Vincent Mazauric, Schneider Digital, Grenoble
vincent.mazauric@se.com

Limite physique des TICs ou quand l’immatériel devient matériel

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ICT in energy systems

Control:

- Provide energy efficiency strategies in a context of tension between demand and supply
- Balance supply and demand in “real time” in a context of decreasing inertia
- Manage highly diluted assets and versatile loads within a general migration of the energy towards electricity
- Signal quality under variability: Enforce synchronism (clock) to provide the lowest dissipative grid

Forecast:

- Local weather to mitigate intermittency
- Predictive maintenance for highly dispersed energy assets

Role:

- Increase the knowledge on the energy system by decreasing its missing information; but
- Spoil the natural evolution of a system (2^{nd} principle)
- Require a **processor** to gain information on the system…
  And reject a larger amount of missing information elsewhere!

Issue:

- Is accurate information (local, real-time) sustainable from a thermodynamic viewpoint?

1	Energy viewpoint
2	Computational viewpoint
3	Switching losses of logical functions
4	IT endogenization in RES
5	Conclusion and forthcoming issues

Energy viewpoint

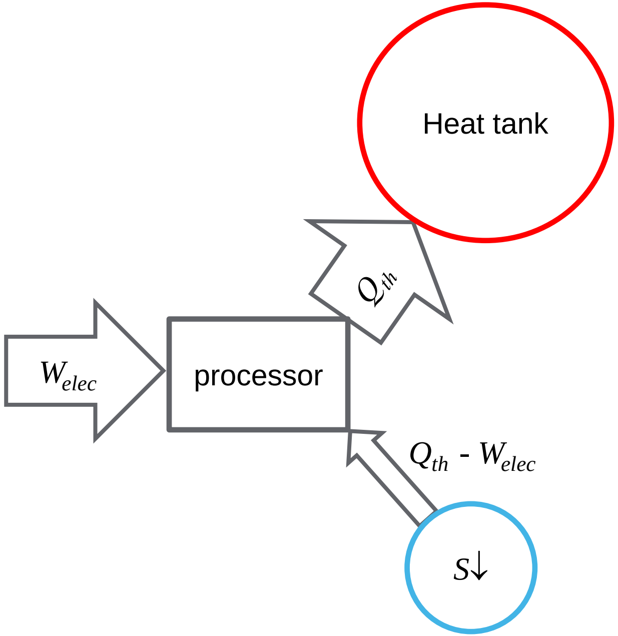
2^{nd} principle of thermodynamics:

- Fix the minimum work W for any energy transaction (reversibility)
- Complement the energy transaction by heat Q (1^{st} principle)
- The higher the degree of irreversibility, the larger the gap between the actual and the minimum works

Information/Entropy equivalence:

- H-Theorem (Boltzmann, 1872)
- Concept of missing information (Shannon, 1948)
- Equivalence between missing information and entropy S (Brillouin, 1956)
- 2^{nd} principle is restored by the Maximum Entropy Principle to describe steady-states and provide time-arrow (Jaynes, 1957)

Processor appears as a cooling (but computing!) machine



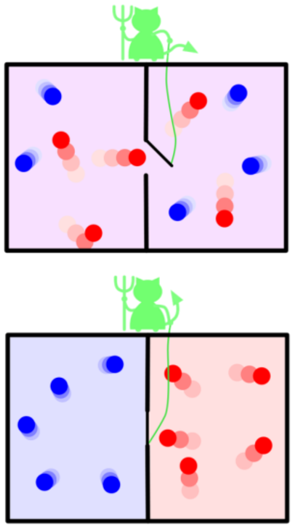
$$COP = \frac{Q_{th} - W_{elec}}{W_{elec}}$$

C. E. Shannon, "A mathematical theory of communication," The Bell System Technical Journal, vol. 27, pp. 379-423, 1948.
L. Brillouin, Science and information theory. New York, USA: Academic Press, 1956
E. T. Jaynes, "Information theory and statistical mechanics," *Physical Review,* vol. 106, pp. 620-630, 1957.

Energy *vs.* Information: Which comes first?

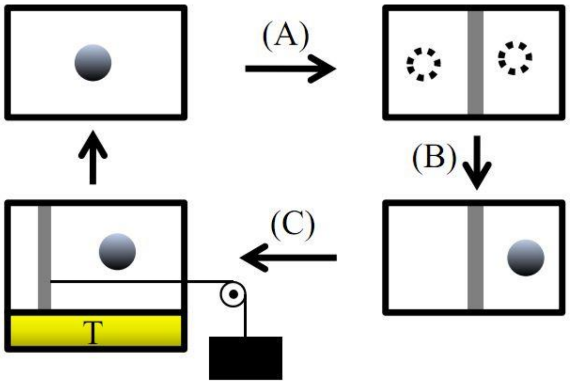
A journey through Thermodynamic History

Turing machine (1936)



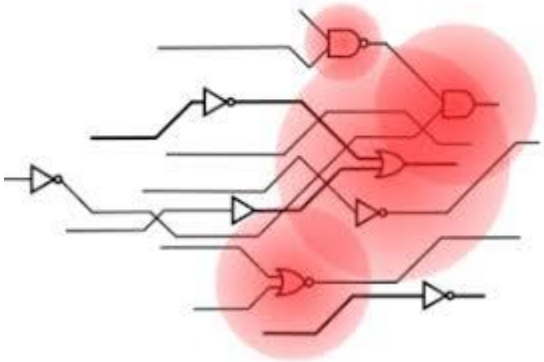
Maxwell's deamon (1867)

L. Brillouin: Maxwell's Demon Cannot Operate: Information and Entropy, Journal of Applied Physics, vol. 22, 1951, p. 334-337



Szillard's engine (1928)

L. Szillard: Über die entropyverminderung in einem tehermodynamischen system bei eingriffen intelligenter wesn, Zeitschrift für Physik 53, 840 (1929)



Landauer's principle (1961)

Computational viewpoint (so far)

Erasing a memory is an irreversible operation because, at the end of one cycle of the computing machine, the knowledge of the final state cannot provide the initial state

Information immunity:
- Binary coding
- Damping and barriers

From logical switches to gates:
- *Reversible: NO*
- Irreversible: AND, **NAND**, OR, **NOR**, XOR, NXOR
- Requires up to 6 switches per gate

Combinatory circuits (the output depends only on the inputs):
- Karnaugh tables
- Applications:
  - Operations (AND, no carry),
  - Comparators (NXOR),
  - Coding/decoding…

Sequential circuits (the output depends on the inputs and history):
- 1-bit latch (2 NAND or 2 NOR)
- **Memory stack** (carry)
- …

Landauer's viewpoint (current paradigm):

- Is it possible to perform logical/binary operations without energy?
- Erasing a bit releases the entropy: k_B Ln2; whereas
- The energy to set a bit is given by the logical technology

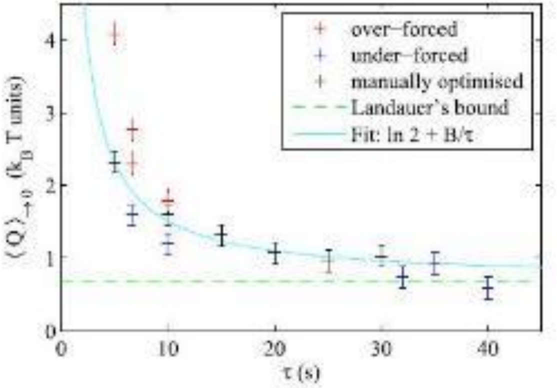
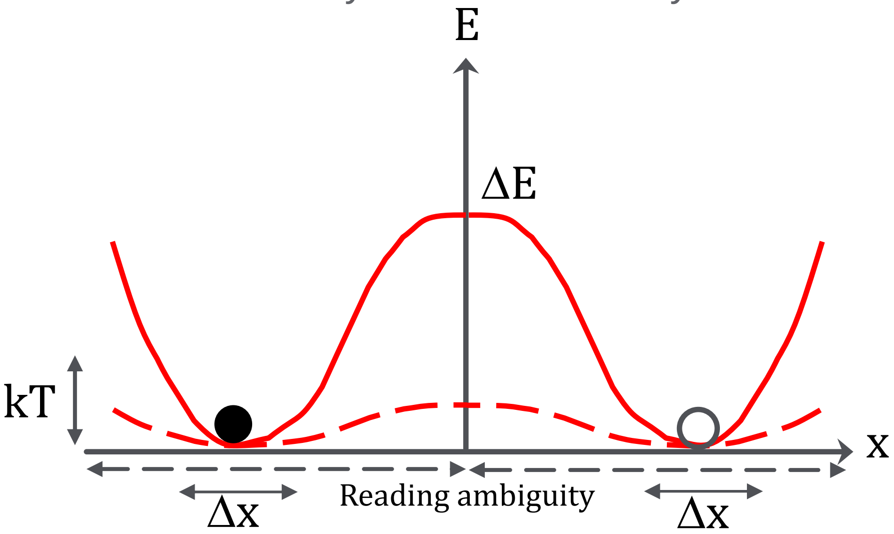


Figure 8. Mean dissipated heat for several procedures, with fixed τ and different values of f_{max}. The red points have a force too high, and a $P_{S\,force} \geqslant 99\%$. The blue points have a force too low and $91\% \leqslant P_{S\,force} < 95\%$ (except the last point which has $P_{S\,force} \approx 80\%$). The black points are considered to be optimised and have $95\% \leqslant P_{S\,force} < 99\%$. The error bars are $\pm 0.15\,k_B T$ estimated from the reproductibility of measurement with same parameters. The fit $\langle Q \rangle_{\to 0} = \ln 2 + B/\tau$ is done only by considering the optimised procedures.

Figure from: A. Berut, A. Arakelyan, A. Petrosyan, S. Ciliberto, R. Dillenschneider, E. Lutz: Experimental verification of Landauer's principle linking information and thermodynamics, Nature, 483, pp. 187-192, 2012.

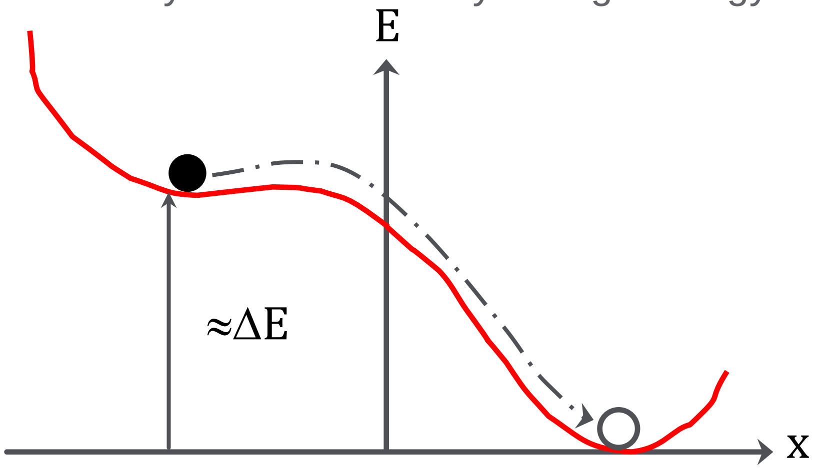
« Flip-Flop » memory

Stability-induced immunity



Tthe louder the thermal noise kT, the highest the barrier ΔE

Immunity-induced memory change energy



The higher the barrier ΔE, the lower the efficiency of erasing operation

Logical electronics manages information and performs its reading:

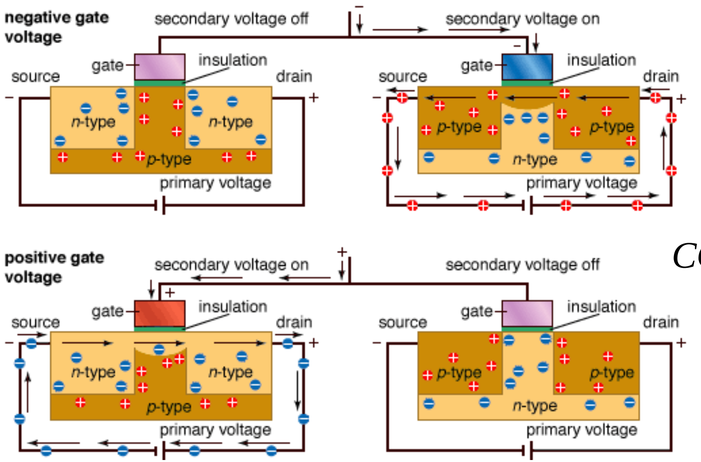
- Purely based on electric currents of free carriers (electron and holes)
- Association of spin- and charge-currents

Logical structures and technologies

Maturity of the state of the art (on shelves)

Combinatory MOS Field Effect Transistor (µm scale):

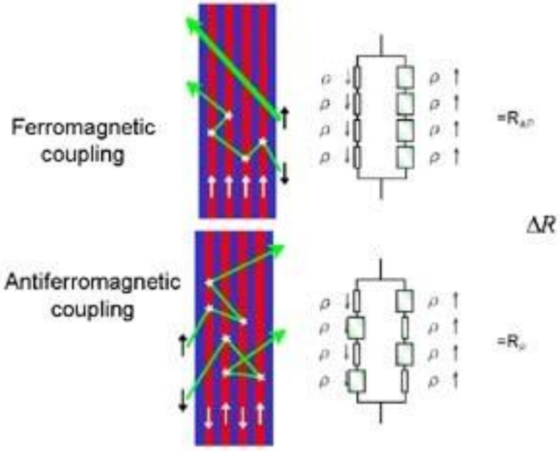
- Voltage on the gate acts on depletion layer (2V)
- Measure logical state with source-drain current
- Switching energy: 40,000 $k_B T$ (dynamic losses)
- Static losses: leakages currents (polarization)



$COP \approx 10^{-6}–10^{-5}$

Giant Magneto Resistance effect (nm scale):

- Magnetic field acts on anti-ferromagnetic multilayer structure
- Electron diffusion by the magnetic structure is spin-dependent, leading to logical states
- Switching energy: 20$k_B T$ (dynamic losses)



$$\Delta R = \frac{R_{AP} - R_P}{R_P}$$

$COP \approx 10^{-3}–10^{-2}$

V.K. Joshi: Spintronics: a contemporary review of emerging electronics devices, Engineering Science and Technology, an International Journal ,19, pp. 1503–1513 (2016).

(active) energy efficiency

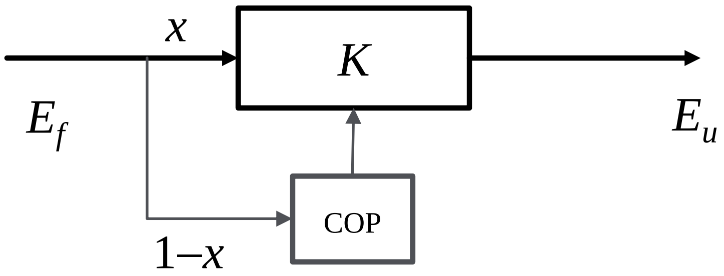
“Beyond the meter”

Any process is characterized by an efficiency K depending on:

- Intensive variables (state variables of the Gibbs free-energy)
- Extensively and linearly from the input xE_f

Maximize the end-use service E_u regarding the final energy E_f :

- Digitalization is efficient for large enough E_f;
- The higher the COP, the bigger the potential for global efficiency



$$\max_{1>x>0} \frac{E_u}{E_f}$$

0<K<1 acts linearly from the input and depends on the information carried out by digitalization
COP is the coefficient of performance of data-processing

Digitalization of energy

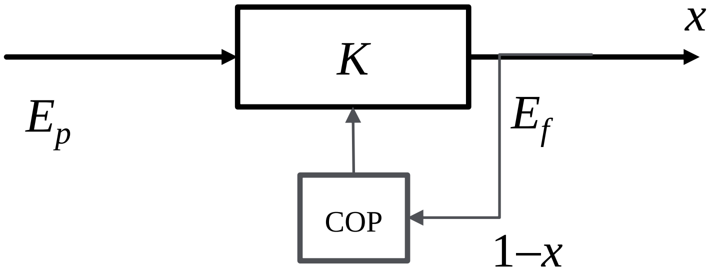
IT endogenization in Reference Energy System

Control:

- Balance supply and demand in “real time” in a context of decreasing inertia
- Manage highly diluted supplying and stability assets with versatile loads
- Traceability of energy (from cardinal to factorial complexity)
- Signal quality under variability: Enforce synchronism (clock) to provide the lowest dissipative grid
- Cybersecurity, redundancy and resilience

Forecast:

- Local weather to mitigate intermittency effect
- Predictive maintenance to keep productive highly dispersed energy assets



$$\max_{1>x>0} \frac{xE_f}{E_p}$$

Maximize the residual final energy xE_f regarding primary energy E_p

0<K<1 acts linearly from the input and depends on the information carried out by digitalization
COP is the coefficient of performance of data-processing

Conclusion and forthcoming issues

Sustainability of digitalization:
- is at concern with CMOS technology; and
- depends on forthcoming IT technology efficiency and its implementation (e.g., spintronics)

Due to energy footprint of digital solution:
- digital and energy transitions (<2050-70) appear intricated; and
- Require long-term planning exercises including IT functional resources availability (energy/information/material > CO_2);
- Magnetism is at the crossroads between energy generation and digitalization!

From a physical viewpoint, value distribution between data and energy also results from:
- Boltzmann constant $k_B = 1.381 \times 10^{-23}$ J/K
- Coefficient of Performance of IT systems (currently around 10^{-6})

Controversy:

- Physical entropy (Boltzmann):
  - Irreversibility is due to finite-time process
  - Dissipation is due to fluctuation of macro-state to reach equiprobability of micro-states
- Computational entropy (Shannon):
  - Irreversibility is due to the loss of memory of the inputs
  - Dissipation is due to stepping voltage charging of switches (50%) and erasure (50%)

➔ From Landauer's to Reversible computation paradigm

Adiabatic logic:

- Process switching energies through ramping voltage sources
- "Rewind" computation to recover switching energies
- Trade-off between extra-memories management and erasure

Massive parallelization:

- Slower computation to allow the latter; but
- Need to consider new programming recipes and new competencies

Quantum Computing…

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