MICROENERGIES

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NiPS Laboratory
Noise in Physical Systems
www.nipslab.org

WISEPOWER

PLAN

- Why micro-energies?
- What are micro-energies?
- What are the fundamental limits?
- The character of nanoscale kinetic energies

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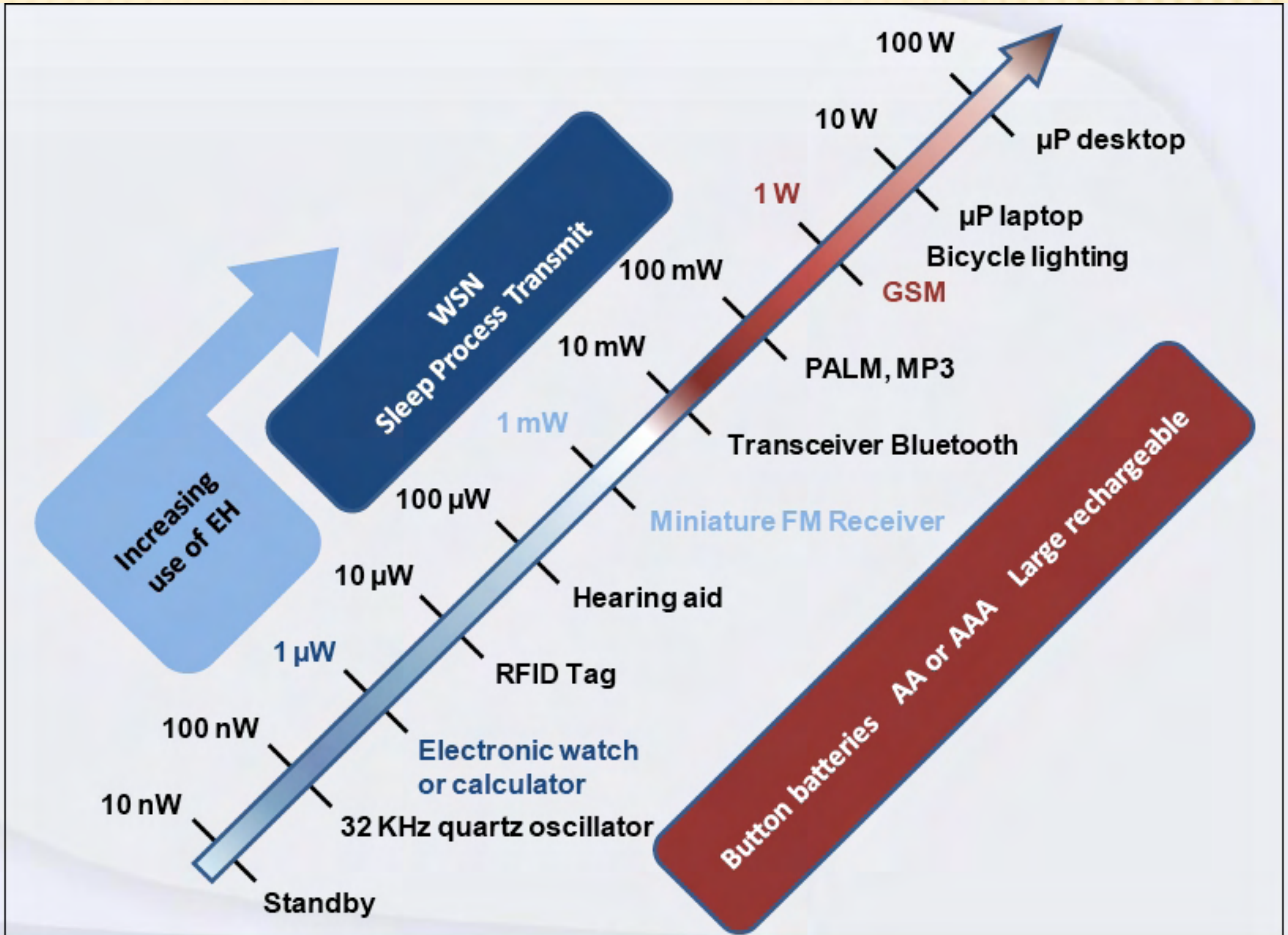
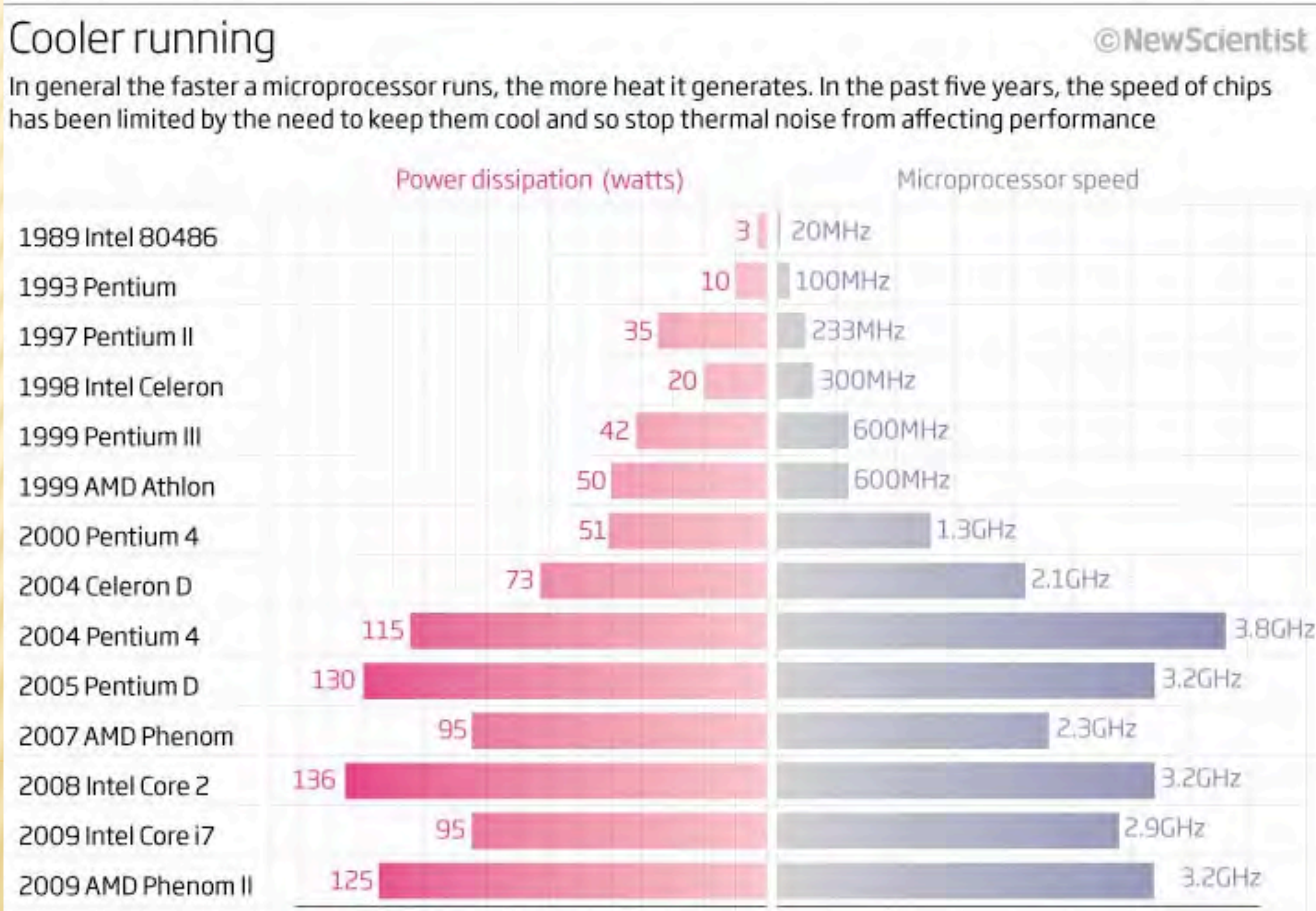
ENERGY NEEDS IN ELECTRONIC DEVICES



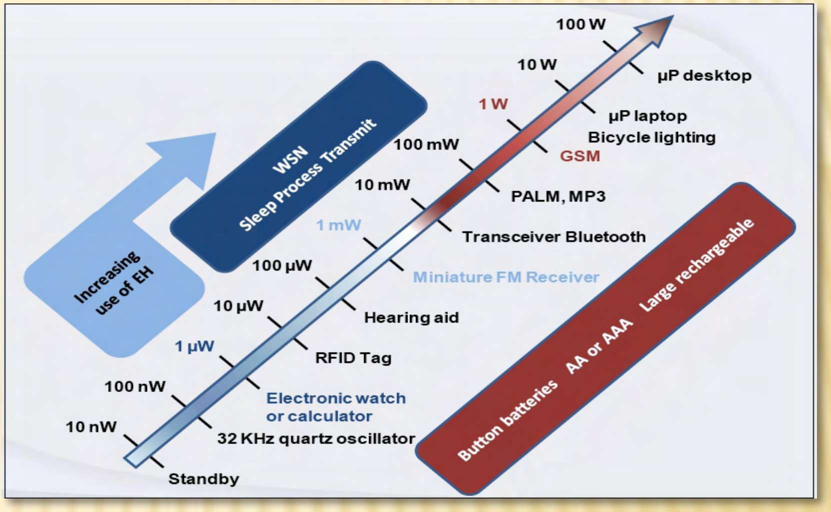
. Source: IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009. EH: Energy Harvesting; WSN: Wireless Sensors Network

ENERGY NEEDS IN ELECTRONIC DEVICES



Why micro energies

1) There is an increasing demand of **portable energy** for powering small electronic devices



Source: IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009.
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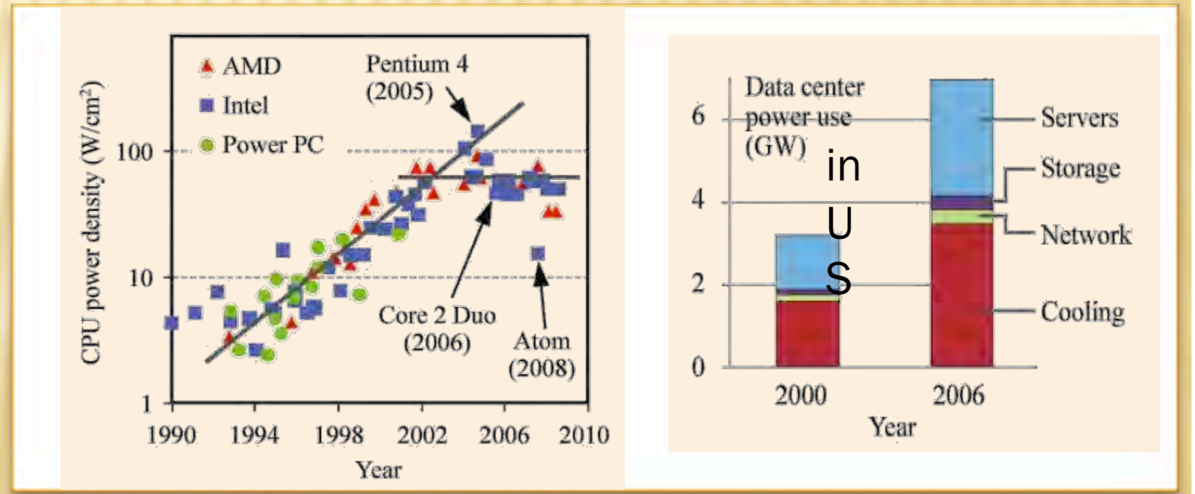
2) **Energy efficiency** in computing systems has become a major issue for the future of ICT



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

WHAT THESE TWO PROBLEMS HAVE IN COMMON?

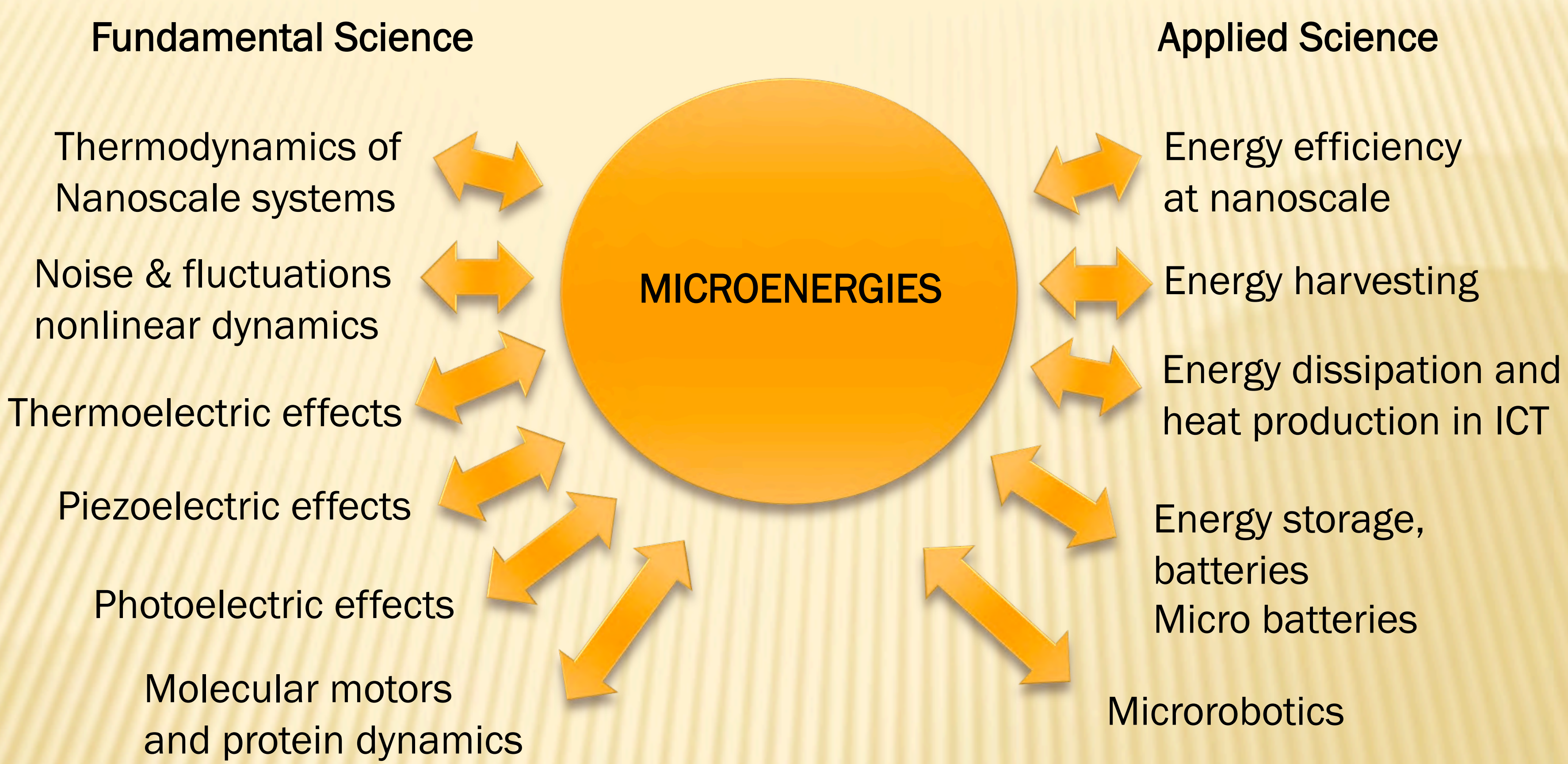
They both sits on a common scientific ground:

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
-...

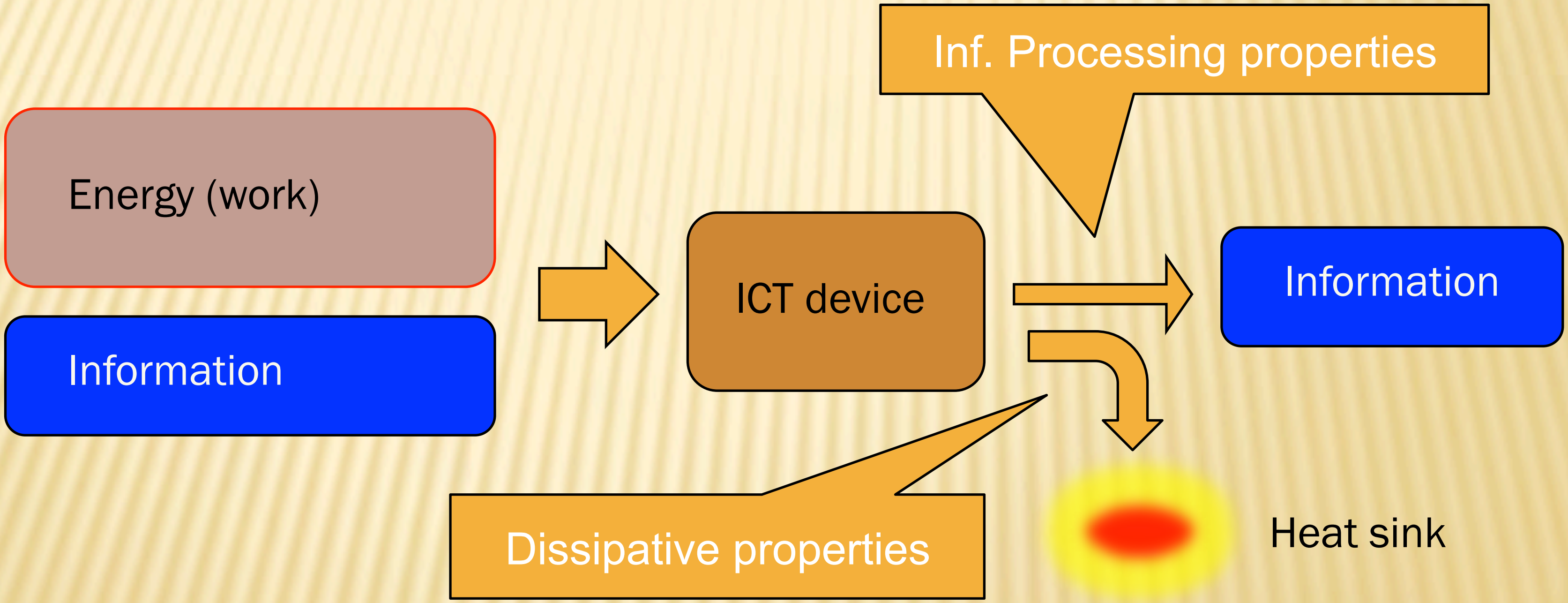
Could be asked and answered within this framwork.



In order to better contestualize the issue let's focus on a scheme for ICT devices…

A NEW APPROACH TO ICT DEVICES

An ICT device is a machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).



Energy efficiency is usually defined as the percentage of energy input to a device that is consumed in useful work and not wasted as useless heat,

Energy efficiency / Dissipative properties

Presently:
the main effort is aimed at cooling down the heat produced during computation with specific attention to the charge transport on one hand and on the other hand on reducing the voltage operating levels up to the point of not compromising the error rate due to voltage fluctuations.

We propose:
to address the problem at a very fundamental level:
- what are the basic mechanisms behind the heat production?
- How can we take advantage of the fluctuations instead of avoiding them?
- How the physics of the heat and charge transport can be merged with the phonon engineering in order to advance the computing tasks?

It is not simply an incremental progress toward the reduction of heat production in room temperature conductors or new technology *beyond CMOS*.

It is a new, visionary approach that challenges the very basic foundation of thermodynamics. We propose to understand the dissipative mechanisms at nanoscale with the aim at setting the bases for a new thermodynamics of ICT devices.

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	ICT Revolution XX-XXI
Heat-Work relations	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.

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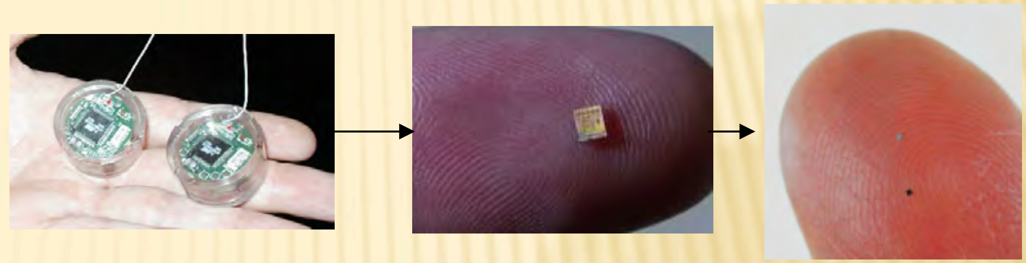
SCALE OF ENERGY

Task	Power (W)	
Average power of a Boing 747 airplane	10^8	100 MW
Full power aircraft fighter	10^6	1 MW
Full power car engine	10^5	100 kW
Operate a microwave oven	10^3	1 KW
Being alive for an average adult human	10^2	100 W
Brain functioning for an average human	10	10 W
mobile phone calling	1	1 W
Emission of a standard WI-FI router	10^{-1}	100 mW
Functioning of a LED light	10^{-2}	10 mW
Functioning of a miniature FM receiver	10^{-3}	1 mW
Functioning o a wireless sensor node	10^{-5}	100 μW
Low power radio module	10^{-4}	10 μW
Functioning of a quartz wristwatch	10^{-6}	1 μW
Operation of a quartz oscillator	10^{-7}	100 nW
Sleep mode of a microcontroller	10^{-8}	10 nW
1 bit information erasure at room T (min)	10^{-21}	1 zW

Wireless sensor networks

- Small (<1cm^3)
- Lightweight (<100 gr)
- **Low Power (<100 μW)**
- Long-lasting (2-10 yr)
- Inexpensive (<1 $)
- Low data rate
- wireless platforms
- Flexibility



Present
(cubic centimeter)

Future
(cubic sub-millimeter
sub-micrometer)

Monitoring and controlling different environments through a network of small, distributed, cheap, low consumption, adaptable, interconnected, smart devices represents a new important opportunity that is rapidly becoming a reality.

Problem: **how to power them?**

Different approaches:

1) Energy produced in one central place: battery-like
2) Energy produced when and where available (and locally stored)

Energy harvesting deals with the approach 2)

There is an increasing demand of portable power that is not satisfied by batteries…

Because they are un-practical:

- they need replacement when exhausted
- They need careful disposal
- They add to pollution
- They are bulky
- They cost money

Because they are unavailable: It is difficult if not impossible to build small batteries with high capacity

The goal is to realize **self-powered** nanoscale electronic devices.

From the solution of this problem major impact on Science, Technology, Economy and Society is expected

ENERGY BASIC IDEAS

Let's start from the very beginning…

Energy… what is it?

Energy appears to be a fascinating subject …usefully introduced to large use during the industrial revolution…

Although not completely well understood (in my opinion)

R. Feynman ideas about energy…

Energy… is conserved

ENERGY BASIC IDEAS

Energy... what is it?

A text-book definition: Energy is the capability to do some work..

... in the meantime energy is transformed from one kind to another...
es: from chemical energy to kinetic energy to thermal energy...

ENERGY BASIC IDEAS

Even if we do not have a very satisfying definition we know how to measure energy: in Joule (J)

1 J = energy that takes to rise 1 m an apple on Earth.

If we do this work in 1 s than we have used 1 W of power

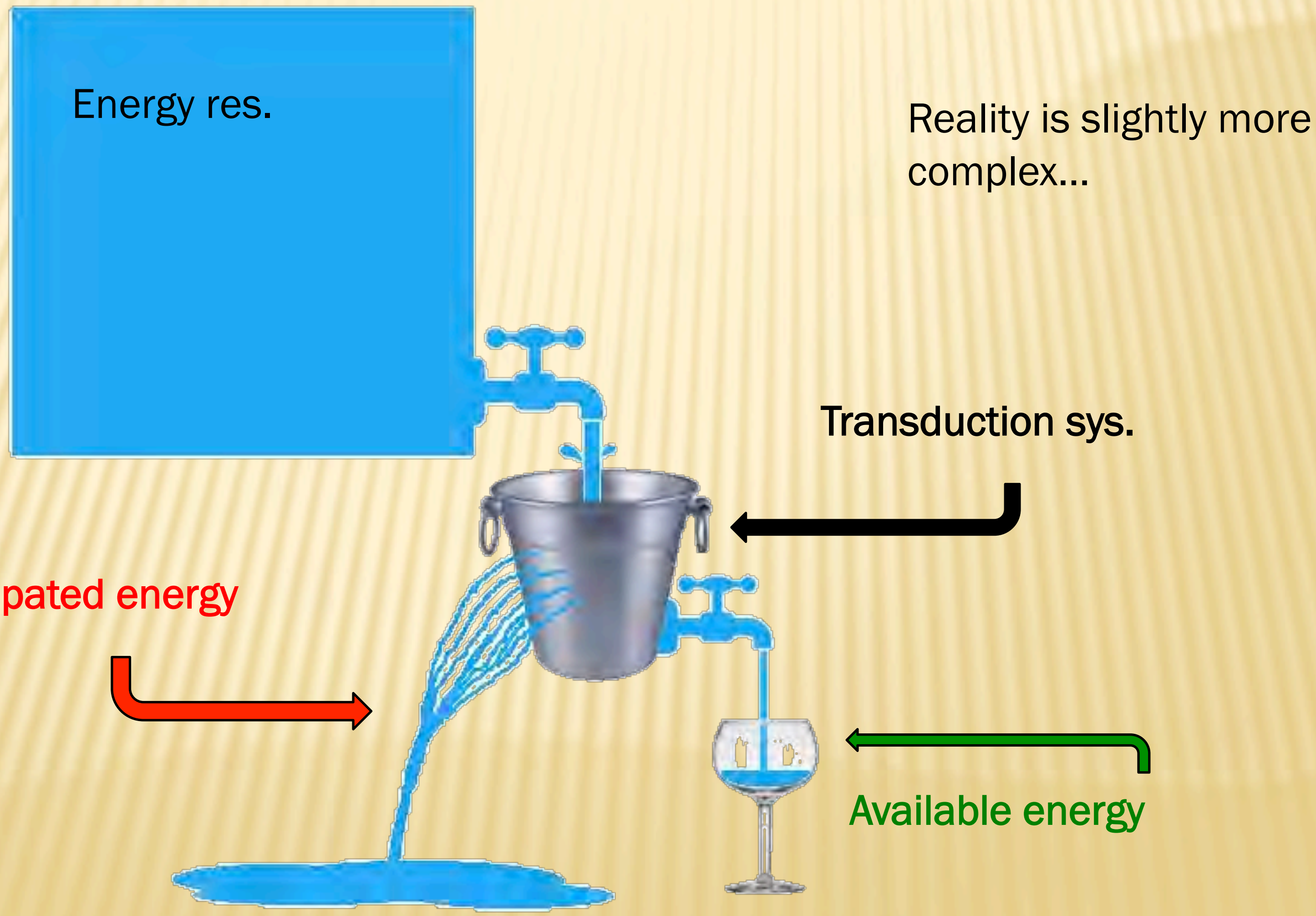
Examples:

- A portable computer needs approx 50-100 W
- A electric oven uses approx 500-1000 W
- A human brain uses approx 20 W

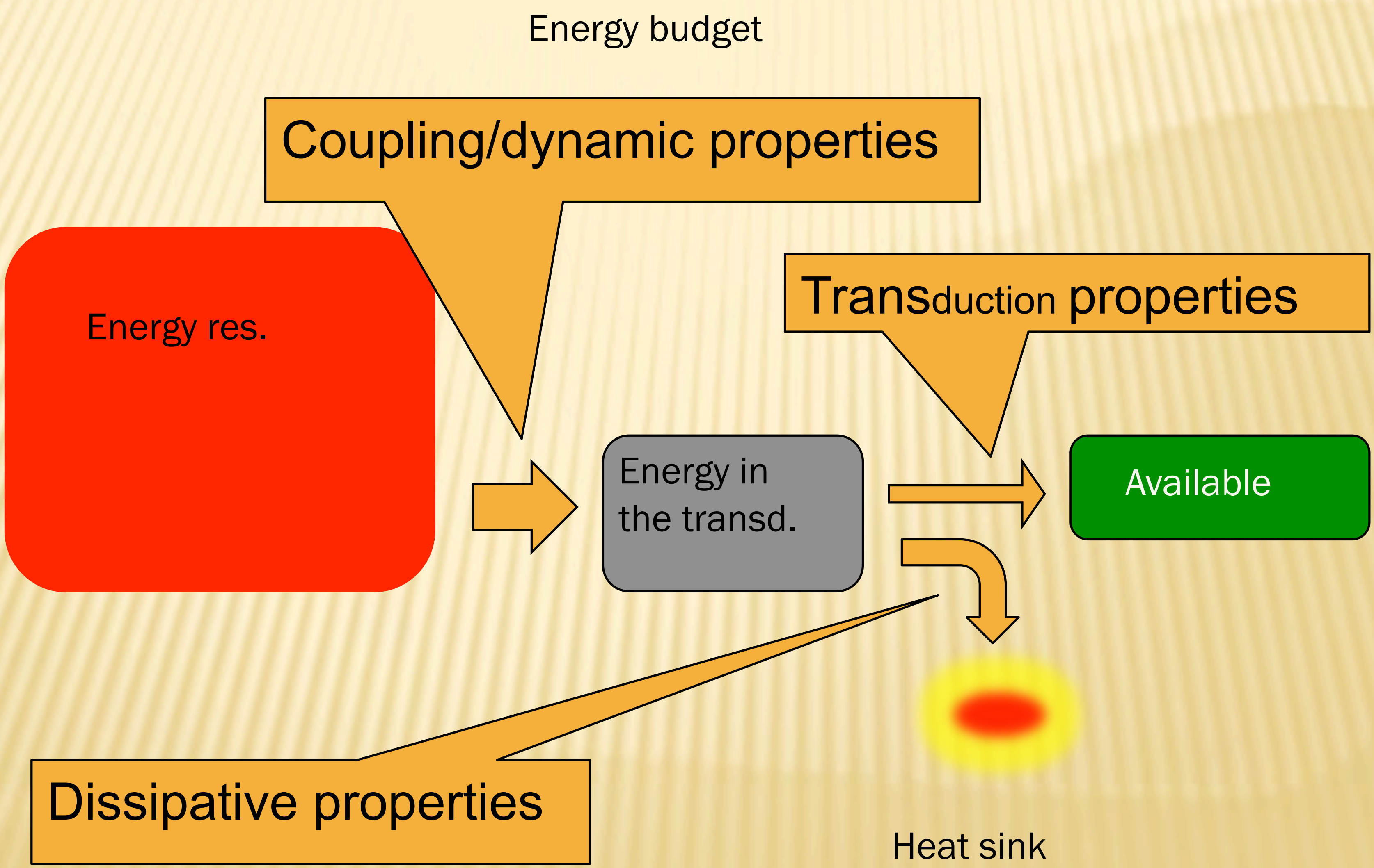
ENERGY HARVESTING BASIC IDEAS

Unlimited source of free energy, readily available for multiple uses…

ENERGY HARVESTING BASIC IDEAS



VIBRATIONS ENERGY HARVESTING



ENERGY HARVESTING BASIC IDEAS

Different kinds of energies… can be ranked by "quality"

 1° Electrical energy…

…

…

…

The last Thermal energy… (we will come back to this)

Thermodynamics helps out with the problem…

ENERGY HARVESTING BASIC IDEAS

Energy is a property of a physical system but it is not the only one that matters

Entropy

rules the capability of transforming one kind of energy into another…

…second principle… increase in Entropy for spontaneous transformations…

ENERGY EFFICIENCY ISSUES

An ICT device is a machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat)

Energy efficiency in operating such devices is presently considered an objective of extremely high relevance.

According to the SMART2020 study, *the share of ICT on the world wide energy consumption today is in the range of 2-5%. Given that the use of ICT will further increase and the overall energy consumption will hopefully decrease due to the help of ICT and other measures, it is expected that the share of ICT on the world wide energy consumption will grow in the future. Hence, it becomes more and more important to consider and improve the energy efficiency of ICT. On the short term, it will be an obvious and practical solution to exploit better the potential of technologies that already exist or are currently in the making. On the long term, new and disruptive ideas will be needed.*

MATCHING GOALS

- Faster computers
- Smaller computers
- More efficient computers
- Less energy needs

How do we match these requirements ?

Is there any physical limits tha we have to take into account ?

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COMPUTING SPEED

Processor	Dhrystone MIPS	D IPS / clock cycle	D IPS / clock cycle / Core	Year
Intel 4004	92 kIPS at 740 kHz (Not Dhrystone)	0.1	0.1	1971
IBM System/370 model 158-3	1 Dhrystone MIPS	1.0	0.1	1972
Intel 8080	500 kIPS at 2 MHz (Not Dhrystone)	0.3	0.3	1974
MOS Technology 6502	500 kIPS at 1 MHz (Not Dhrystone)	0.5	0.5	1975
VAX-11/780	500 kIPS at 5 MHz 1 Dhrystone MIPS	0.2	0.2	1977
Motorola 68000	1 MIPS at 8 MHz (Not Dhrystone)	0.1	0.1	1979
Intel 286	2.66 MIPS at 12.5 MHz	0.2	0.2	1982

(...)

COMPUTING SPEED

Intel Atom N270 (Single core)	3,846 MIPS at 1.6 GHz	2.4	1.2	2008
ARM Cortex M0	45 MIPS at 50MHz	0.9	0.9	2009
ARM Cortex A9 (Dual core)	5,000 MIPS at 1.0 GHz	5.0	2.5	2009
AMD Phenom II X4 940 Black Edition	42,820 MIPS at 3.0 GHz	14.3	3.5	2009
IBM 5.2-GHz z196 (4 cores)(released 9/2010)	52,286 MIPS at 5.2 GHz	10.05	2.5	2010
AMD Phenom II X6 1100T	78,440 MIPS at 3.3 GHz	23.7	3.9	2010
ARM Cortex-A15 (Dual Core)	14,000 MIPS at 2.0 GHz	7.0	3.5	2010
Intel Core i7 Extreme Edition i980EE	147,600 MIPS at 3.3 GHz	44.7	3.7	2010
Intel Core i7 Extreme Edition 990x	159,000 MIPS at 3.46 GHz	46.0	3.8	2011

Is there any limit?

Ultimate physical limits to computation

Seth Lloyd

d'Arbeloff Laboratory for Information Systems and Technology, MIT Department of Mechanical Engineering, Massachusetts Institute of Technology 3-160, Cambridge, Massachusetts 02139, USA (slloyd@mit.edu)

Computers are physical systems: the laws of physics dictate what they can and cannot do. In particular, the speed with which a physical device can process information is limited by its energy and the amount of information that it can process is limited by the number of degrees of freedom it possesses. Here I explore the physical limits of computation as determined by the speed of light c, the quantum scale $\hbar$ and the gravitational constant G. As an example, I put quantitative bounds to the computational power of an 'ultimate laptop' with a mass of one kilogram confined to a volume of one litre.

-Seth Loyd, Nature, vol. 406, 31/8/2000, p. 1054

The first limit comes from quantum…

Heisemberg

$$\Delta E \Delta t \geqslant \hbar$$

Aharonov and Bohm interpretation[1]:

a quantum state with spread in energy ΔE
takes time at least Δt
to evolve to an orthogonal (i.e. distinguishable) state, with:

$$\Delta t = \pi \hbar / 2 \Delta E$$

[1] Aharonov, Y. & Bohm, D. Time in the quantum theory and the uncertainty relation for the time and energy domain. Phys. Rev. 122, 1649–1658 (1961).

More recently, Margolus and Levitin15,16 extended this result to show that a quantum system with average energy E takes time at least Δt to evolve to an orthogonal state.

$$\Delta t = \pi\hbar/2E$$

Larger the energy of the physical state ---> lesser the time that it takes

[2] Margolus, N. & Levitin, L. B. The maximum speed of dynamical evolution. Physica D 120, 188–195 (1998).

How fast can we go if we use all the energy in a PC to do a single NOT operation?

$$\Delta t = \pi\hbar/2E$$

In present computers.... We have 10^{11} operation per s and we spend 100 W
Thus we have 100 J/10^{11} = 10^{-9} J per operation

The Heisemberg limit for this energy would be Δt = approx = 10^{-34} /10^{-9} = 10^{-25} s

PRESENTLY the time required by an operation is $10^{-11} >> 10^{-25}$

We are still far from being limited by this !!!

What can we do about energy ?

What is the minimum energy required to perform computation ?

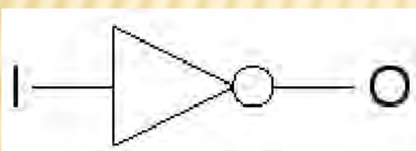
in 1961 R. Landauer has shown that:

Minimum energy required to make any calculation is ZERO

If the operation is REVERSIBLE

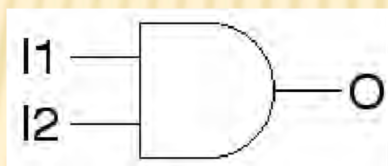
REVERSIBLE = Physically reversible and logically reversible

NOT



I	O
0	1
1	0

AND



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

What if the operation is not logically reversible ?

There is a minimum energy to be paid as a consequence of the decrease in entropy

$S = K_B \text{ Log } \Omega$ (L. Boltzmann)

Ω Number of available states

Let's consider a typically irreversible operation: register reset (or bit erasure)

0,1 -----> 0

$S_i = K_B \text{ Log } 2$ -------------> $S_f = K_B \text{ Log } 1$

$\Delta S = S_f - S_i = -K_B \text{ Log } 2$

Energy: $Q = T\Delta S = - T K_B \text{ Log } 2$

"-" sign states tha energy has to be provided

If the operation is logically irreversible there is a minimum amount of energy that is required. This minimum energy is:

$$Q = T K_B \text{ Log } 2 = 10^{-21} \text{ J}$$

Present status

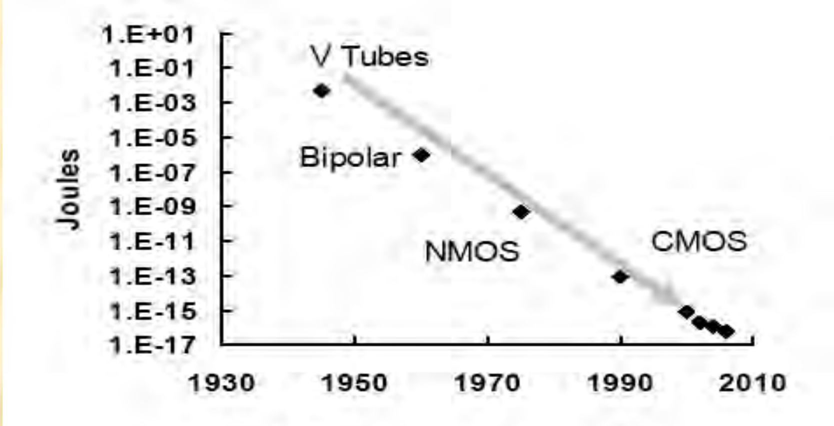


Figure 3: Energy per logic operation

After **Electronics Beyond Nano-scale CMOS,** Shekhar Borkar

Out of curiosity…. If E=10-^{17}, the Heisemberg limit for this energy would be Δt = approx = $10^{-34}/10^{-17} = 10^{-17}$ s not so far away… 10^{-11}…

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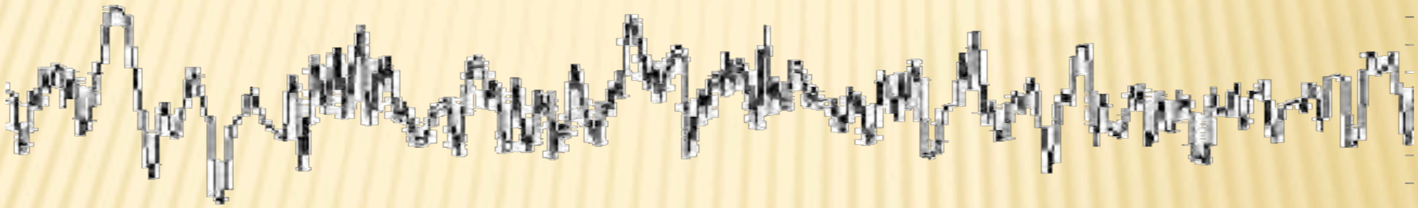
THE RANDOM CHARACTER OF KINETIC ENERGY

What does it look like?



At the micro-to-nano scales most of the energy available is **kinetic energy** present in the form of **random fluctuations**, i.e. **noise**.

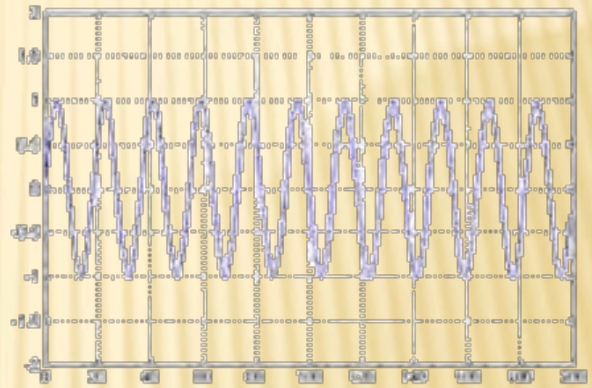
What do we mean with noise ?

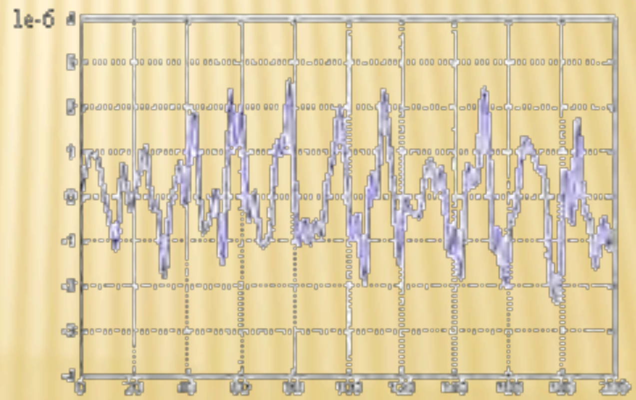
Noise in Physics means:
A disturbance, especially a random and persistent disturbance, that obscures or reduces the clarity of a signal.

Noise becomes relevant when we try to measure a physical quantity with high precision

"**Precision** is the ability of an instrument to produce the same value or result, given the same input"

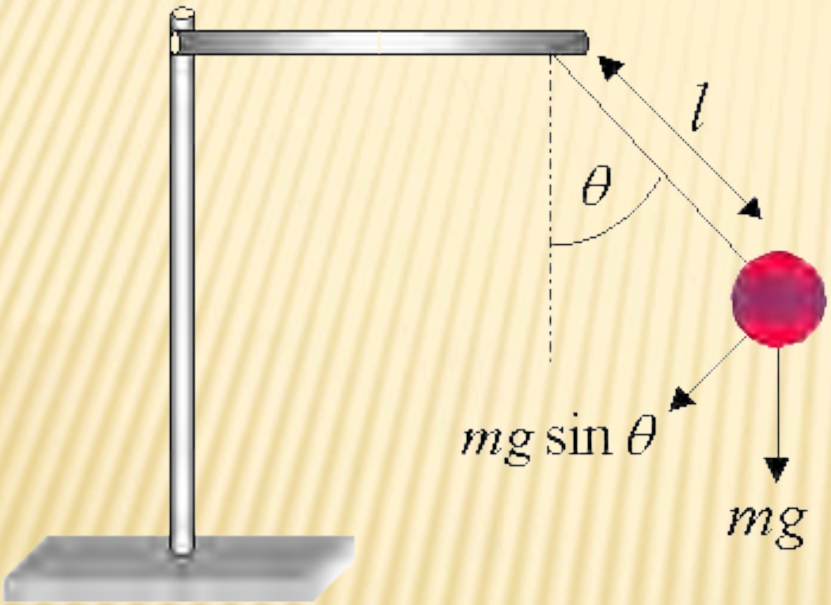
Example: the measurement of the pendulum position





Where does this noise comes from?

The almost “simple” pendulum



Motion equation

$$ml^2\frac{d^2\theta}{dt^2}+mgl\sin\theta = 0$$

Small oscilation approximation, with damping

$$\frac{d^2\theta}{dt^2}+\left(\frac{1}{q}\right)\frac{d\theta}{dt}+\omega^2\sin\theta = 0$$

What if we wait long enough ?

The **very small** oscillation limit.
Let the pendulm swing freely…

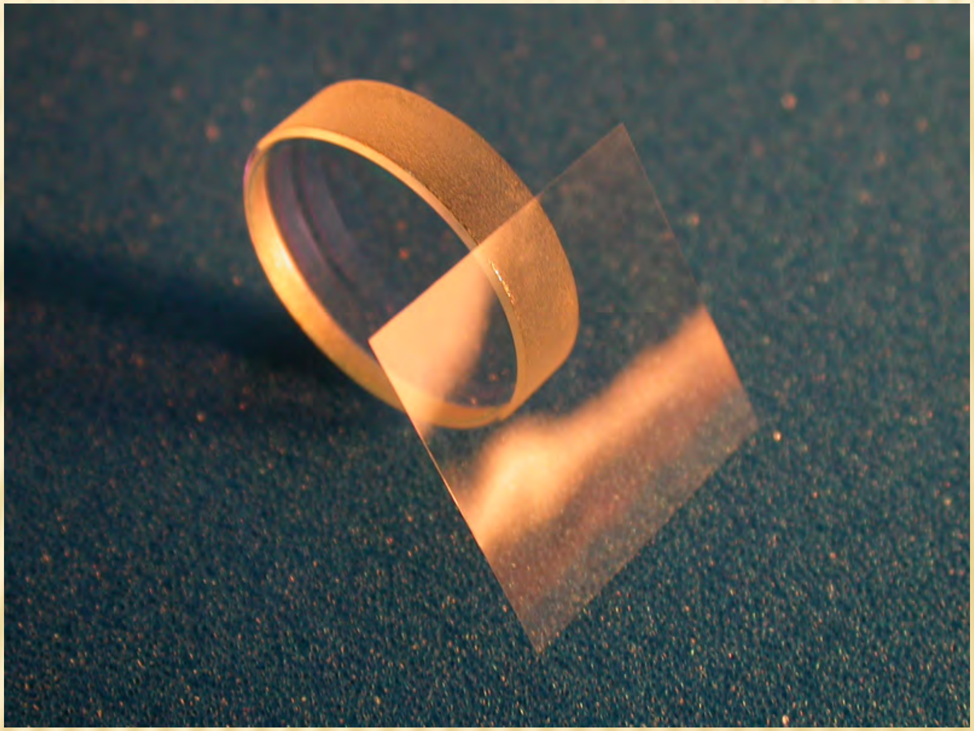
Example: the real measurement of a free swinging pendulum

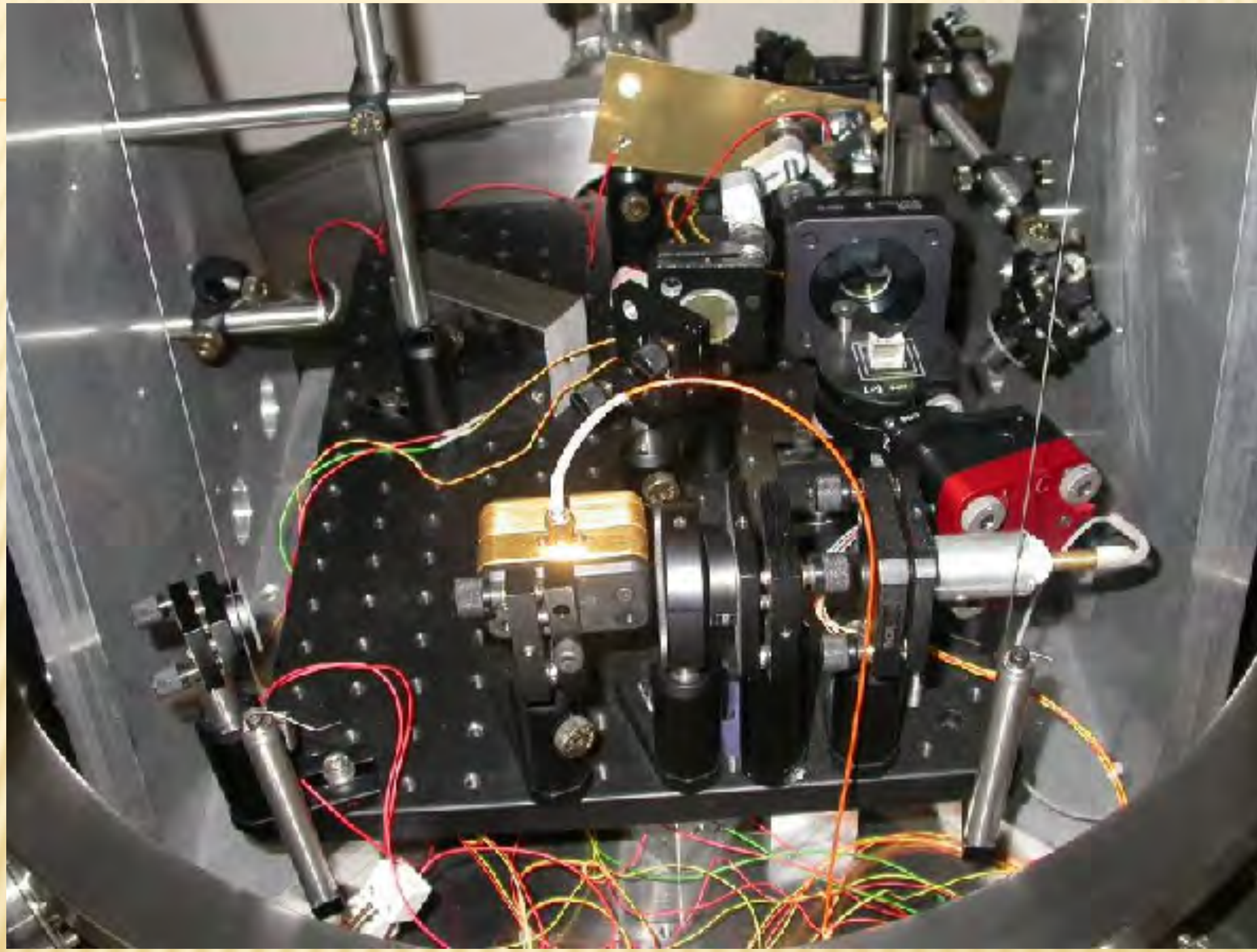
Mass m= 1 Kg
Length l = 1 m
rms motion = 2 10^{-11} m

Mass m= 1 g
Length l = 1 m
rms motion = 6 10^{-10} m

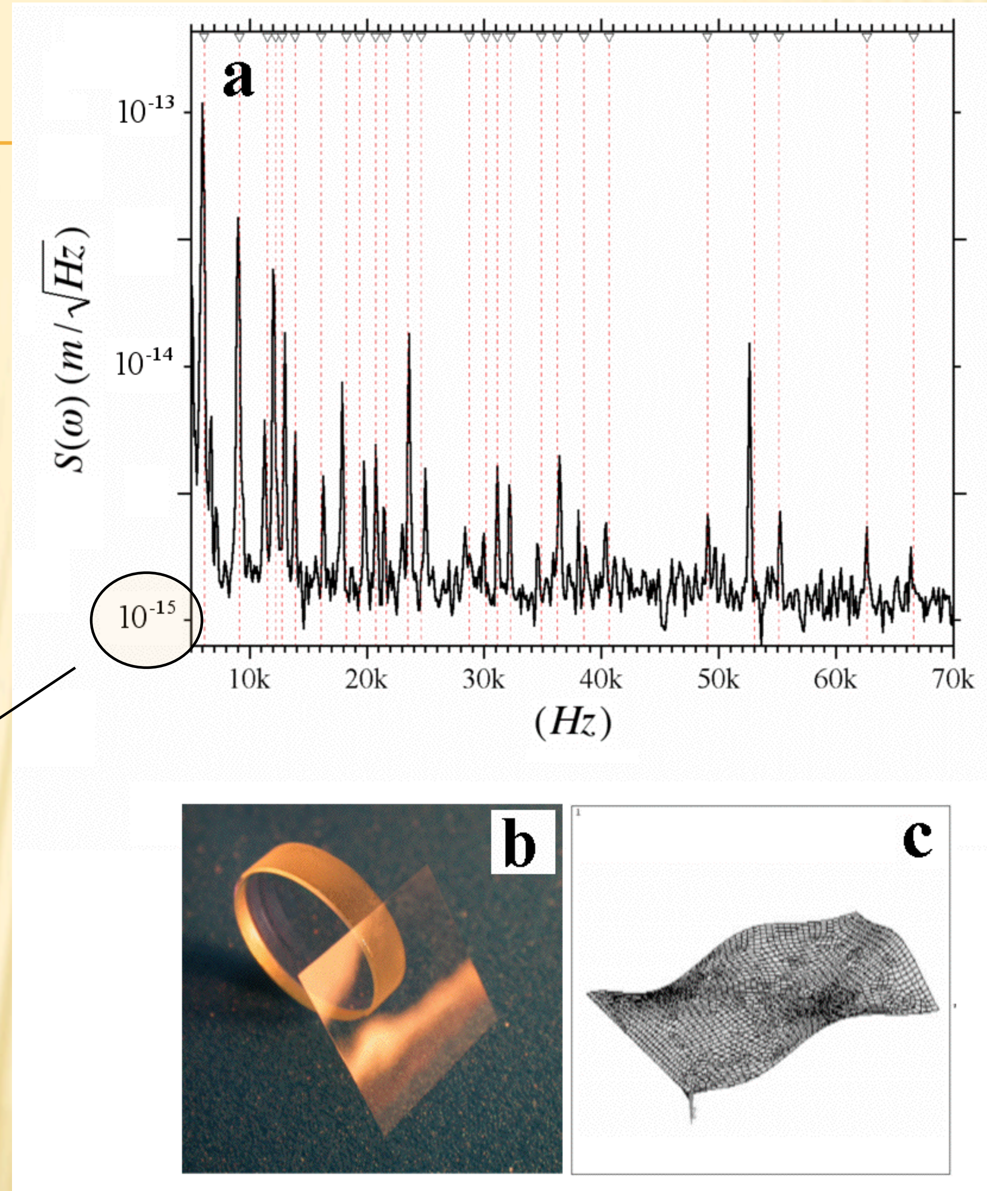
Mass m= 10^{-6} g
Length l = 1 m
rms motion approx 1 mircon

DIRECT MEASUREMENT OF INTERNAL VIBRATION ON A THIN FUSED SILICA SLAB





EXPERIMENTAL RESULTS

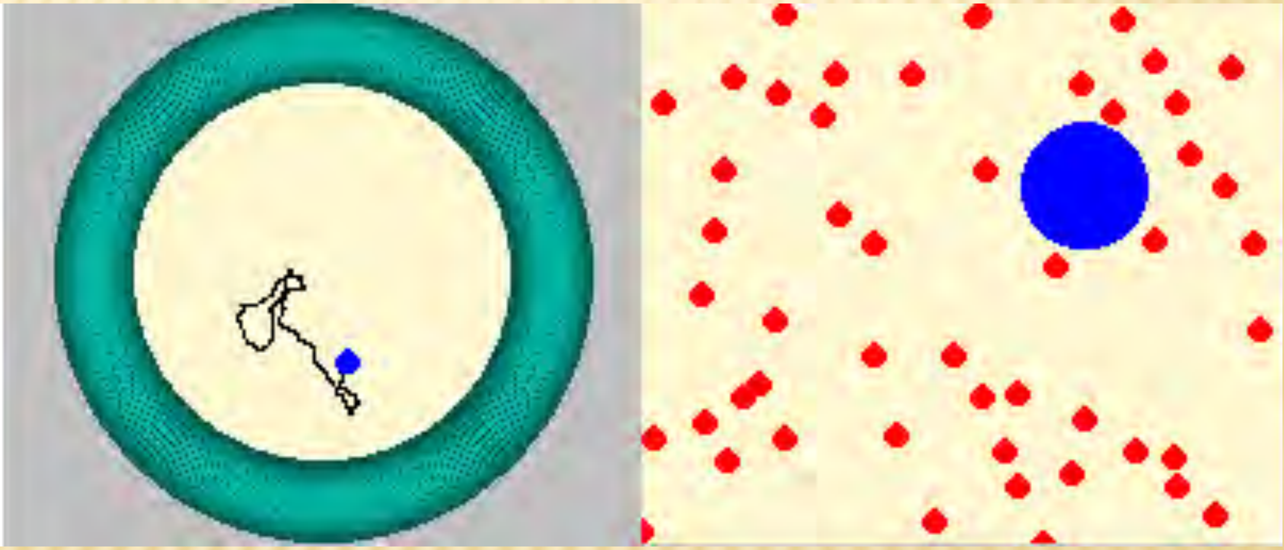


10^{-15}

For further info see: www.nipslab.org

Where all these fluctuations come from?

1828 R. Brown
1905 A. Einstein



The mother of all noises: **thermal noise**

Brownian motion → thermal noise

thermal noise is the name commonly given to **fluctuations** affecting a physical observable of a macroscopic system at thermal equilibrium with its environment.

The internal energy of a macroscopic apparatus at thermal equilibrium is shared between all its degrees of freedom or, equivalently, between all its normal modes each carrying an average energy kT, where T is the equilibrium temperature.

This is true also for such modes as the oscillations of springs, pendula, needles, etc.

Such an energy manifests itself as a random fluctuation of the relevant observable experimentally perceived as the noise affecting its measured value.

How to model **thermal noise**

To describe such a dynamics it is necessary to introduce a statistical approach

a) Fokker-Plank equation
b) Langevin Equation

The usual equation of motion (Newton f = ma) should be changed in order to accomodate non deterministic forces. What we get is called **Langevin equation**:

The are two kind of forces acting on the pollen grain:

1) A viscous drag (motion in a fluid) $-6\pi\eta a\dot{x}$

2) A fluctuating force (representing the incessant impact of the molecules) $\zeta(t)$

$$m\ddot{x} = -6\pi\eta a\dot{x} + \zeta(t)$$

Generalization:

The viscous drag expression can be generalized in order to describe a wider class of damping functions

$$-m \int_{-\infty}^{t} \gamma(t-\tau)\, \dot{x}\, d\tau$$

Generalized Langevin equation

$$m\, \ddot{x} = -m \int_{-\infty}^{t} \gamma(t-\tau)\, \dot{x}\, d\tau + \zeta(t)$$

$\zeta(t)$ Is the stochastic force with known statistical properties:

Probability density function, moments, correlations, ...

For the pendulum we get:

$$\ddot{x} = -\omega_p^2 \, x - \int_{-\infty}^{t} \gamma(t-\tau)\, \dot{x}\, d\tau + \frac{\zeta(t)}{m}$$

The arbitrariness in our choice of the damping function and the stochastic force is constrained by the so-called Fluctuation-Dissipation theorem which suffices to enforce the energy equipartition

$$\langle \zeta(t)\zeta(0) \rangle = k\,T\, m\gamma(|t|)$$

In the spectral domain, for a linear system, is always possible to write its response to an external force like:

$$X(\omega) = H(\omega)F(\omega)$$

Where H is the system transfer function.

$$H(\omega) = H'(\omega) + i\,H''(\omega) = \left|H(\omega)\right| e^{i\phi(\omega)}$$

The F-D Theorem can be written here as:

$$S_x(\omega) = -4\,k\,T\,\frac{H''(\omega)}{\omega}$$

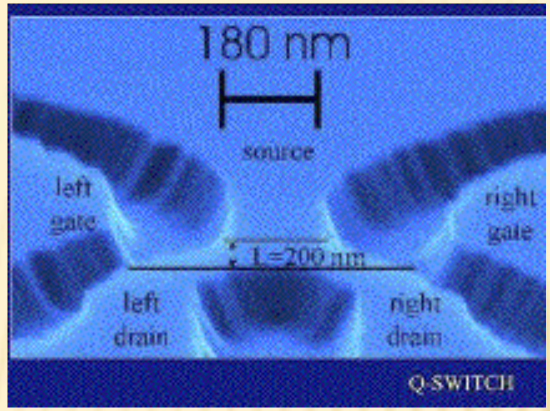
The dissipative properties of the dynamical system are thus directly related to the equilibrium fluctuations.

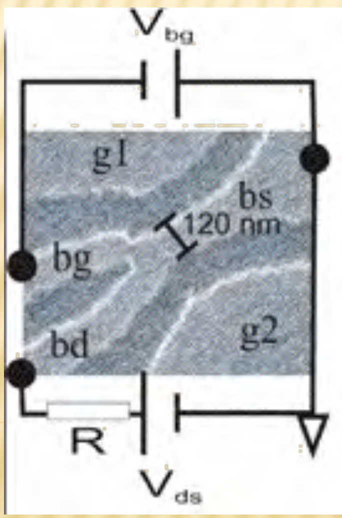
Fluctuation-Dissipation theorem

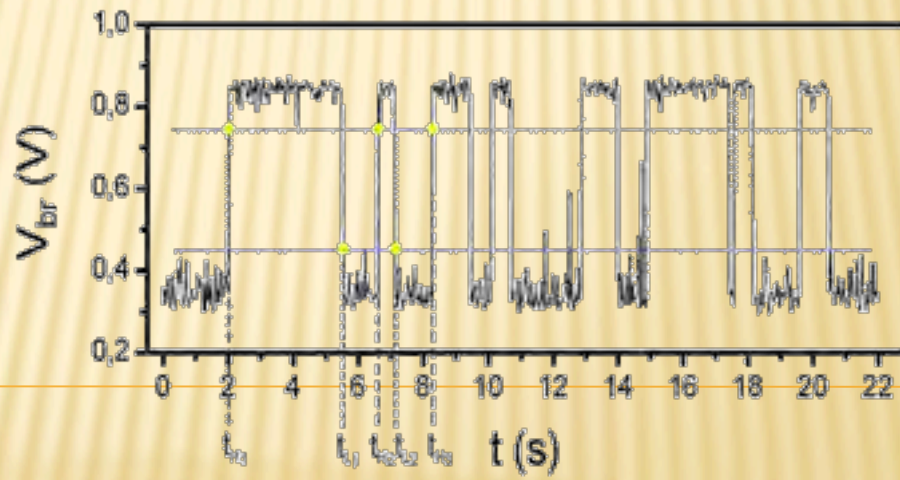
The **dissipative properties** of the dynamical system are thus directly related to the equilibrium fluctuations.

Physical connection:
the source of the fluctuations is the very same of the source of the dissipation

NANO SYSTEMS AFFECTED BY NOISE



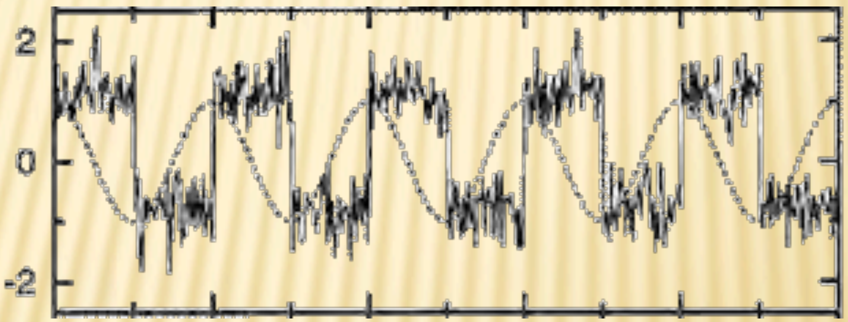




See **SUBTLE:** SUB KT Transistors and Sensors, FPVI FET
http://subtle.fisica.unipg.it/

New paradigma for the role of noise.

The role of noise has been promoted from simple disturb to potentially fruitful resource, due to progresses in nonlinear stochastic dynamics. Phenomena like "**Stochastic Resonance**" and "**thermal ratchets**" have popularized the idea that noise can be exploited to produce improvements in system performances.



ICT RELATED INITIATIVES FUNDED BY EC (COORDINATED BY NIPS LAB)

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www.nanopwr.eu

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