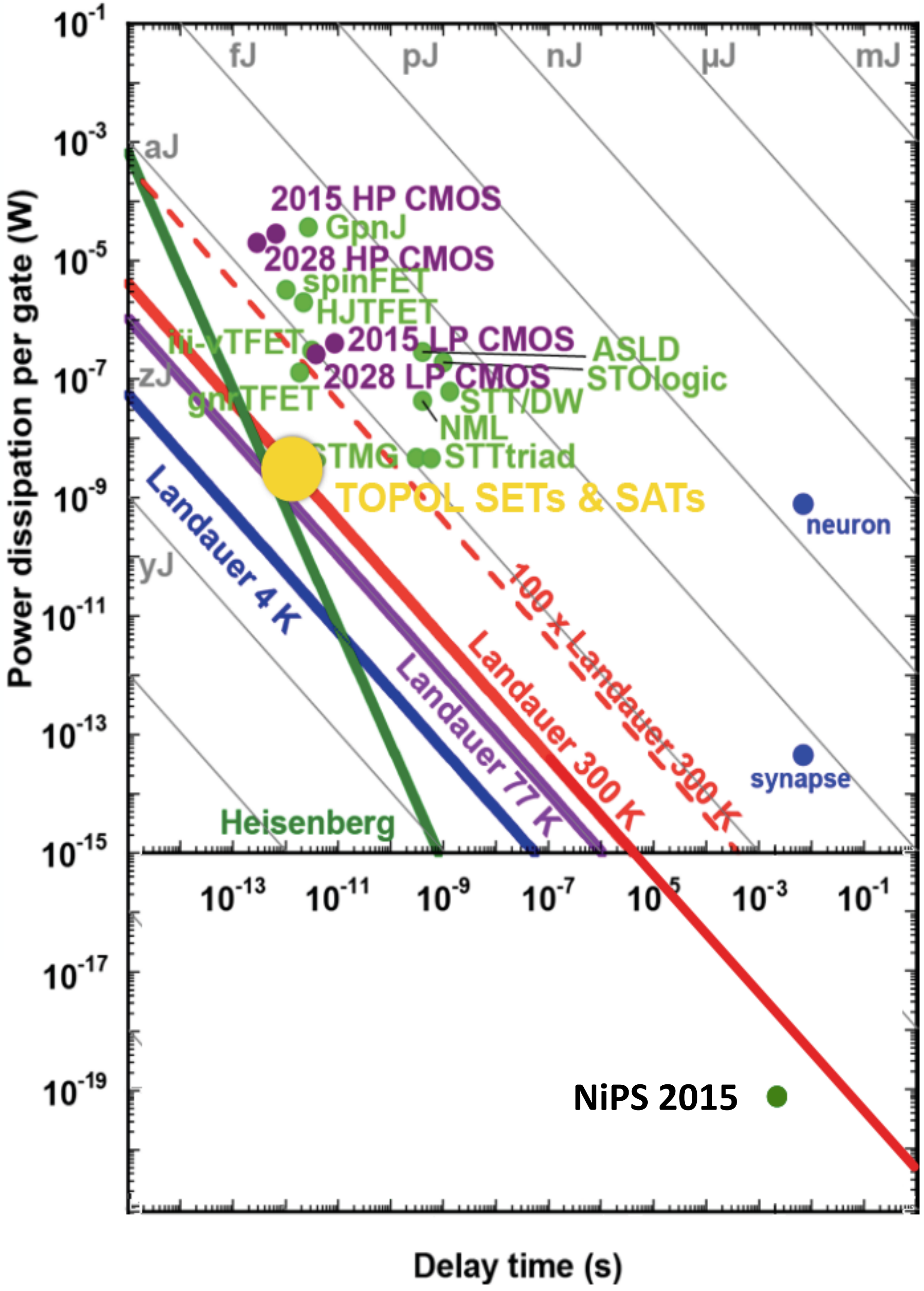
This is not apparently the case.
Logical reversibility is not needed in order to perform zero-dissipation computing.

The state of the art



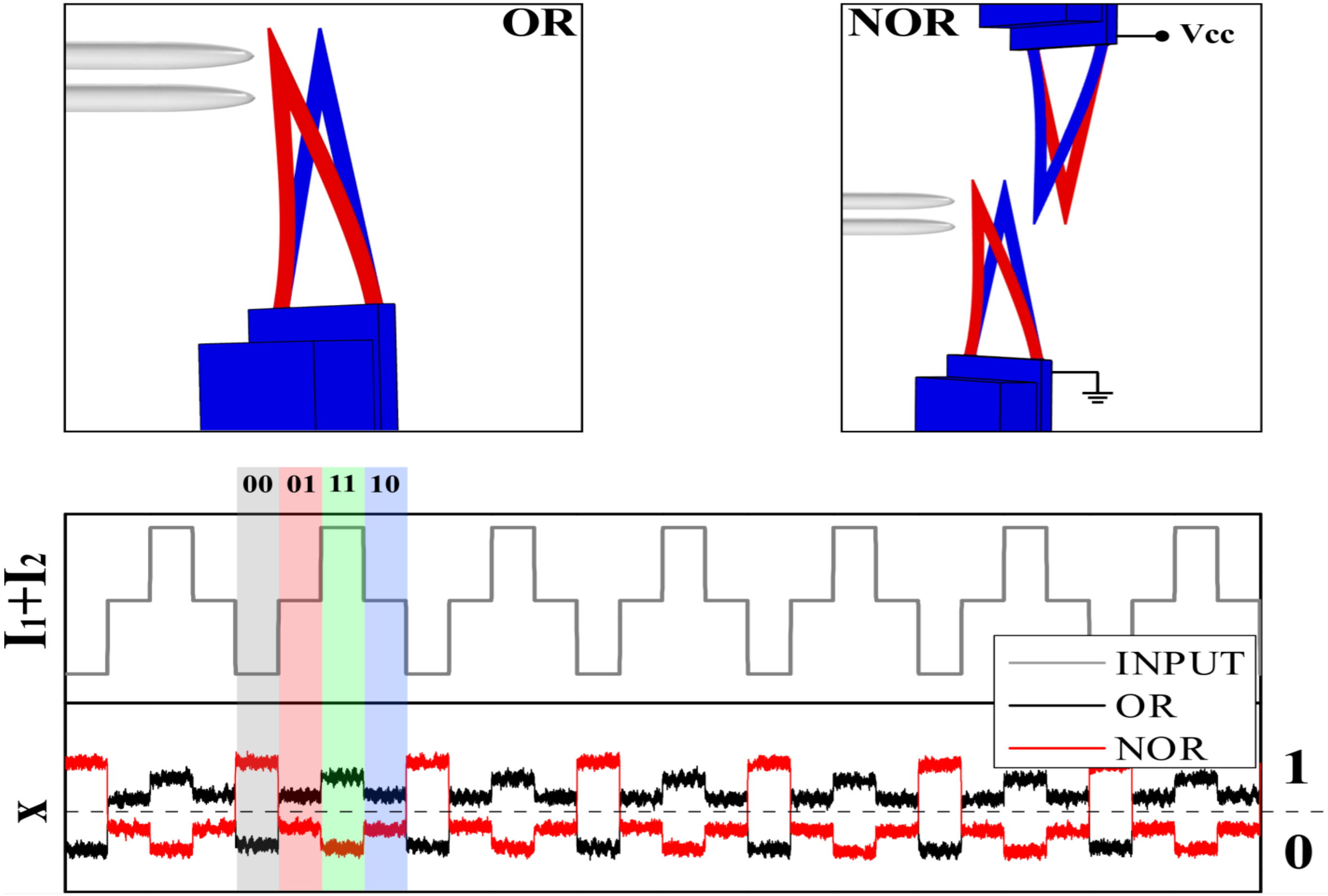
Source: D. Paul, ICT-Energy Research Agenda, 2015

The state of the art

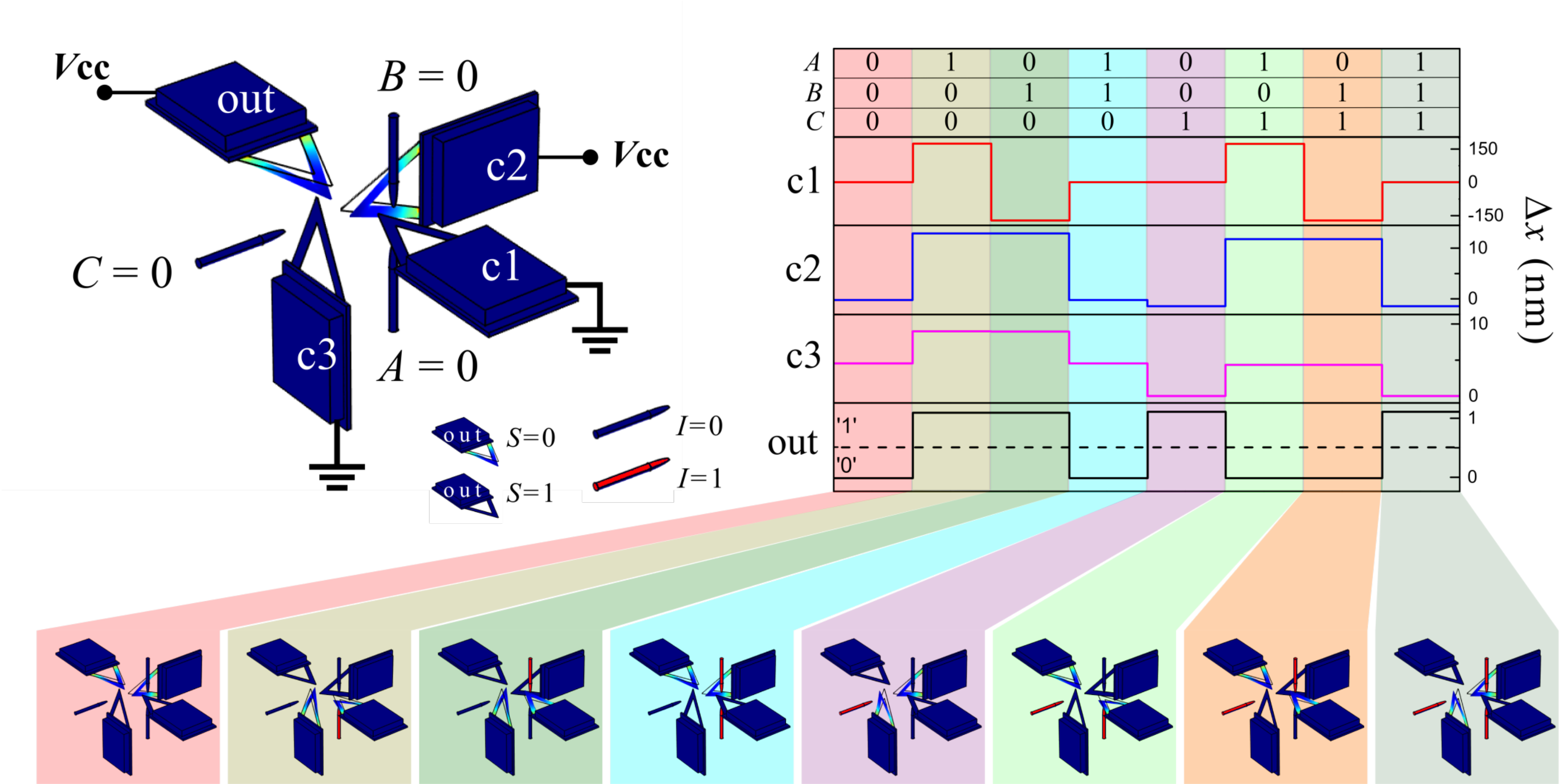


Source: D. Paul, ICT-Energy Research Agenda, 2015

Universal logic gate



One bit full adder



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