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Dissipation in ICT Devices

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ICT-Energy Summer school 2016, Aalborg

NiPS Laboratory
Noise in Physical Systems

Minimum energy

1) What is the minimum amount of energy required to operate a combinational switch?

2) What is the minimum amount of energy required to operate a sequential switch?

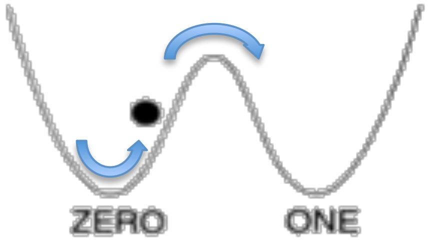
The answer to these questions is associated with the change in entropy of the switches, during the change of state.
If we can realize a change of state without entropy reduction* (and no friction), then the **minimum amount is zero**.

*this is a sufficient condition

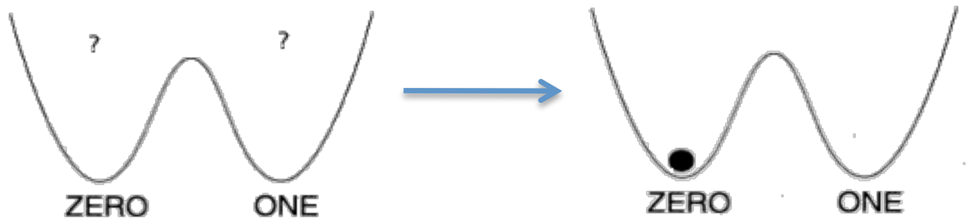
The reset operation in a sequential switch

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

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

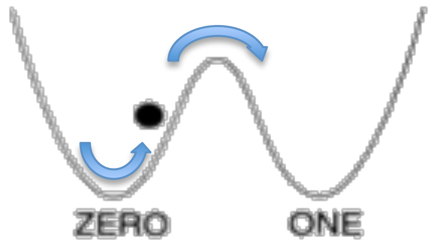


The reset operation (i.e. the set of a given state starting from an unknown state)



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

The single switch operation



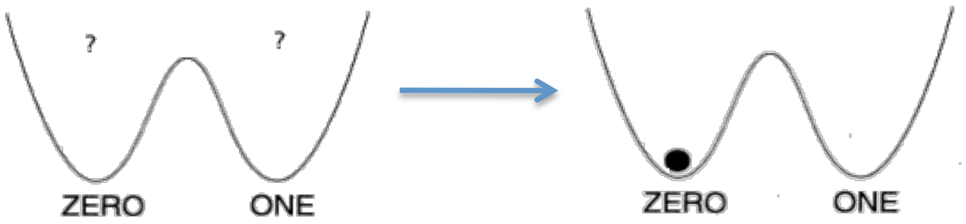
$$0 \longrightarrow 1$$

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 energy expenditure 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.

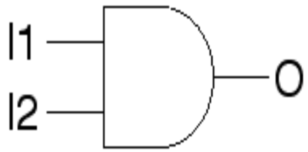
(1) R. Landauer, "Dissipation and Heat Generation in the Computing Process" *IBM J. Research and Develop. 5,* 183-191 (1961),

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.



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

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

I_{out} Information out

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

REVERSIBLE COMPUTING

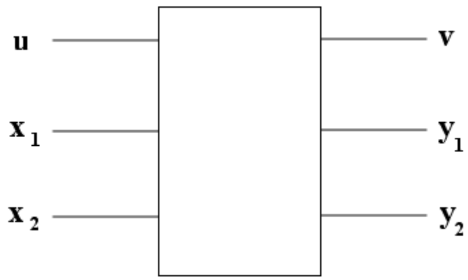
The motivation that led Bennet to introduce logical reversible operations was to overcome the minimum energy expenditure introduced earlier by Landauer.

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* $\mathbf{10^{-21}}$ *Joule at room temperature) for each bit of information it erases or otherwise throws away.*

LOGICALLY REVERSIBLE GATES

E. Fredkin



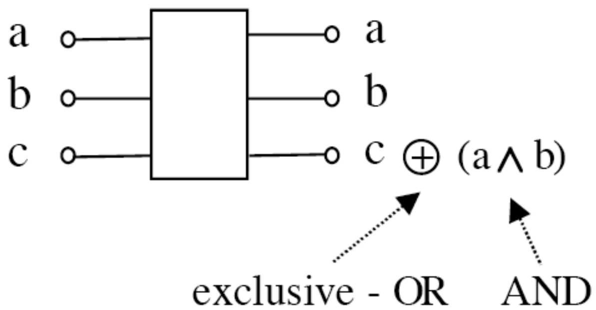
$v = u$

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

$y_2 = u'\,x_1 + ux_2$

B. Toffoli

Toffoli gate



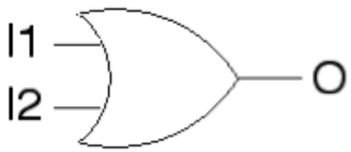
When and only when *a* and *b* are *1's*, *c* is inverted.

I_{in} Information in

I_{out} Information out

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

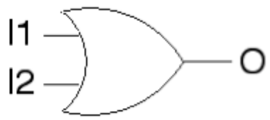
OR



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

Experimental realization of a "OR" logic gate with MEMS

OR



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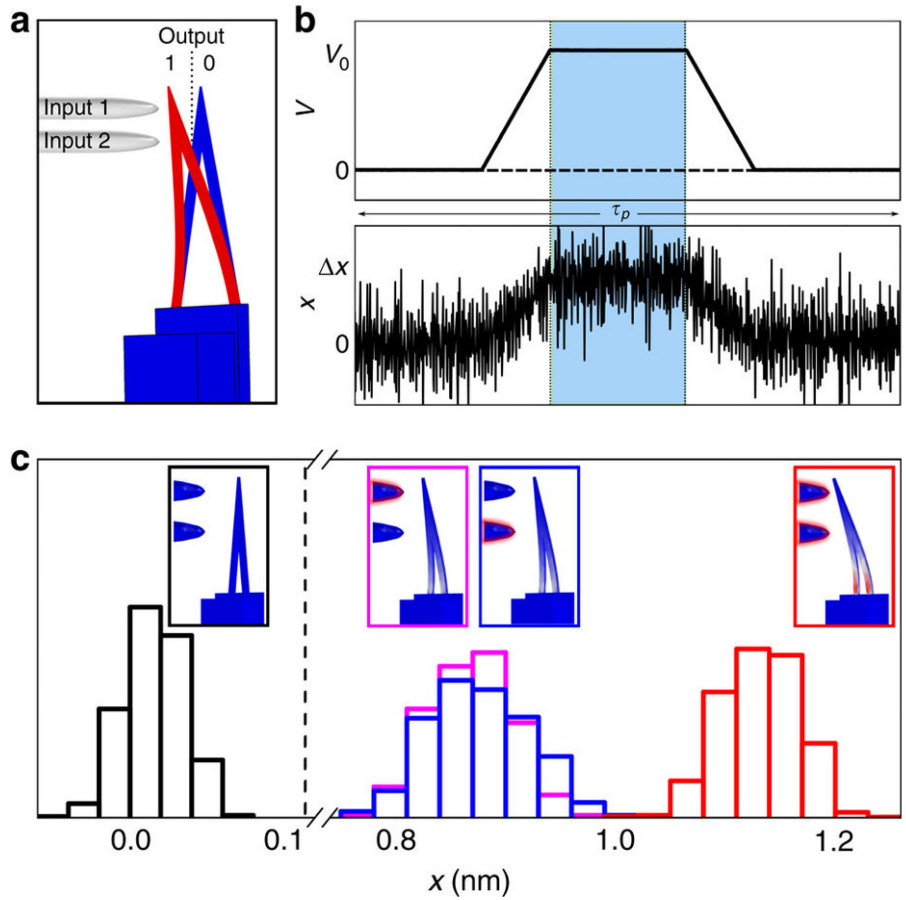

Sub-kBT micro-electromechanical irreversible logic gate,
M. López-Suárez, I. Neri, L. Gammaitoni.
Nature Communications 7, Article number: 12068 (2016)

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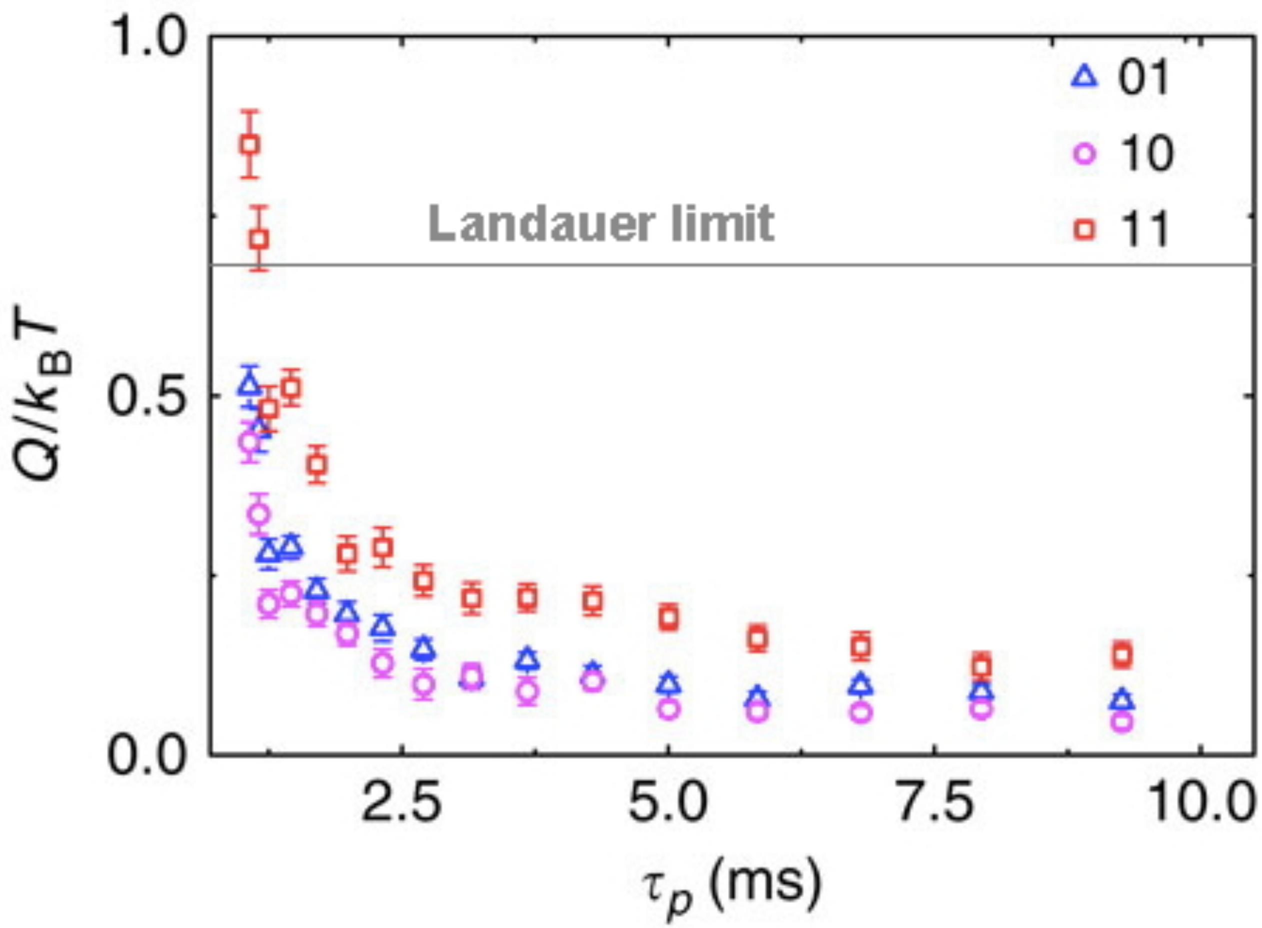

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This is not apparently the case.
Logical reversibility is not needed in order to perform zero-dissipation computing.

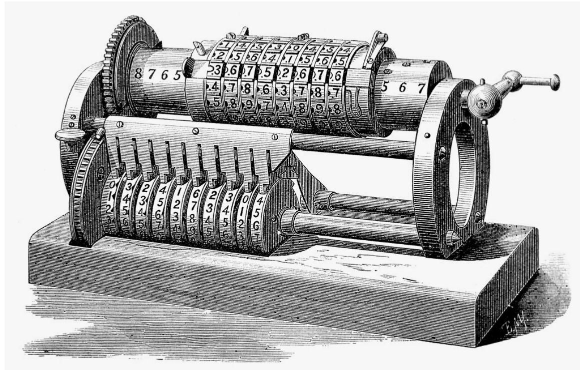
Summary

1) Information is formally connected with entropy
2) Computers obey the laws of physics
3) Computing is altering information and thus may take energy
4) Reversible computing is not necessary

To learn more:

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

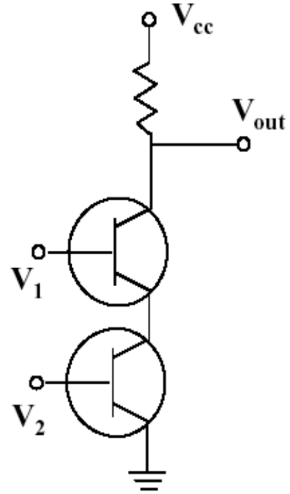
Computing devices



Logic gates and switches

In a practical computer, transistor is the electronic device that performs the role of a combinational **switch** by letting or not-letting the electric current go pass through. The bit value is represented by electric voltage.

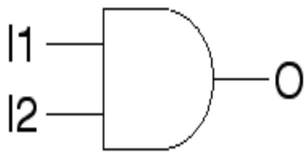
Modern logic gate devices are made by assembling more elementary units: i.e. the **transistors**.



Es: the NAND gate with 2 transistor

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.



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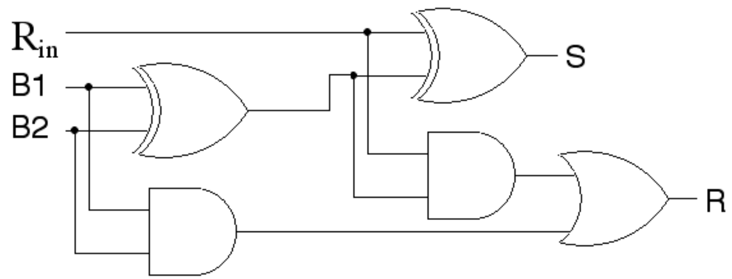
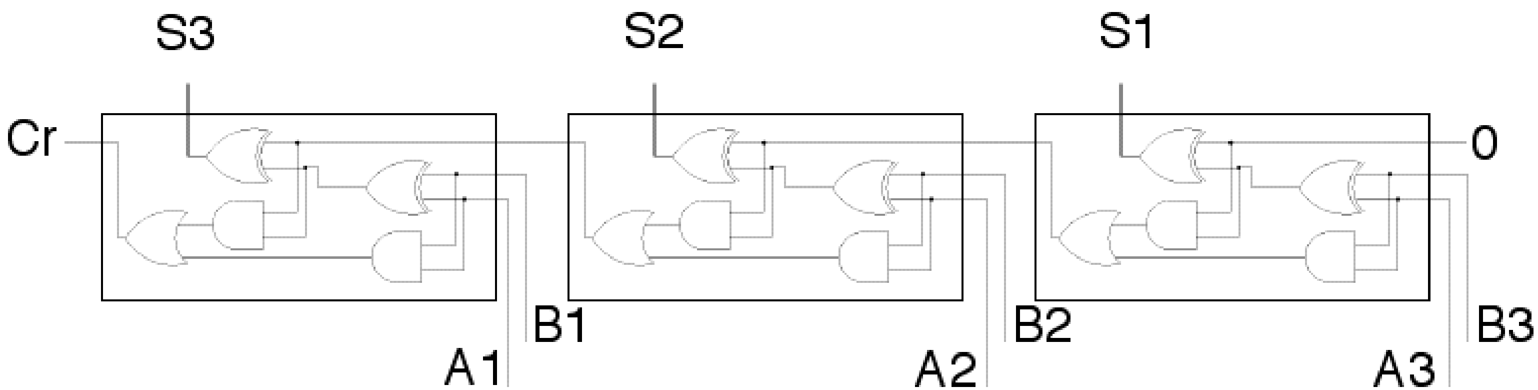




Switches based on capacitors

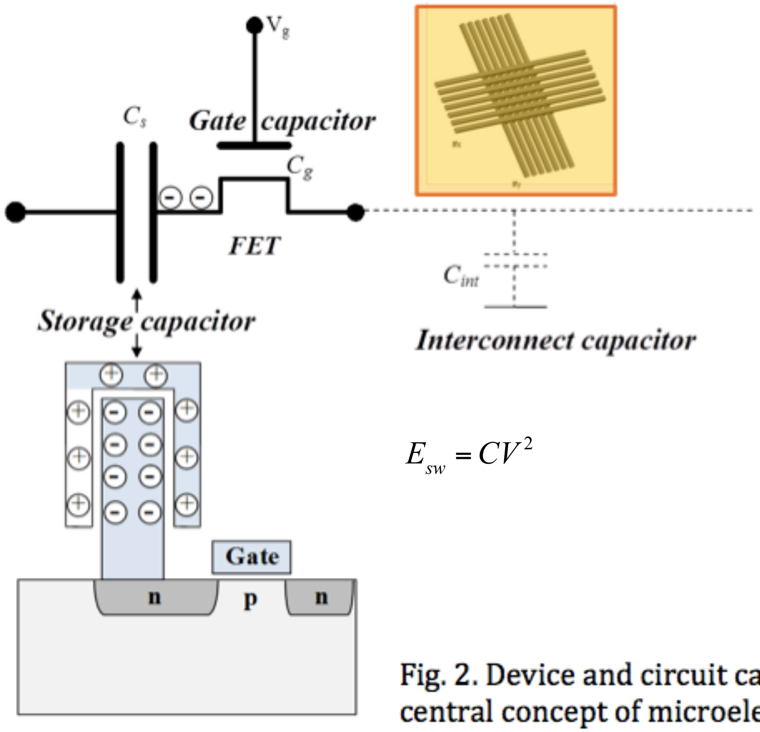


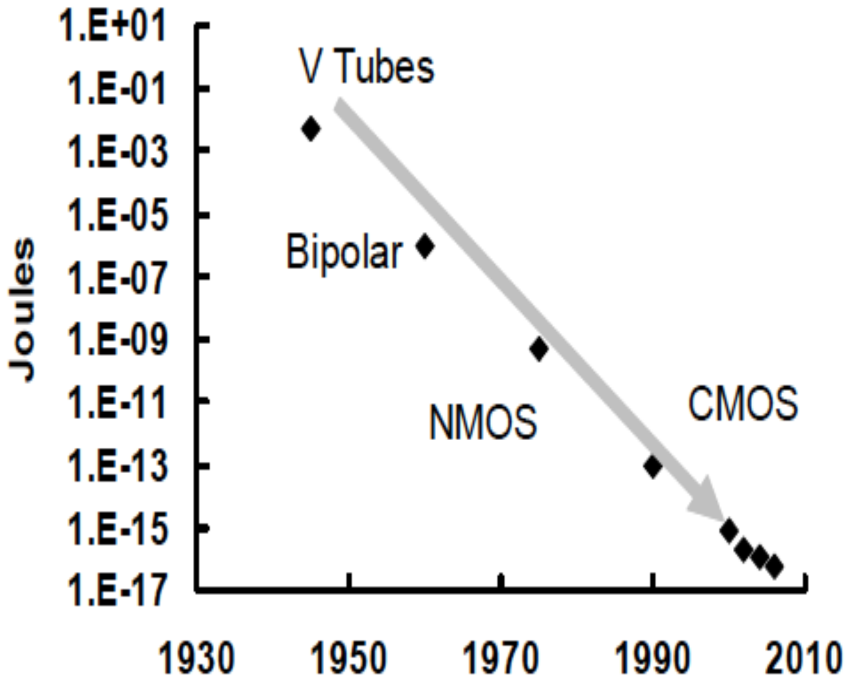
Fig. 2. Device and circuit capacitance as a central concept of microelectronics.

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

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

switch - energy

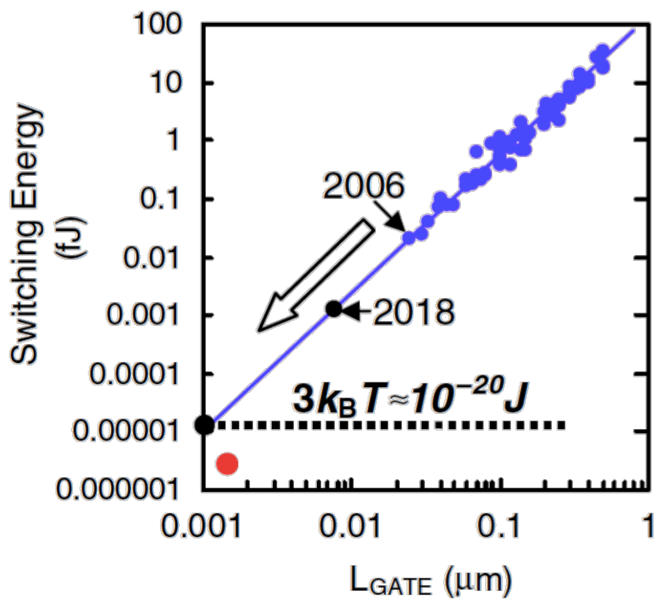
On the other end… there is an impressive track record in reducing consumption



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

Switch - energy

The present trend…

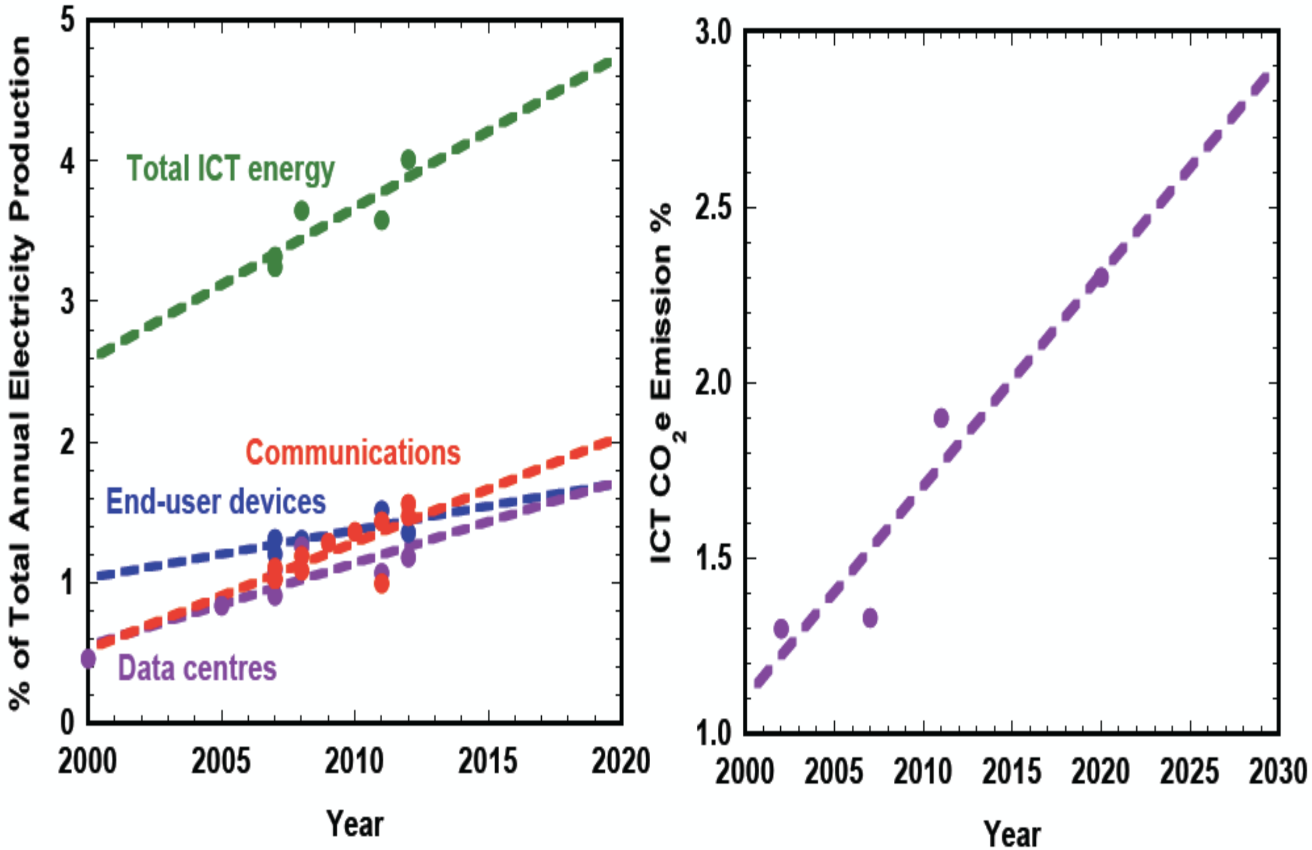


Research directions and challenges in nanoelectronics
R. K. Cavin1, V. V. Zhirnov, D. J. C. Herr1, Alba Avila and J. Hutchby, 2006

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 global energy consumption



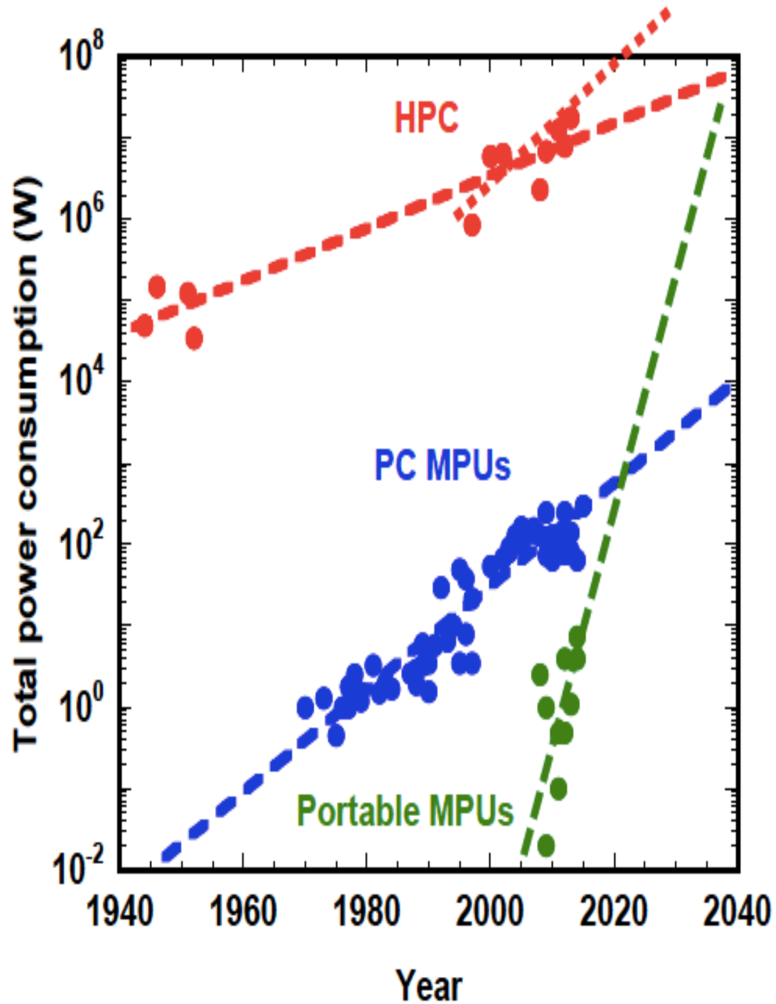
- **This excludes TV, media, publishing, games, power switches, domestic & industrial ICT devices**

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

Reducing energy is strategic

If we want more powerful supercomputers

…to avoid microprocessor burning



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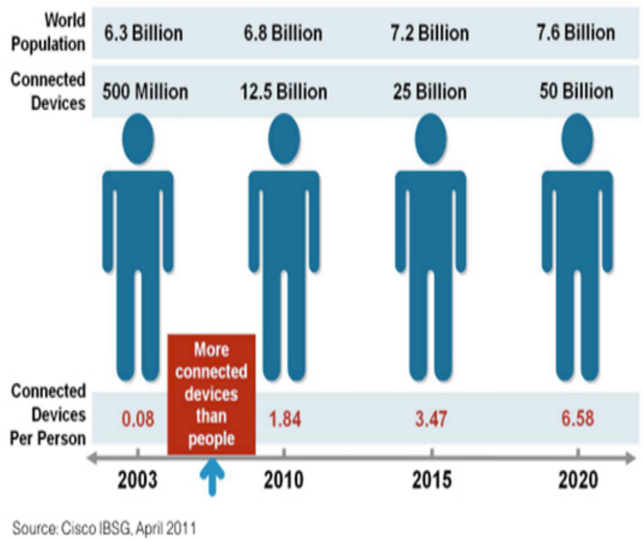
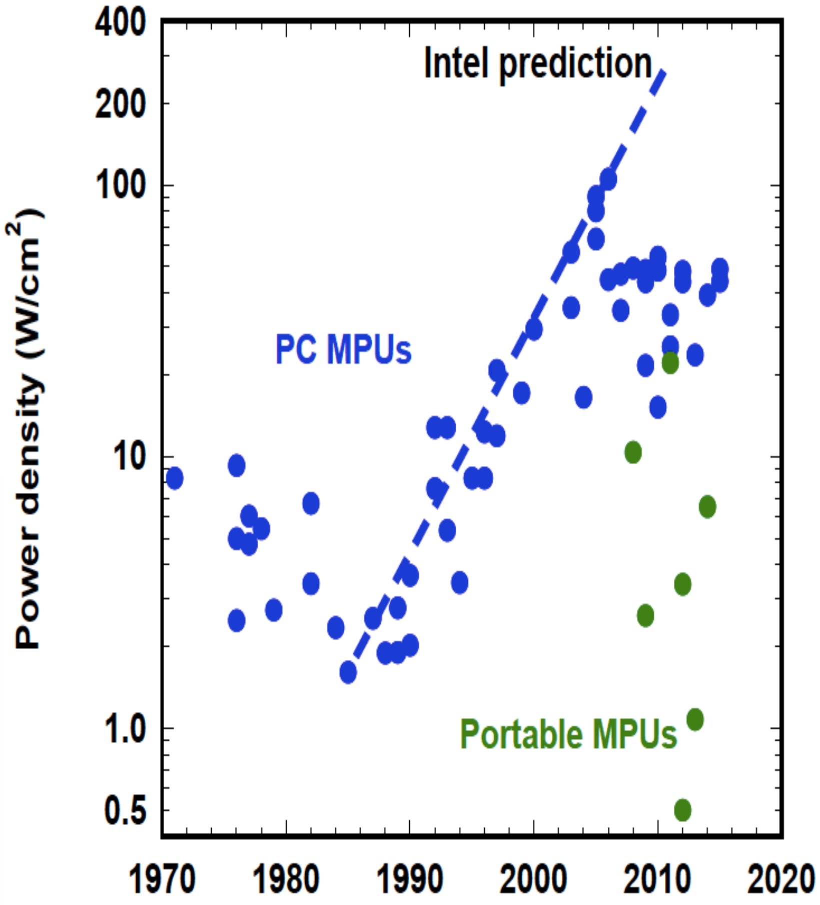
Reducing energy is strategic

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



...to avoid lacking autonomous power



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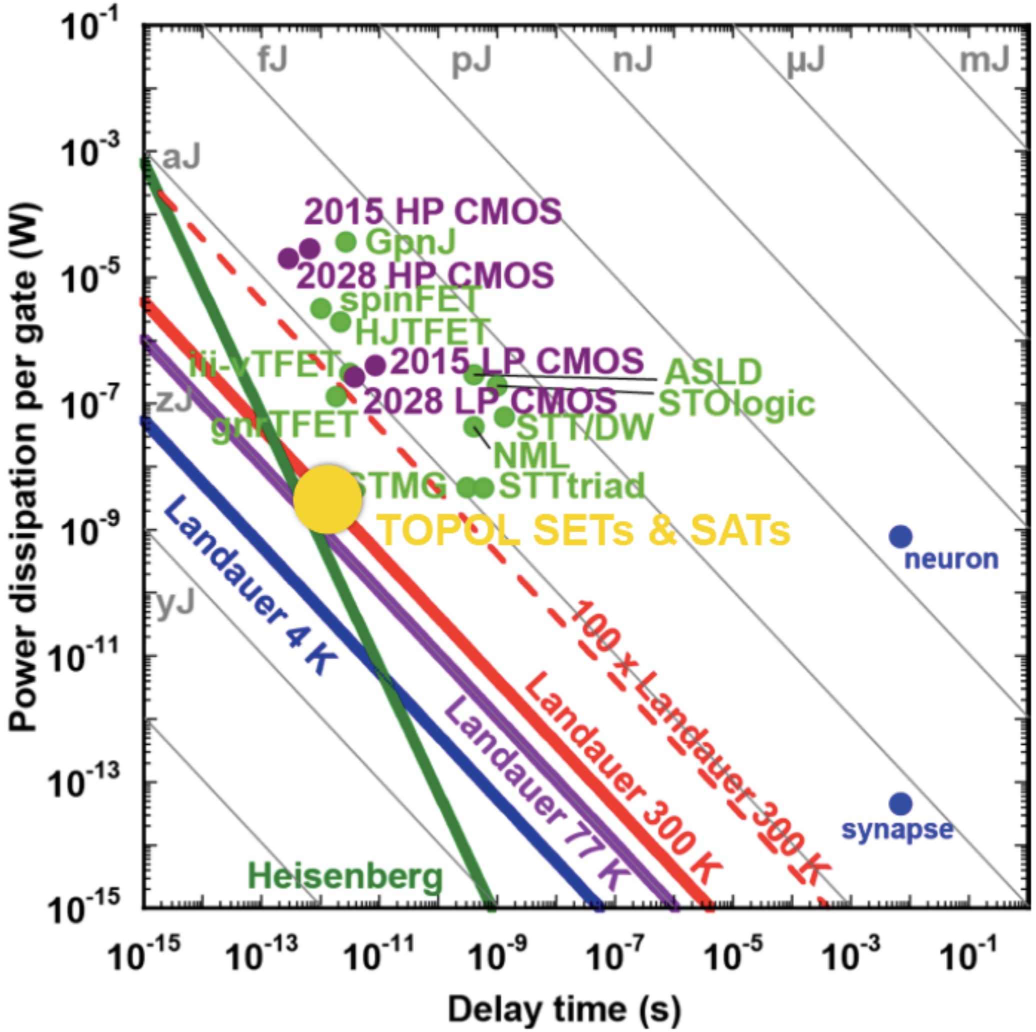
Present trends



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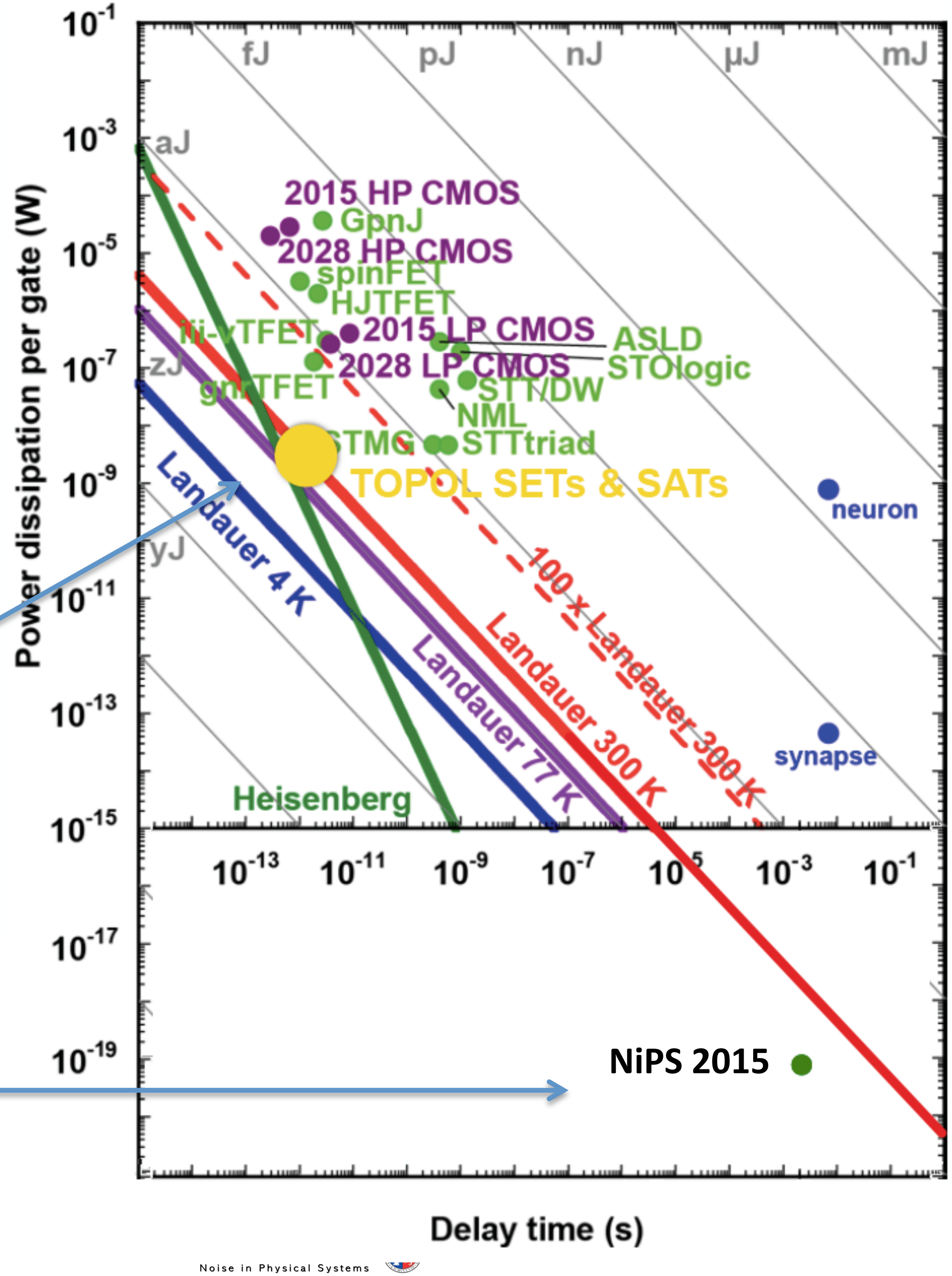

F. Gonzalez Zalba, talk

M. Lopez-Suarez, talk

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

ICT-ENERGY LETTERS

www.ict-energyletters.eu

Present issue Aug 1th 2016

To know more

- www.ict-energy.eu

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

- Reserch Agenda: http://www.ict-energy.eu/sites/ict-energy.eu/files/ICTEnergySRA5.3.pdf

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