Introduction to Energy Harvesting

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NiPS Summer school 2017, Gubbio

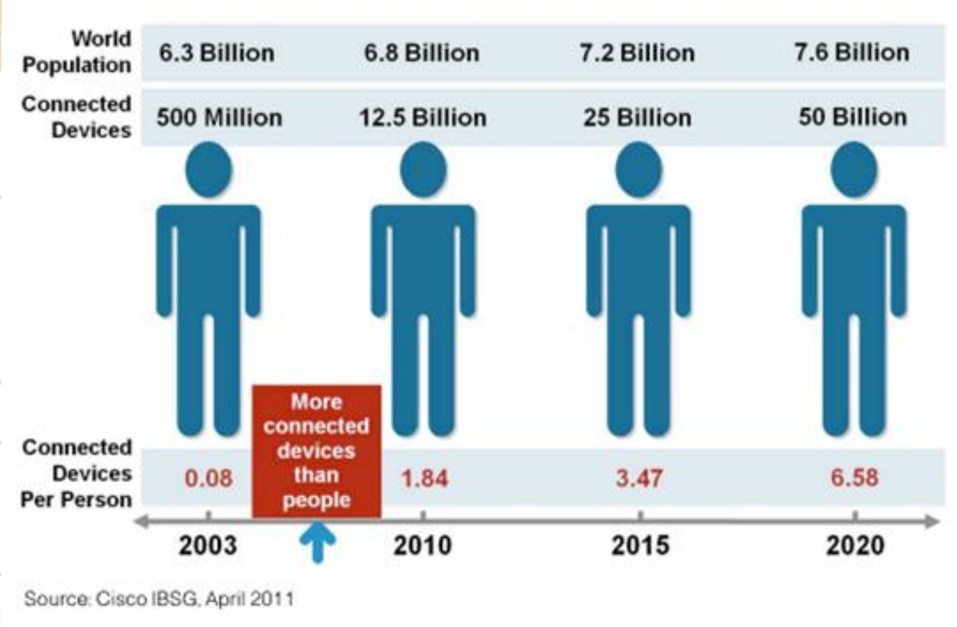
NiPS Laboratory
Noise in Physical Systems

Energy Harvesting

The Harvest, Camille Pissarro, 1882

What is it and why it is important?

A growing number of people accepted to join the so-called internet-of-things scenario



Before this scenario becomes a reality the device powering issue needs to be addressed and solved.

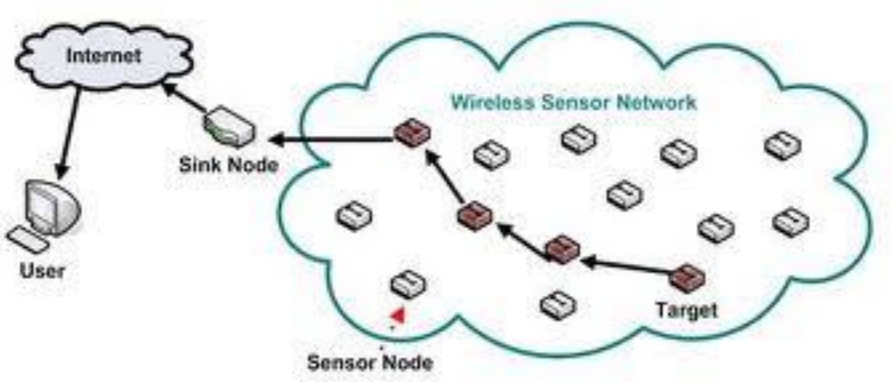
The challenge of efficient management of energy is a key aspect to consider in computing systems, especially for applications in smart sensors and Internet of Things devices.

European Commission **Workshop** on "Energy-Efficient Computing Systems, dynamic adaptation of Quality of Service and approximate computing". Nov. 27 2014 - Brussels

Energy consumption has become a major issue for the future of ICT and robotics as well

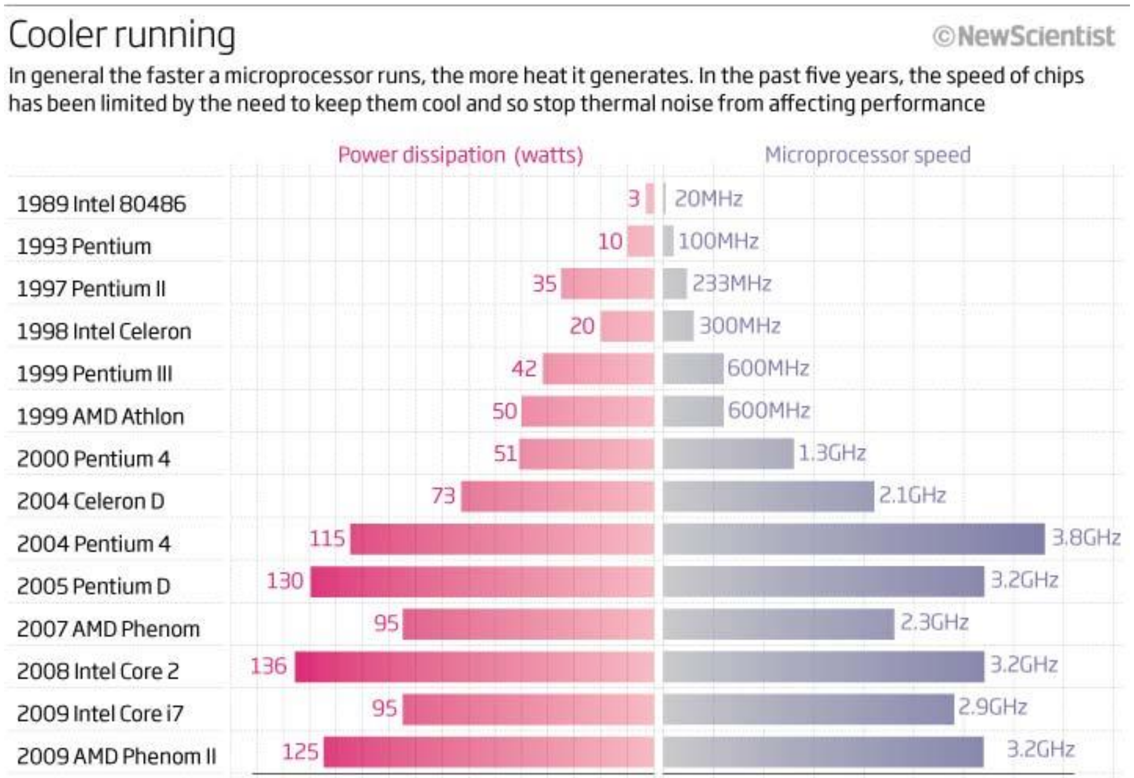
1) High performance computing systems

2) Autonomous microdevices, micro robots, wireless sensor networks



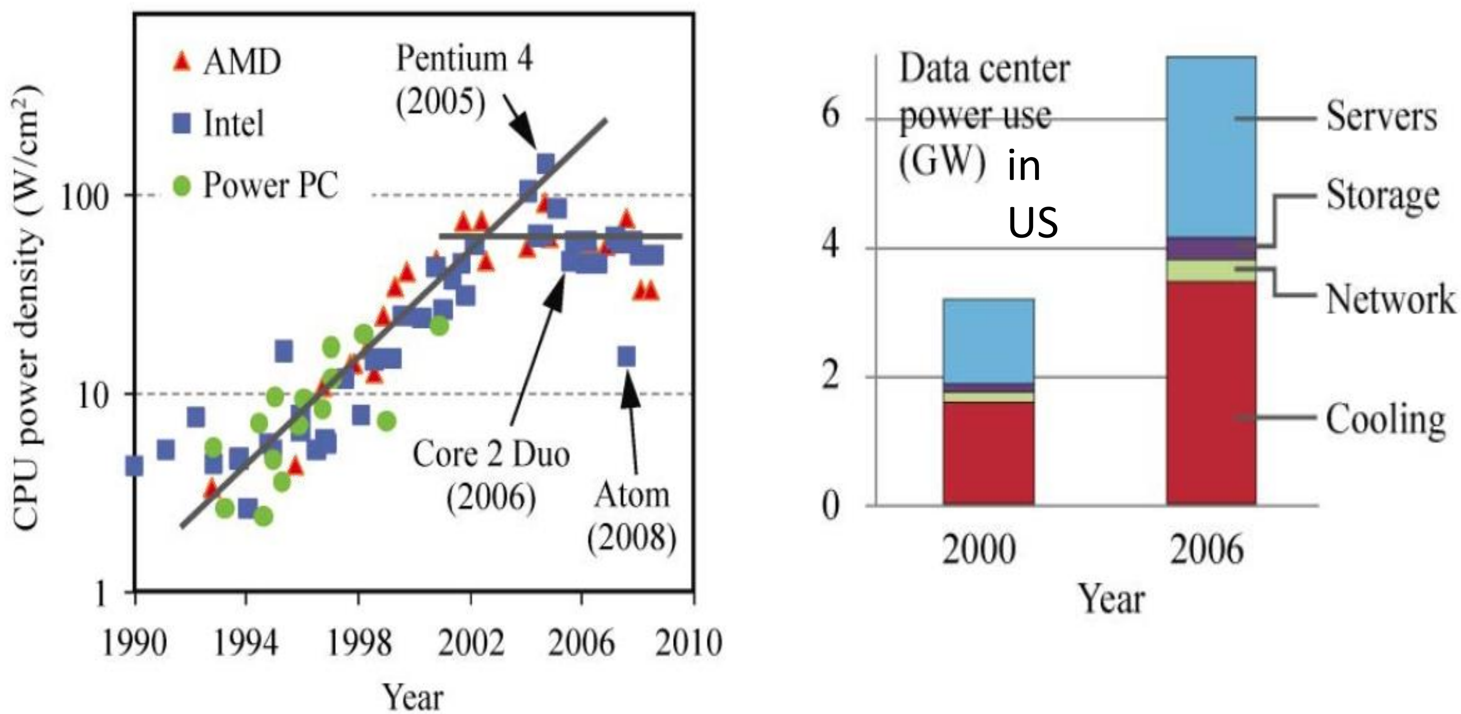
1) High performance computing systems

Energy consumption in computing systems has become a major issue for the future of ICT



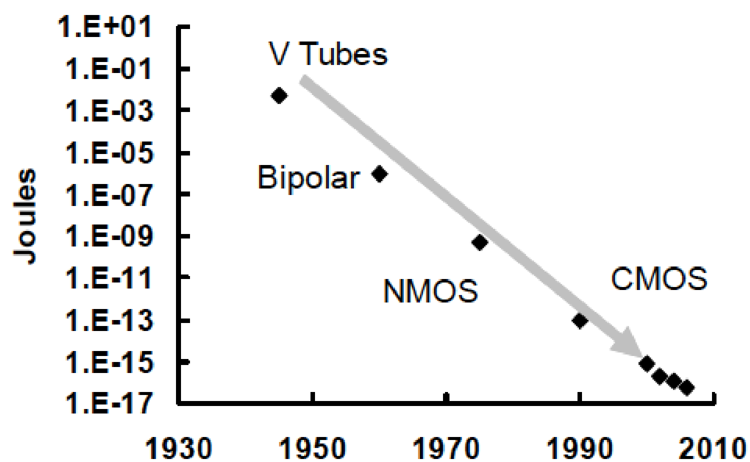
ICT - Energy

The binomial **ICT-Energy** has become the focus of future ICT research world wide



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

Energy required to operate microprocessors

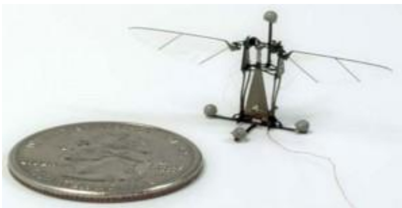


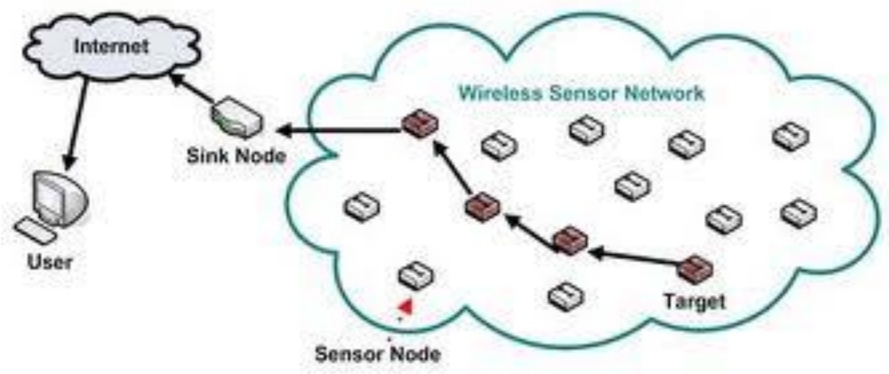
Shekhar Borkar, **Electronics Beyond Nano-scale CMOS,** Design Automation Conference, 2006 43rd ACM/IEEE

*"...the resulting power density for these switches at **maximum packing density** would be on the order of 1MW/cm^2 – orders of magnitude higher than the practical air-cooling limit.."*

Jeffrey J. Welser
The Quest for the Next Information Processing Technology , **2008**

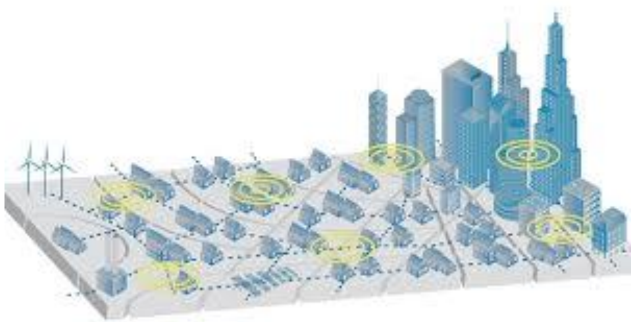
2) Autonomous microdevices, micro robots, wireless sensor networks

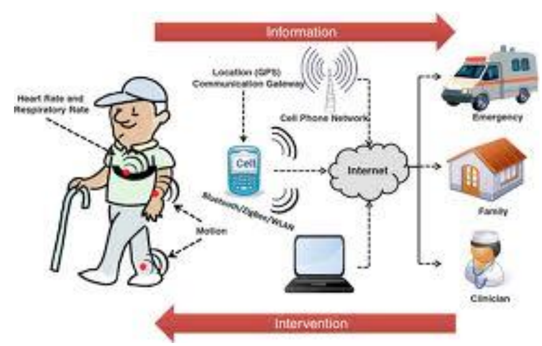




The promised land of ubiquitous computing

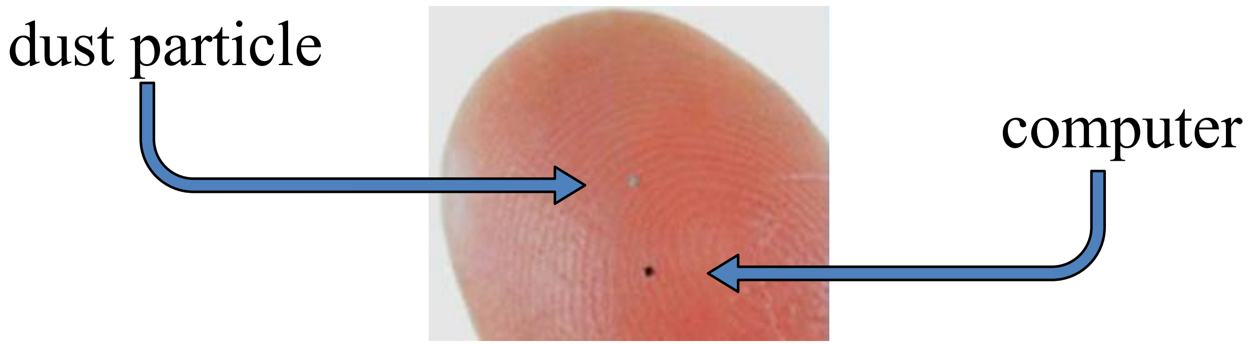
This is the land of wireless micro-sensors that continuously and ubiquitously measure, process and transmit data to improve our living.





This is the long-time announced revolution where the cities become smart and the human and animal health is monitored and controlled.

The promised land of ubiquitous computing

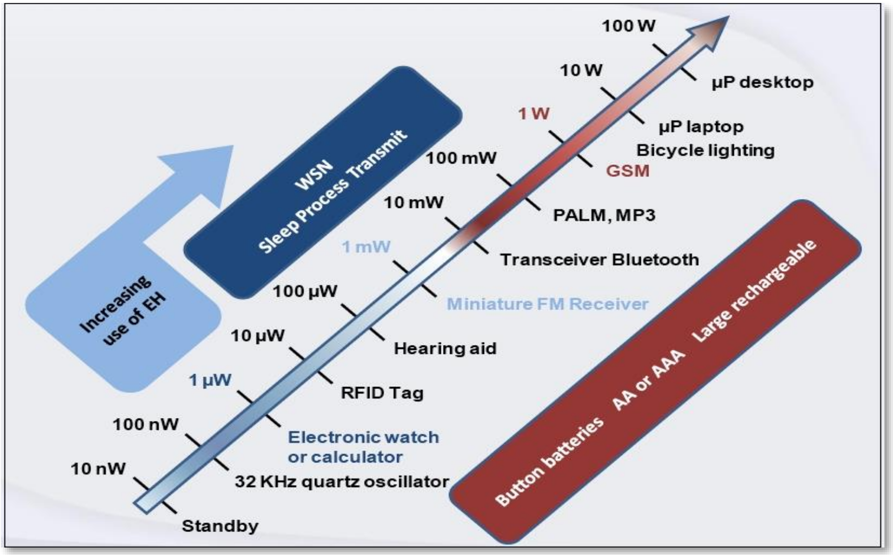


The land where computers are as small as dust particles

and bio-inspired robots appear

Why are we not there yet?

Energy required to operate the portable devices



Energy available from portable sources (energy harvesting)

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

Energy required to operate the portable devices

We need to bridge the gap by acting on both arrows

Energy available from portable sources

Energy required to operate computing devices

Why does it make sense to talk of a new field ICT-Energy ?

Energy available from the environment

“battery-free” devices

1) Energy dissipation in high performance computing systems

2) Powering autonomous microdevices, micro robots, wireless sensor networks

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 vibrations to power micro/nanoscale devices
-…

Could be asked and answered within this framwork.

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

Heat-Work relations

ICT Revolution
XX-XXI

Fluctuation-Dissipation relations

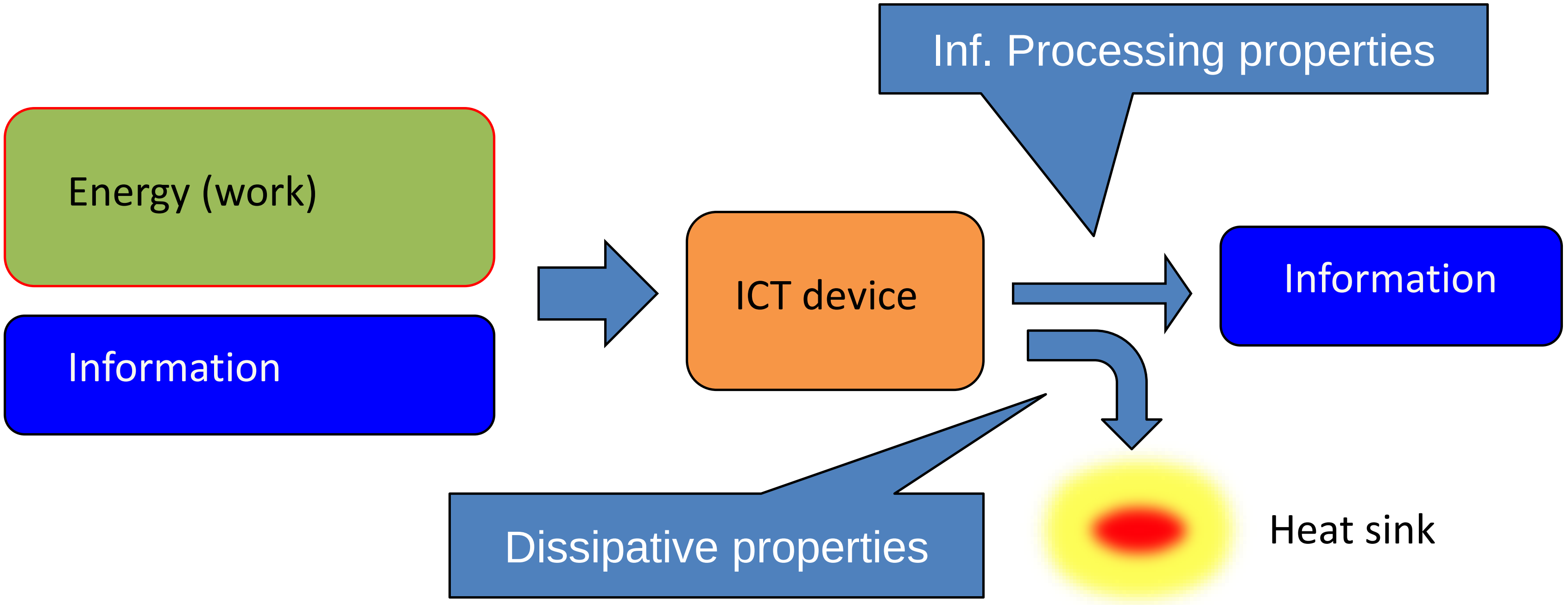
Information is physical !!!

CHALLENGE:

the description of **energy transformation processes at the nanoscale** aimed at unveiling new mechanisms for powering next generations of ICT devices.

A different approach to heat production: an ICT device is a special thermal machine

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).



L. Gammaitoni, There's plenty of energy at the bottom, Contemporary Physics, vol. 53, issue 2, pp. 119-135

Some modeling

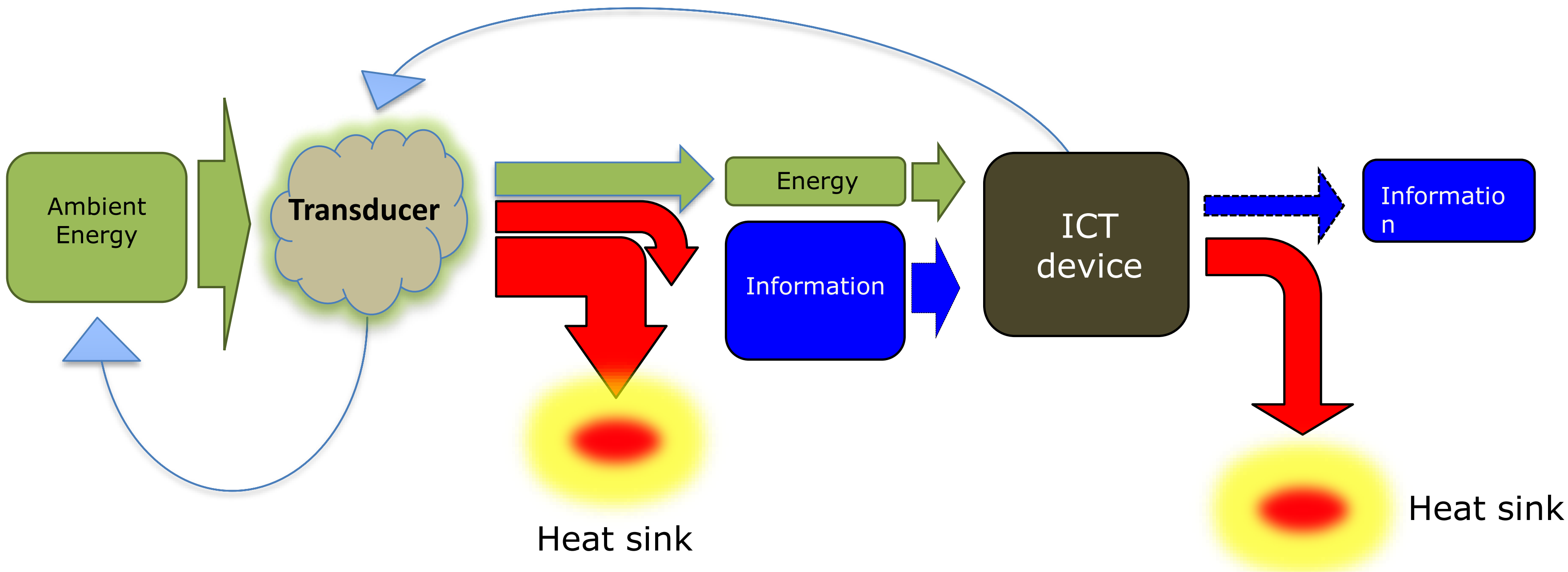
The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

We consider devices at MEMS scale and below

We consider "ICT devices": i.e. devices mainly devoted to computing task

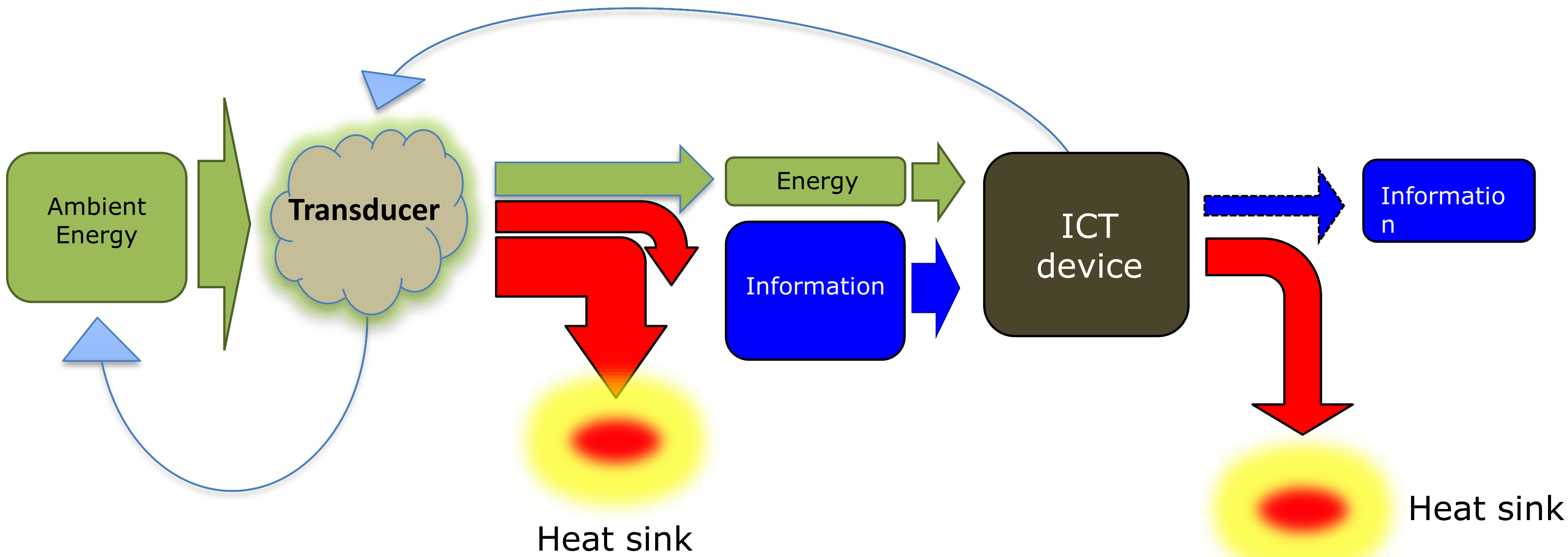


An **ICT device** is an info-thermal machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

Some interesting questions:

Why all the energy ends up in heat? What does it mean “energy dissipation”? Can be avoided?

What is the role of information? Is this a physical quantity that affects the energy transformations?



We need a physical model…

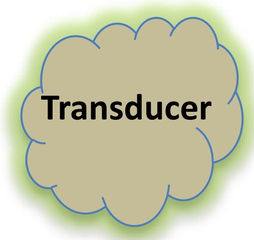
Two physical systems:

They transform energy

They have many d.o.f. (presence of fluctuations)

They are operated in a changing environment

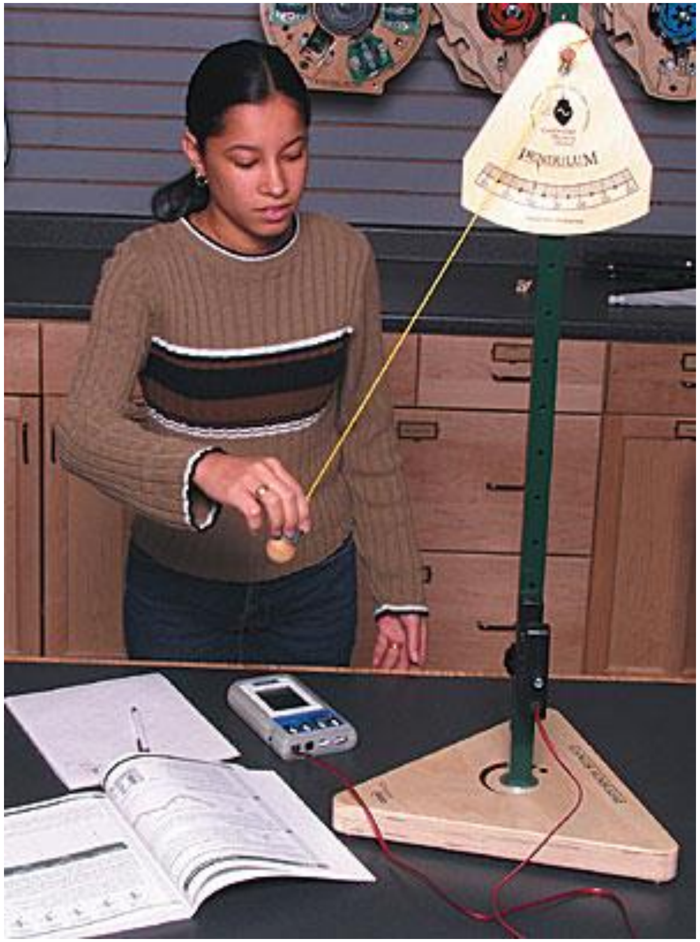
~~Thermodynamics~~ ~~Statistical mechanics~~ Non-equilibrium statistical mechanics



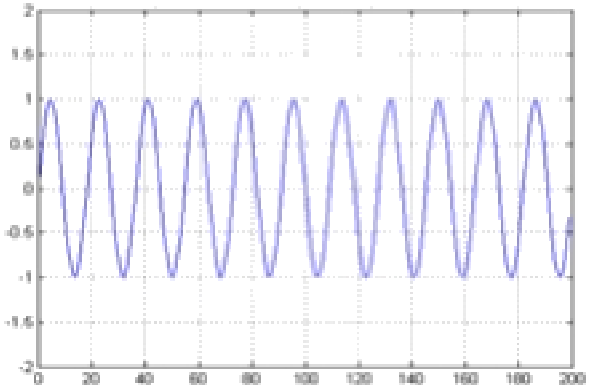
In this framework we can describe the device behavior in terms of few relevant d.o.f. via a procedure called "adiabatic elimination" or "coarse graining approach": we exchange the dynamics of a *not small isolated system* with *small not isolated system.*

Let's see an example…

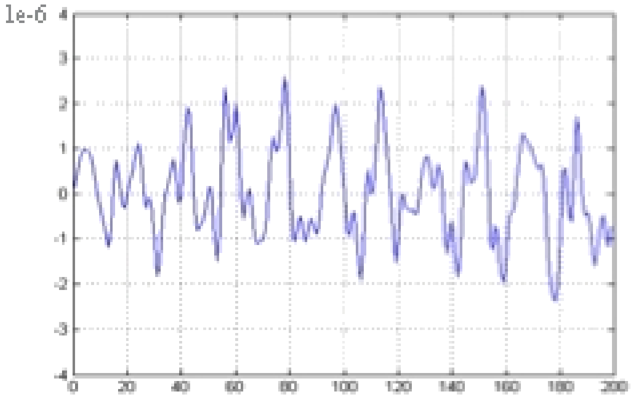
Example: physical system pendulum



Focus on the pendulum angle

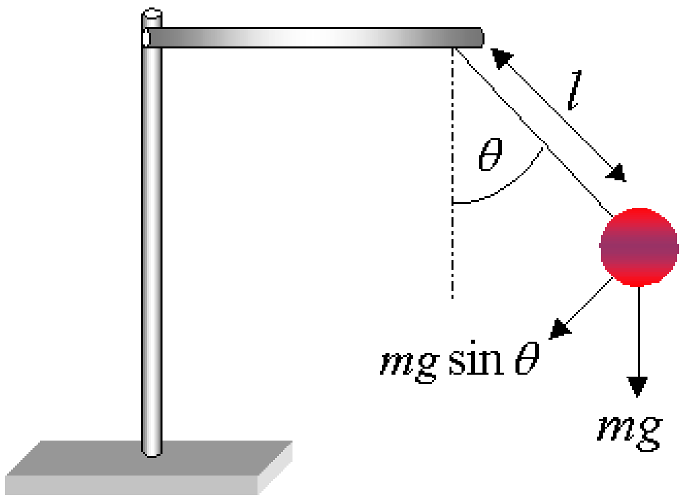


If we come back after a while..



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

How to model such a behavior?



Motion equation for the angle variable:

$$m\,l^2\,\ddot{\theta} + mgl\sin\theta = 0$$

This is clearly an approximation that does not describe the whole phenomena:

1) Amplitude decay is missing
2) Zero amplitude fluctuation is missing

Improved motion equation for the angle variable $$m\,l^2\,\ddot{\theta} - \gamma\,\dot{x} + mgl\sin\theta + \zeta(t) = 0$$

They come from the neglected N-1 d.o.f.

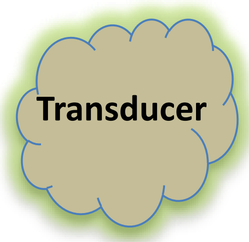
$$< \zeta(t)\ \zeta(0) > = 2\,K_B T\,\gamma\,\delta(t)$$

The viscous drag expression can be generalized in order to describe a wider class of damping functions $$-\int_{-\infty}^{t} \gamma(t-\tau)\,\dot{x}\,d\tau \quad \Longrightarrow \quad \langle z(t) z(0) \rangle = k\,T\,g(|t|)$$

Fluctuation – Dissipation theorem

Two physical systems whose dynamical behavior can be described in the framework of non-equilibrium statistical mechanics.

Langevin equation approach



$$m\ddot{x} = -\gamma \dot{x} + \zeta + F_{ext}$$

$$F_{ext} = -\frac{dU(x,t)}{dx} + z_z$$

Deterministic force depending on *x, t*

Random force depending on *t*

If $F_{ext} >> \zeta$ then the thermal noise contribution can be ignored

$$m\ddot{x} = -\frac{dU(x,t)}{dx} - \gamma \dot{x} + \zeta_z$$

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Langevin equation approach

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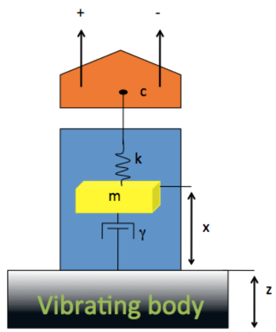

ICT device

(example from vibration harvester)

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - c(x,V) + \zeta_z + \zeta$$

$$\dot{V} = F(\dot{x}, V)$$

$$< \zeta(t)\, \zeta(0) > = 2\, K_B T\, \gamma\, \delta(t)$$

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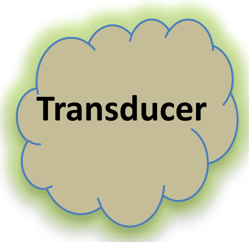
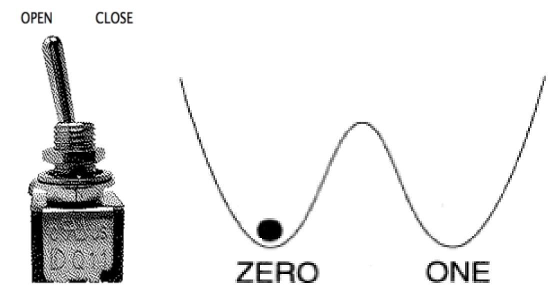
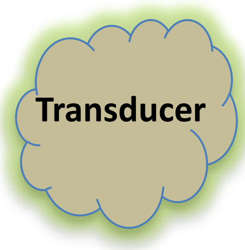




(example from a digital binary switch)

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} + F_{sw} + \zeta$$

$$< \zeta(t)\ \zeta(0) > = 2\ K_B T\ \gamma\ \delta(t)$$



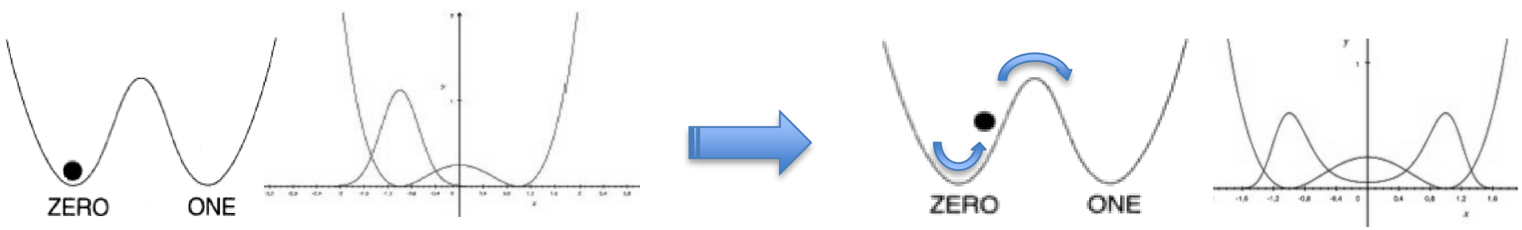
Langevin equation approach

$$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \gamma\dot{x} + \zeta$$

ICT
device

This is a stochastic dynamics whose solution *x(t)* appears like

Probability density *P(x,t)*.
P(x,t)dx represents the probability for the observable *x* to be in (*x* , *x+dx*).



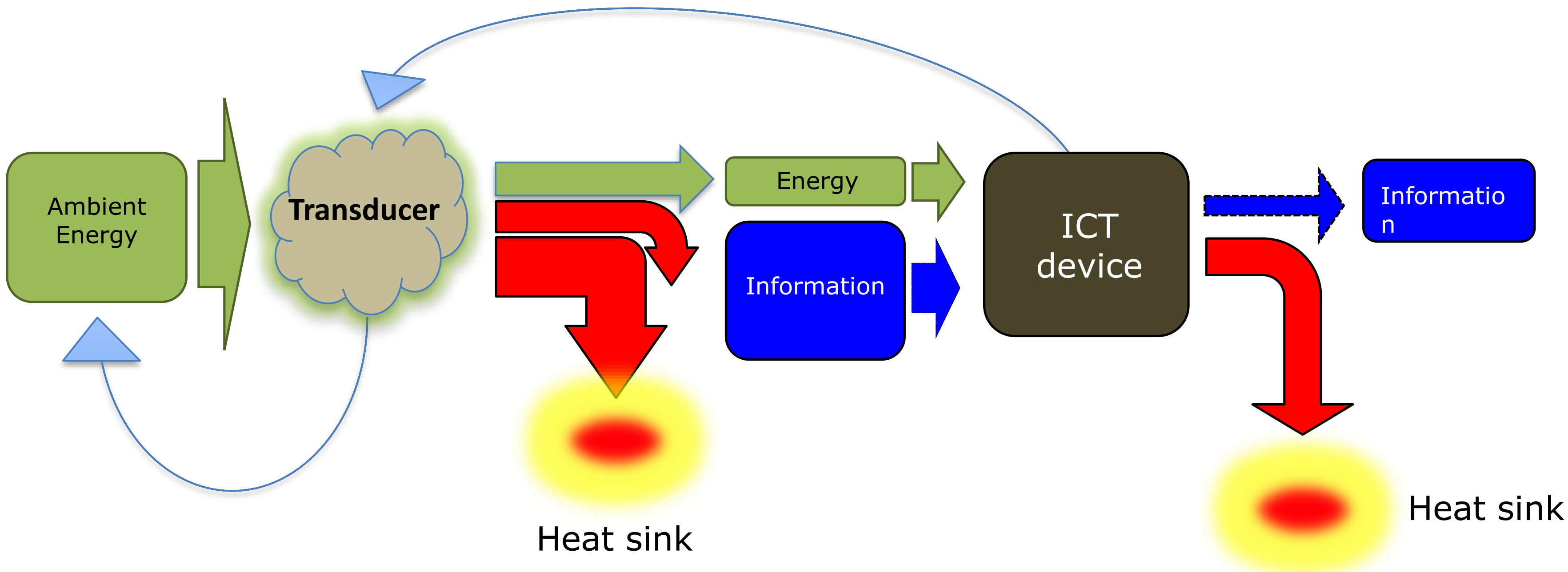
P(x,t) is a deterministic quantity and its time evolution of can be described in terms of the associated Fokker-Planck equation.

Some considerations

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?



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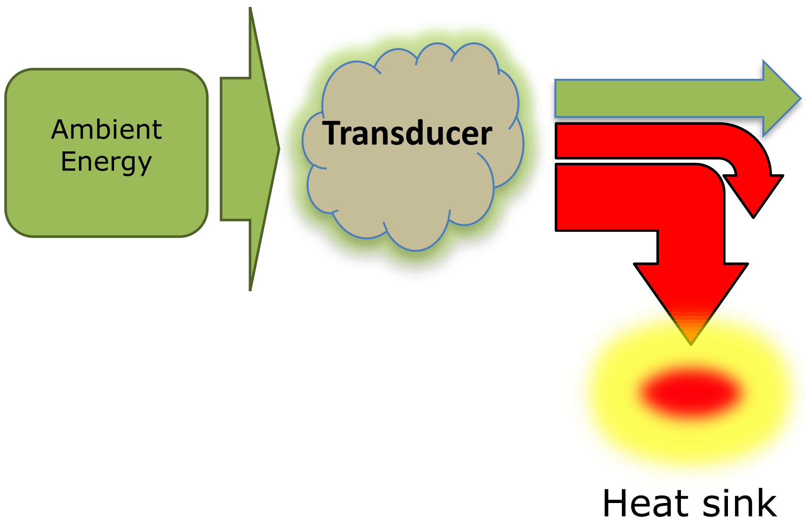
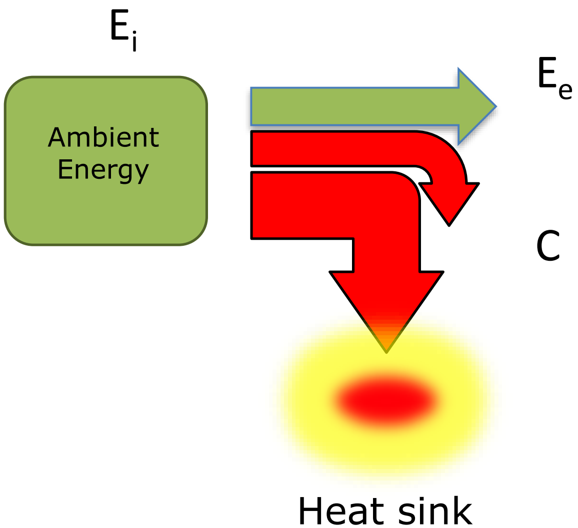


Clearly this energy is obtained from the ambient…

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?



Energy is conserved….

$E_e = E_i - C$

Question: can we make C = 0 ?

C is the energy dissipated during the transformation. $$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \gamma\dot{x} + \zeta$$

C=C(γ) and γ is associated with the relaxation to equilibrium and depends on the characteristics of the device/material.

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

C is the energy dissipated during the transformation. $$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \gamma\dot{x} + \zeta$$

The usual solution is to go very slow, i.e. to minimize $\dot{x}$

Good news: In principle there is no physical law that forbids to make C = 0

Bad news: This affects the power we can use in the device

C=C(γ) can be a function of time and change with the dissipation process.
Viscous damping, thermo-eleastic damping, structural damping, …

Generalized Langevin equation $$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \int_{-\infty}^{t} \gamma(t-\tau)\,\dot{x}\,d\tau + \zeta$$

The device powering issue:

1) How much energy is needed to power a device ?

2) Where does the device get the needed energy ?

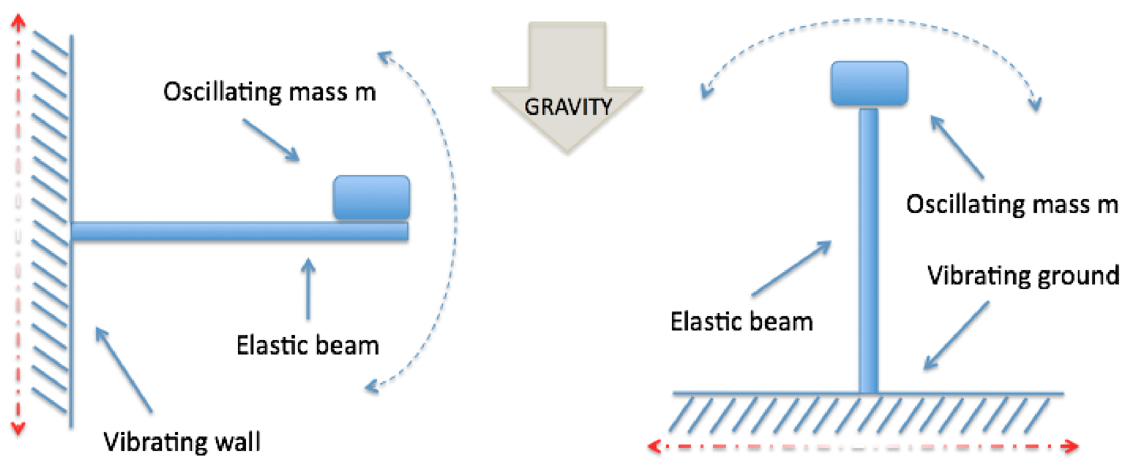
$$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \gamma\dot{x} + \zeta$$

Finally, the role of the potential energy *U(x,t)*

linear oscillator approach

$$U(x) = \frac{1}{2}ax^2$$

cantilever

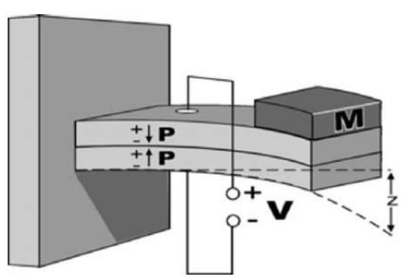


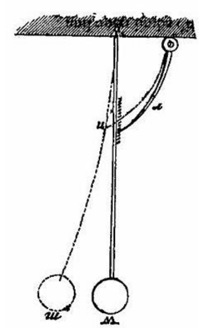
Left: configuration for harvesting vertical vibrations.
Right: configuration for harvesting horizontal vibrations.

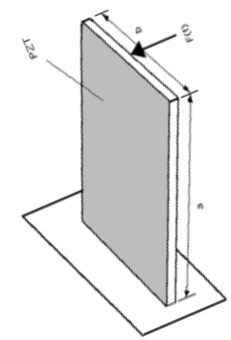
When $U(x) = \frac{1}{2} k x^2$ it is called a **linear system**

Linear systems have some interesting features… (and engineers like them most)

1) There exist a simple math theory to solve the eq.s
2) They have a resonant behaviour (resonance freq.)
3) They can be “easily” realized with catilevers and pendula





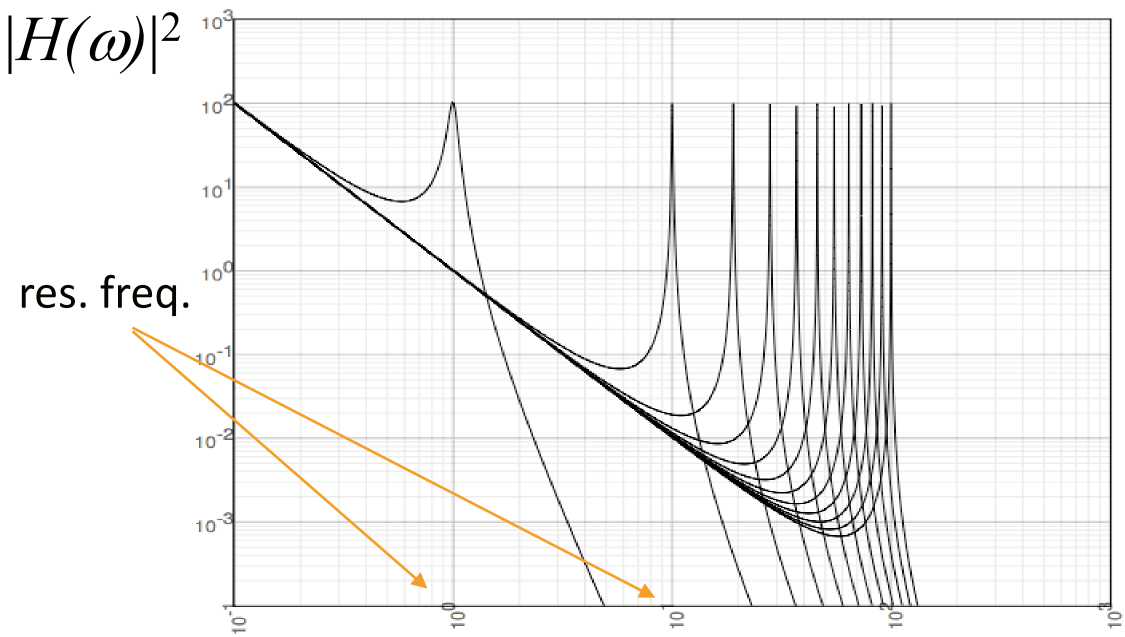


Transfer Function $H(\omega)$

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.

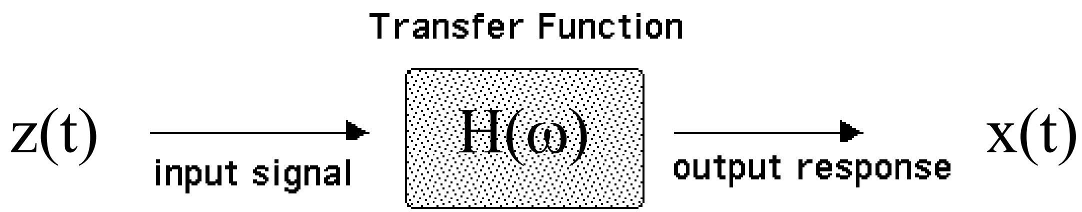
$$H(\omega) = H'(\omega) + i\,H''(\omega) = |H(\omega)|\,e^{i\varphi(\omega)}$$



Vibrations energy harvesting

Linear systems

In a linear system, thanks to the transfer function H(ω), the output spectrum can be obtained from the input spectrum through a simple multiplication…

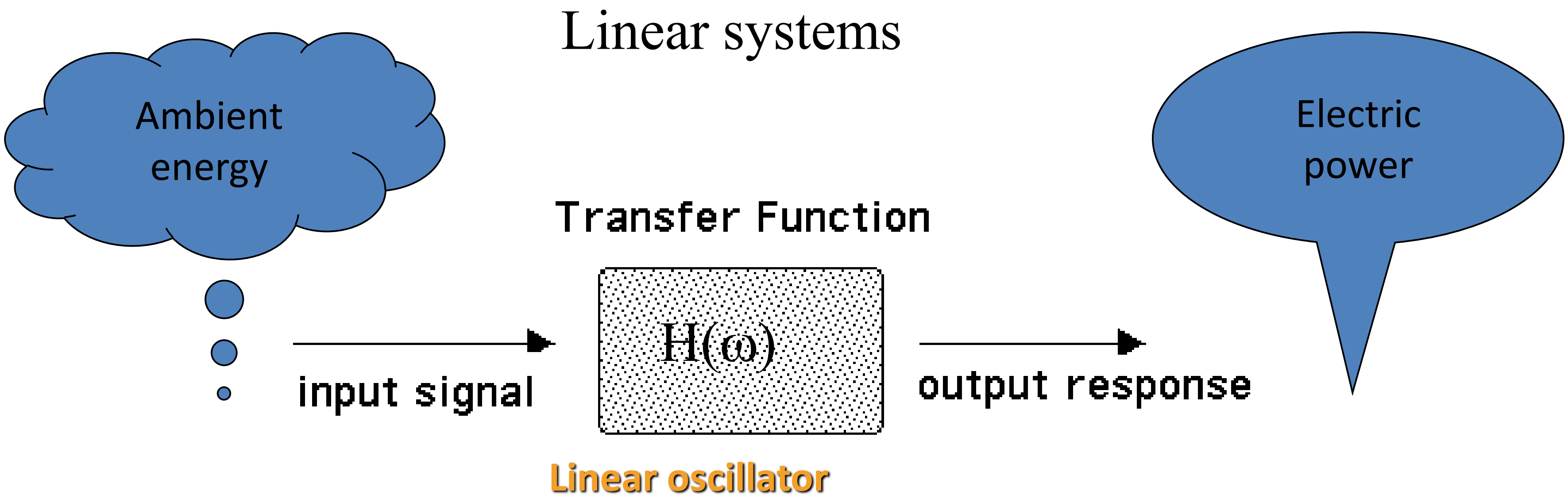


$$S_x(\omega) = |H(\omega)|^2 \, S_z(\omega)$$

Output power spectrum

Input power spectrum

Vibrations energy harvesting

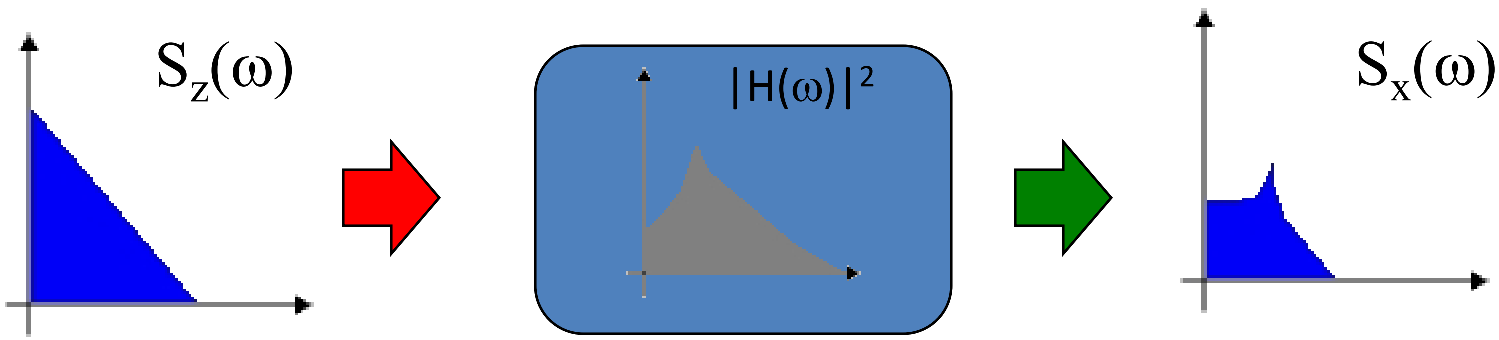


The transfer function is a math function of the frequency, in the complex domain, that can be used to represent the performance of a linear system

For a linear system the transfer function presents one or more peeks corresponding to the resonace frequencies and thus it is efficient mainly when the incoming energy is abundant in that regions…

Linear systems

The transfer function is important because it acts as a filter on the incoming energy…



Freq. spectrum of the available energy

Transfer function of the transducer

Freq. spectrum of the usable energy

$$S_x(\omega) = |H(\omega)|^2 \, S_z(\omega)$$

The random character of kinetic energy

Random vibrations / noise

Thermal noise
Acoustic noise
Seismic noise
Ambient noise (wind, pressure fluctuations, …)
Man made vibrations (human motion, machine vibrations,…)

All different for intensity, spectrum, statistics

Vibration database: RealVibrations

It is very important that we can characterize the spectral features of the vibration we want to harvest…

Vibration sources digital library

This Task is devoted to the realization of database containing digital time series and spectral representations of experimentally acquired vibration signals.

WISEPOWER

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Signal presentation:

- Description
- Power spectrum
- Statistical data
- Time series download (authorized users)

realvibrations.nipslab.org

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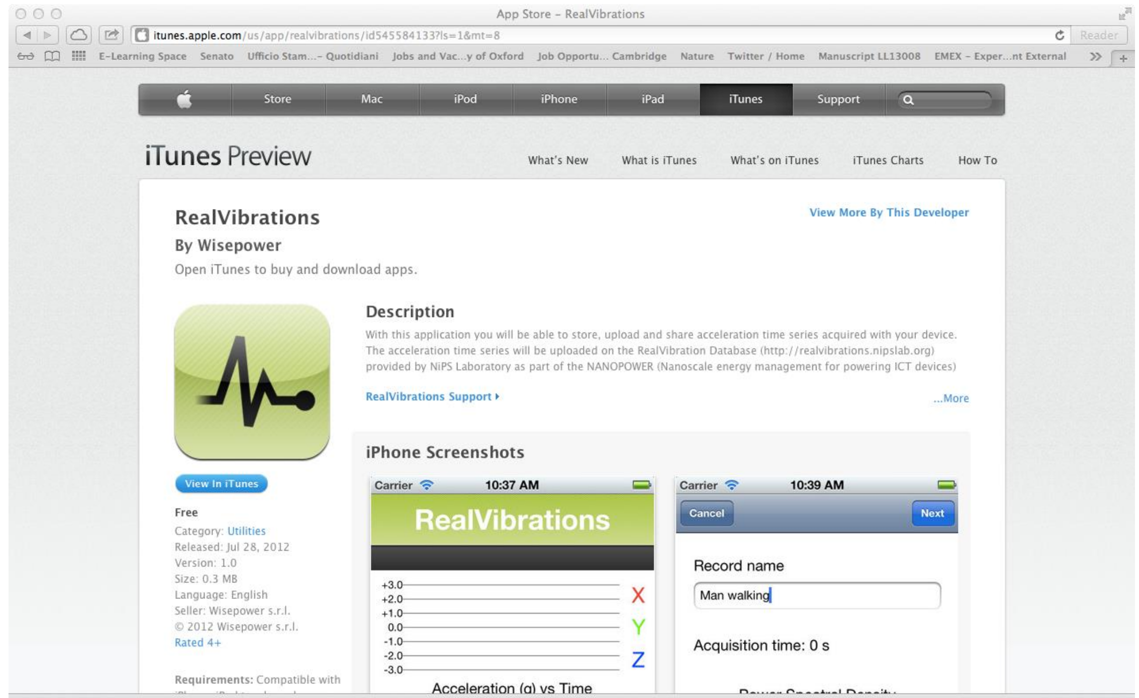
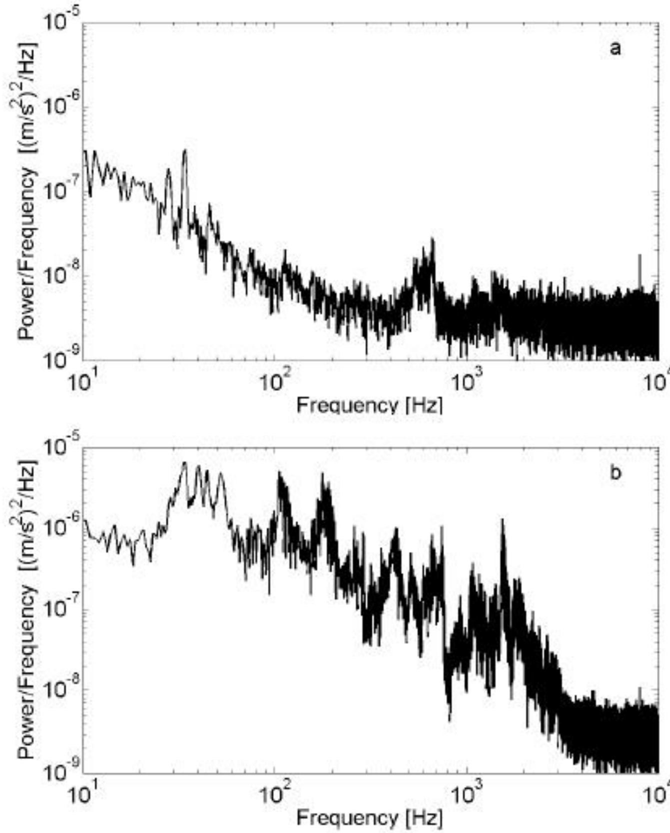
New App for contributing to the database



Available for free on the App Store: **RealVibrations**

Bridge vibrations



realvibrations.nipslab.org

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Noise in Physical Systems

Chicago North Bridge

Submitted by admin on Mon, 08/20/2012 - 11:22 | Ave | Bridge | Chicago | chicago north | Chicago River | Michigan | michigan ave | North | north bridge

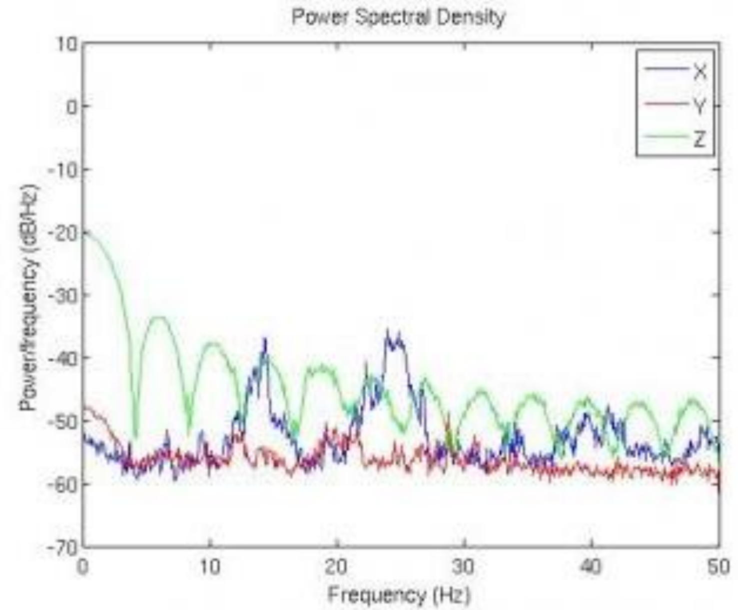
‹ previous 147 of 313 next ›

Chicago North Bridge over Chicago River on Michigan Ave. 400 N Michigan Ave, Chicago, IL 60611

Length: 358s

Sampling Rate: 100Hz

Acquisition Kit: EVAL-ADXL345Z



RMS	STD	Mean
X: 0.03113800 g	**X:** 0.02632800 g	**X:** 0.01662700 g
Y: 0.03565100 g	**Y:** 0.01086900 g	**Y:** -0.03395400 g
Z: 0.89531800 g	**Z:** 0.01795200 g	**Z:** 0.89513800 g

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NiPS Laboratory Noise in Physical Systems

Woman walking

Submitted by admin on Mon, 03/17/2014 - 10:26

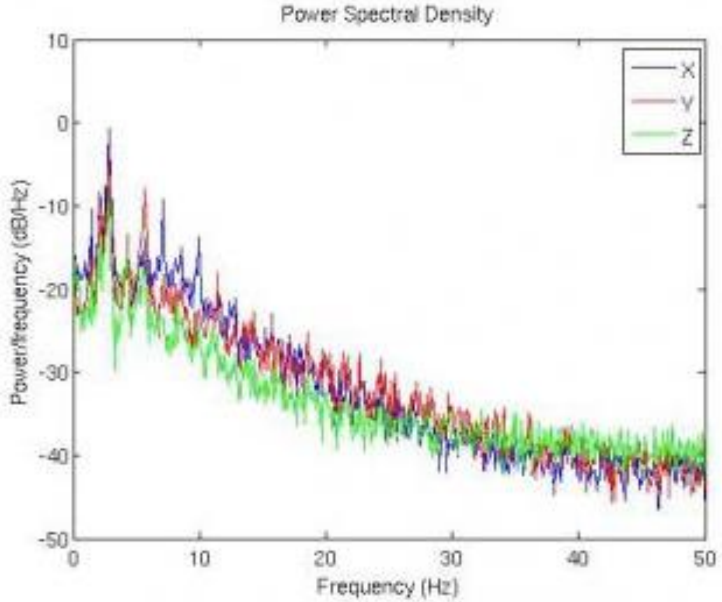
‹ previous 4 of 313 next ›

Woman walking, accelerometer in the pocket

Length: 104s

Sampling Rate: 100Hz

Acquisition Kit: EVAL-ADXL345Z



RMS	STD	Mean
X: 1.07838600 g	**X:** 0.63895600 g	**X:** 0.86872900 g
Y: 0.69502700 g	**Y:** 0.55951600 g	**Y:** 0.41235300 g
Z: 0.48628000 g	**Z:** 0.36751500 g	**Z:** -0.31845600 g

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NiPS Laboratory Noise in Physical Systems

Child walking

Submitted by admin on Mon, 03/17/2014 - 10:26

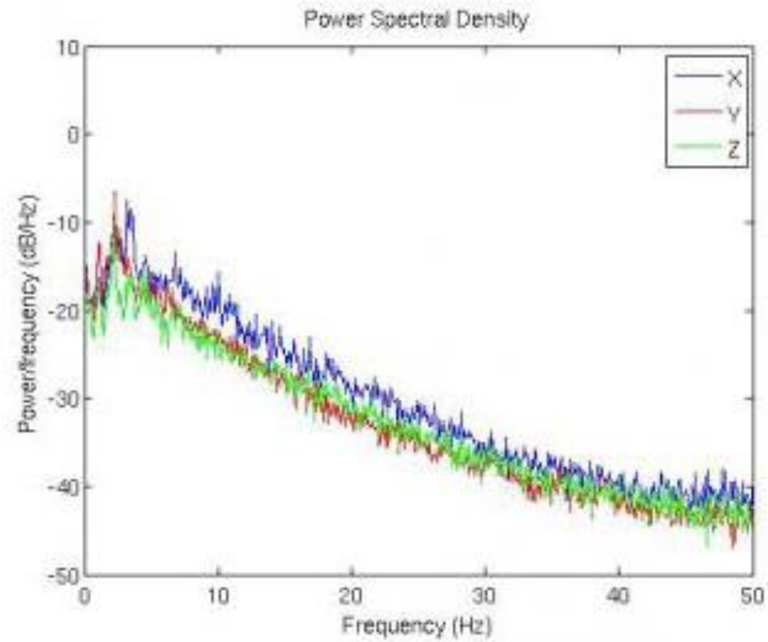
‹ previous 6 of 313 next ›

Child walking, accelerometer in the pocket

Length: 192s

Sampling Rate: 100Hz

Acquisition Kit: EVAL-ADXL345Z



RMS	STD	Mean
X: 1.07091700 g	**X:** 0.66398100 g	**X:** 0.84024700 g
Y: 0.68002500 g	**Y:** 0.57957400 g	**Y:** 0.35573300 g
Z: 0.49744100 g	**Z:** 0.37653900 g	**Z:** -0.32507400 g

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NiPS Laboratory Noise in Physical Systems

Running BMW X3

Submitted by igor.neri on Thu, 05/02/2013 - 15:57

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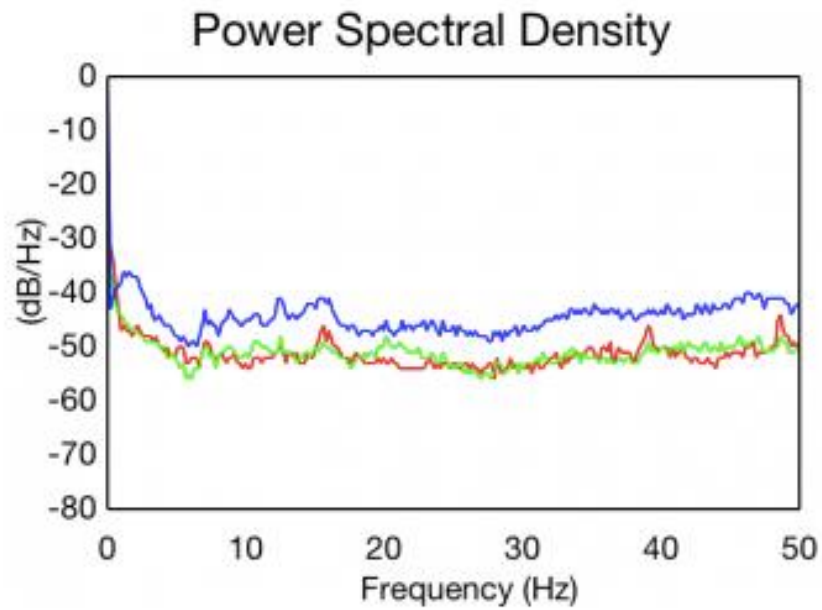
Ventura Freeway - CA, at the speed of 65 mi/hr. Sensor on the front dash.

Length: 308s

Sampling Rate: 100Hz

Acquisition Kit: iPhone



RMS	STD	Mean
X: 0.00567000 g	**X:** 0.00292000 g	**X:** -0.05242000 g
Y: 0.00901000 g	**Y:** 0.00252000 g	**Y:** -0.08053000 g
Z: 0.99528000 g	**Z:** 0.00488000 g	**Z:** -0.99519000 g

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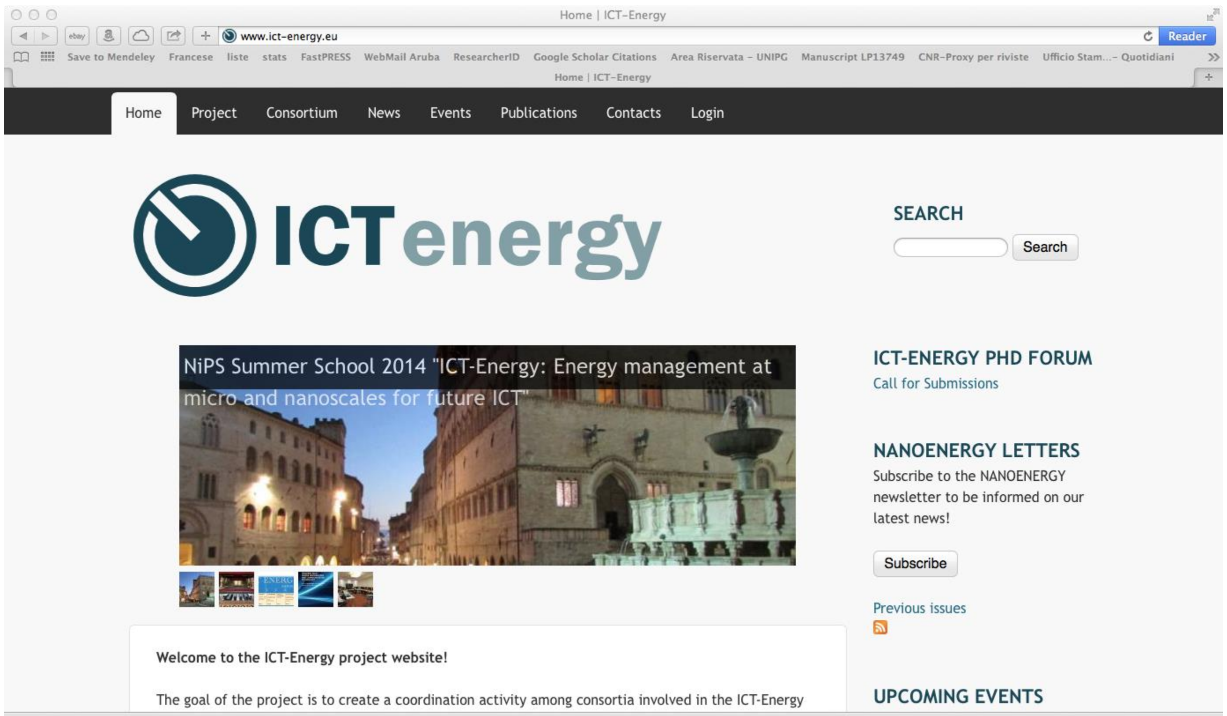
Noise in Physical Systems

Some conclusions

ICTenergy

ICT-Energy community



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ICT-ENERGY LETTERS

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We have started a special session devoted to the publication of original scientific papers. Instruction for submission procedure is available at: www.ict-energyletters.eu/submission

Next issue Jul 1st 2017

The future of powering for small mobile electronic devices

Present solution: - ~~disposable batteries~~

- rechargeable batteries **energy storage issue**

Future solution: - energy harvesting + storage

Take-home message:

1) Focusing **only** on energy harvesting produces misconception. The focus should be on energy transformation processes.
2) Both ends of the gap should be addressed if we want to move from labs to market.

What future for the subject of **energy harvesting / autonomous devices** ?

Bright!

The problem of powering small (and not so-small) autonomous devices has been already addressed and solved by nature. There is plenty of devices that process information (and actuate) while transforming energy from low entropy sources into heat.

None of them carries disposable batteries !

To know more

- www.nipslab.org

- www.ict-energy.eu

- Books on your “didactic materials”.