

Introduction to Energy Harvesting

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NiPS Summer school 2017, Gubbio

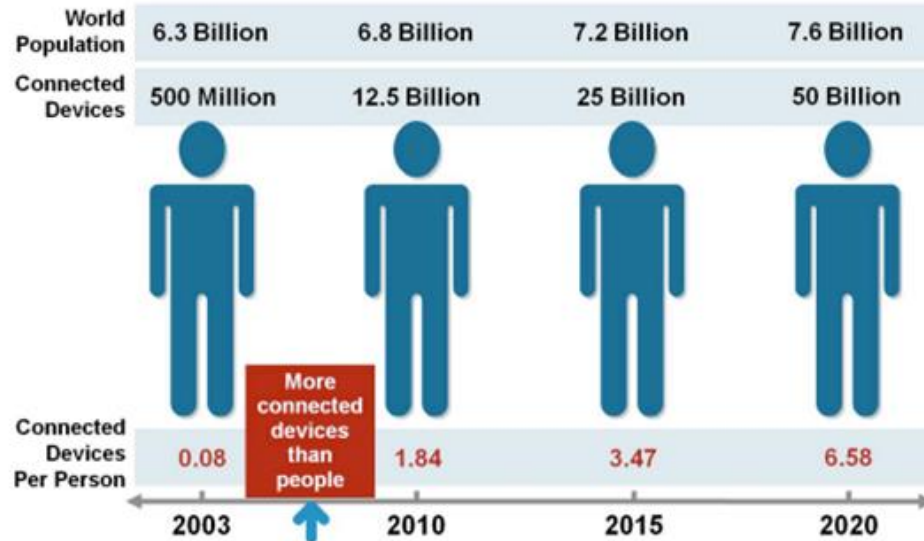
Energy Harvesting



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



Source: Cisco IBSG, April 2011

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.

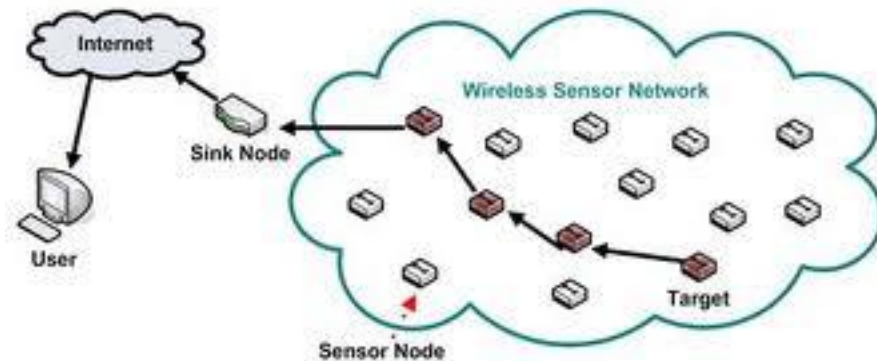
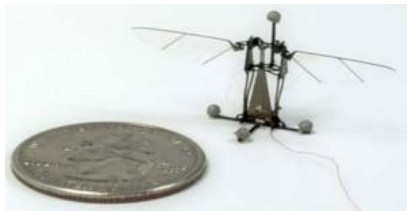
European Commission **Workshop** on “Energy-Efficient Computing Systems, dynamic adaptation of Quality of Service and approximate computing”. Nov. 27 2014 - Brussels

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

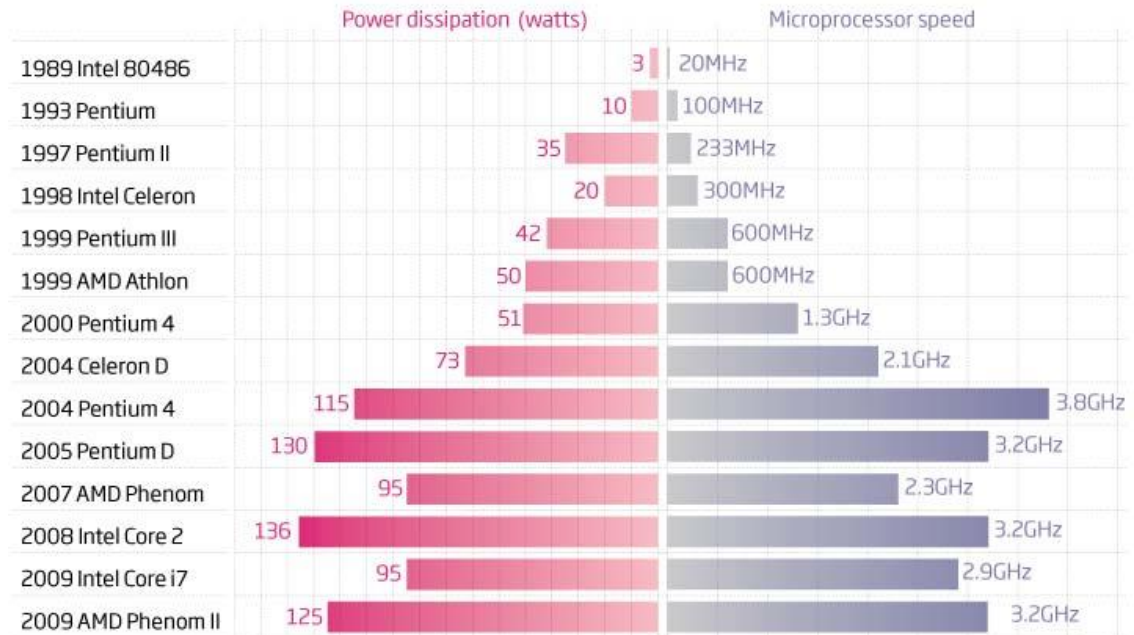


Energy consumption in computing systems has become a major issue for the future of ICT

Cooler running

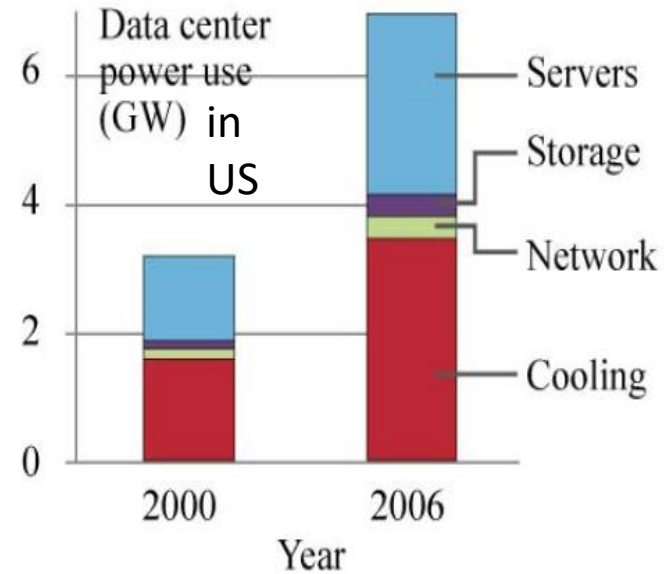
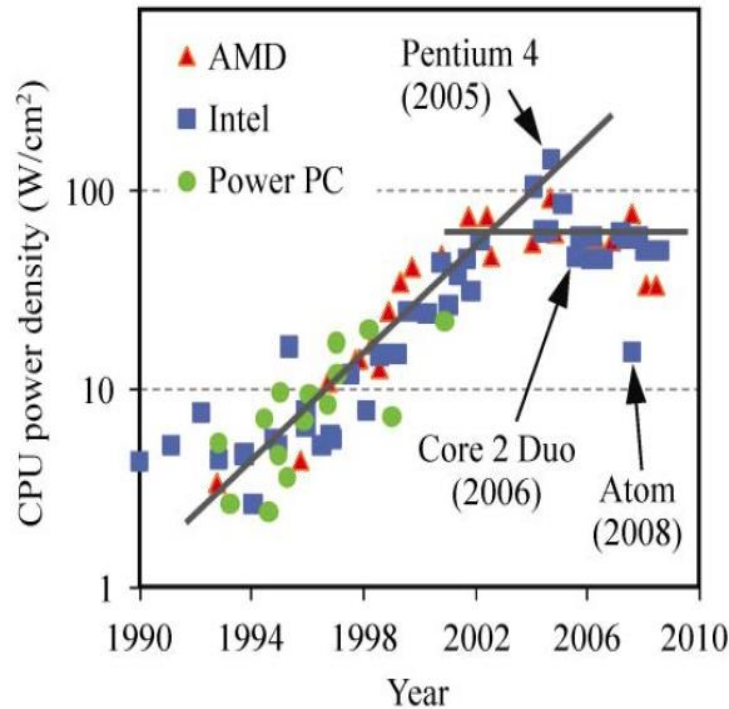
©NewScientist

In general the faster a microprocessor runs, the more heat it generates. In the past five years, the speed of chips has been limited by the need to keep them cool and so stop thermal noise from affecting performance



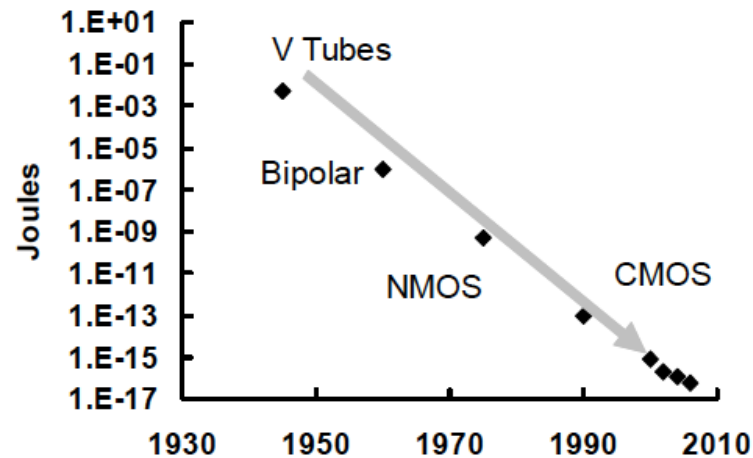
ICT - Energy

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

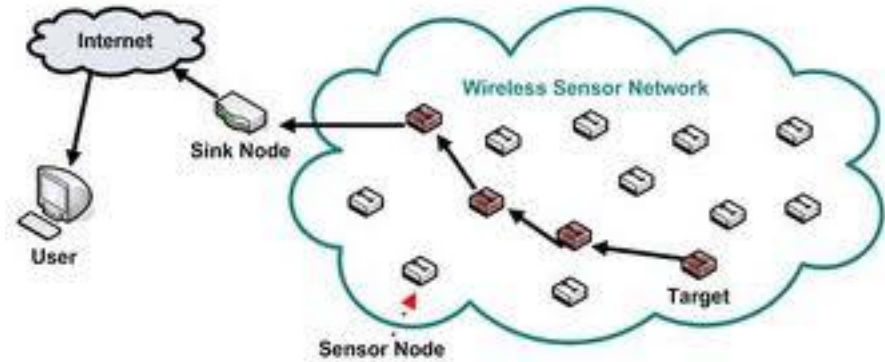
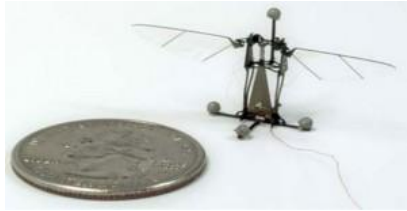


Shekhar Borkar, *Electronics Beyond Nano-scale CMOS*, Design Automation Conference, 2006
43rd ACM/IEEE

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

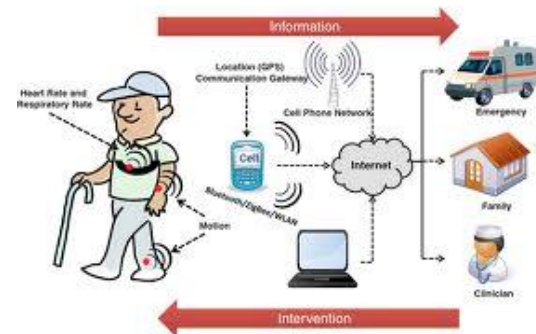
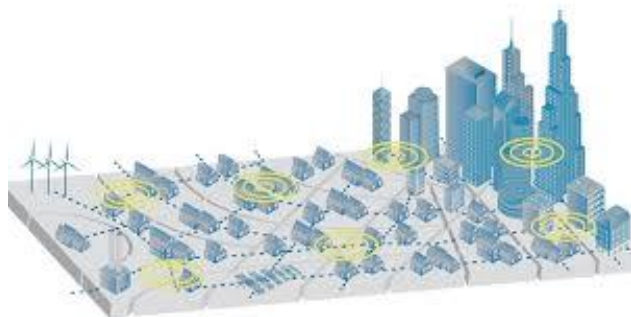
Jeffrey J. Welser
The Quest for the Next Information Processing Technology ,
2008

2) Autonomous microdevices, micro robots, wireless sensor networks



The promised land of ubiquitous computing

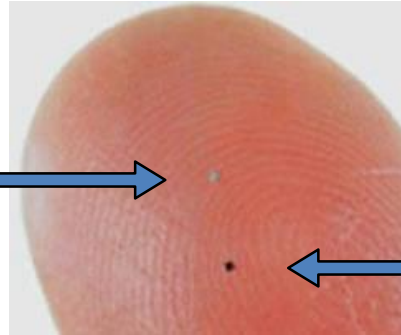
This is the land of wireless micro-sensors that continuously and ubiquitously measure, process and transmit data to improve our living.



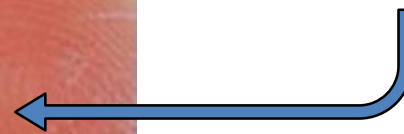
This is the long-time announced revolution where the cities become smart and the human and animal health is monitored and controlled.

The promised land of ubiquitous computing

dust particle



computer



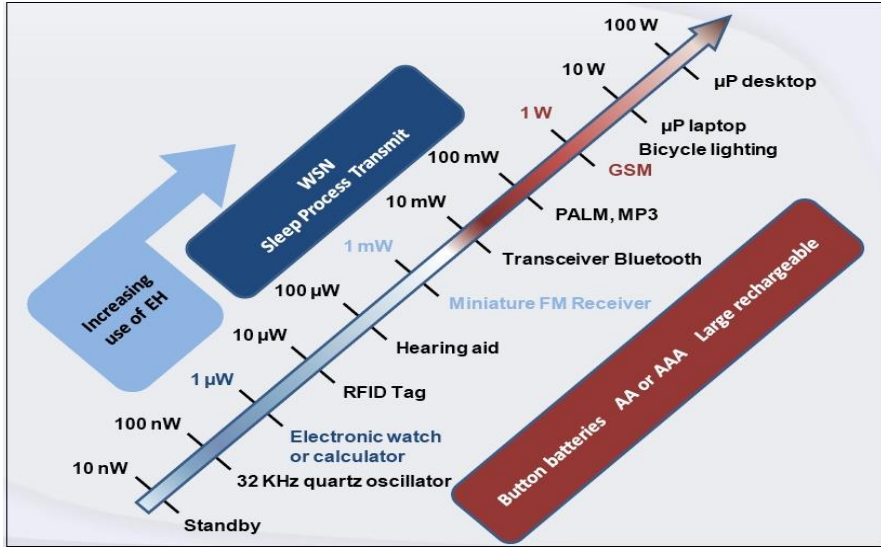
The land where computers are as small as dust particles



and bio-inspired robots appear

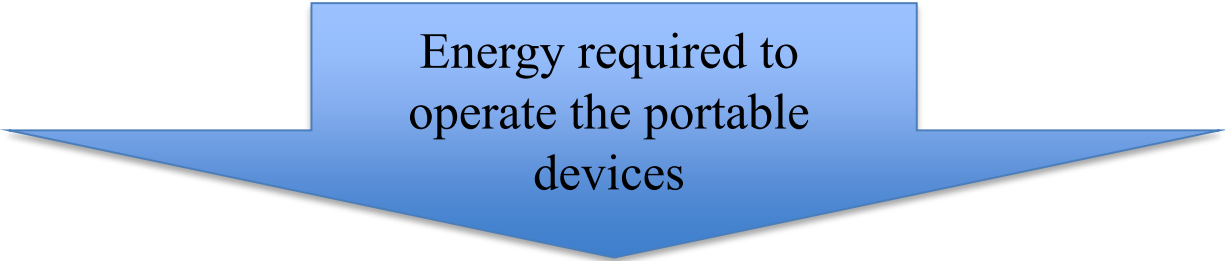
Why are we not there yet?

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 Sensor 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

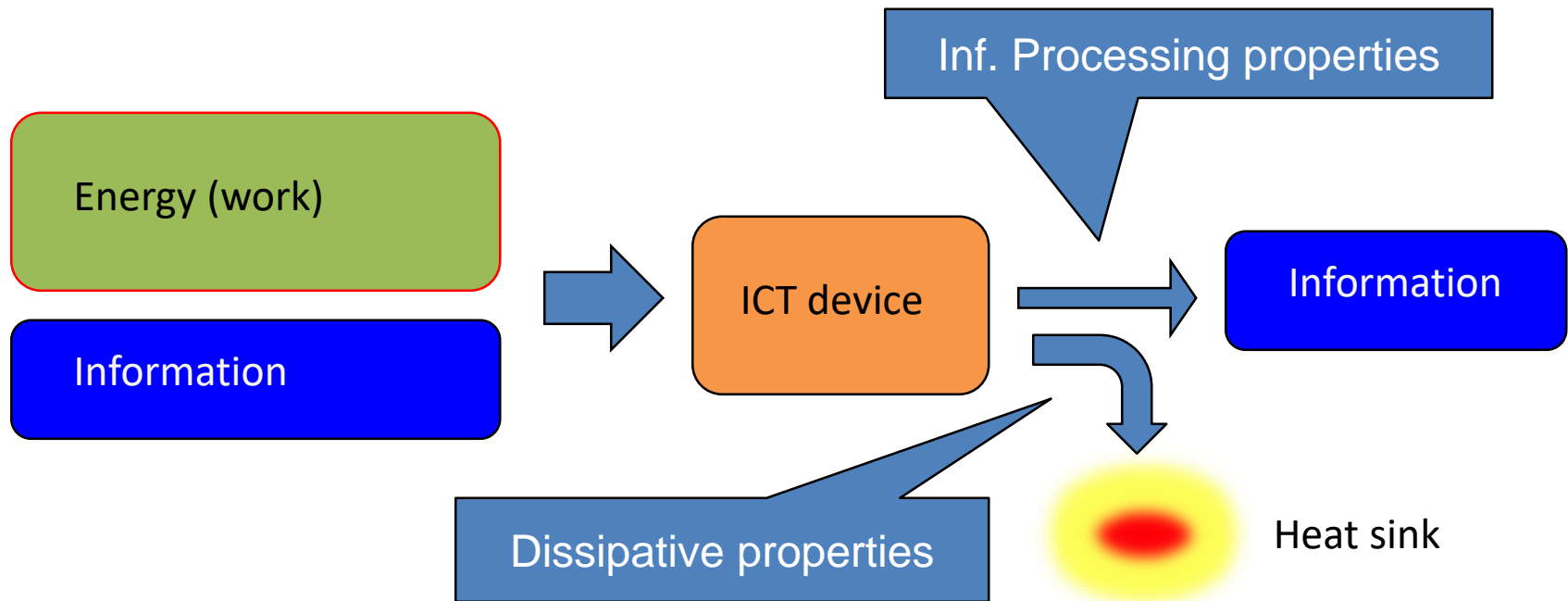
Information is physical !!!

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

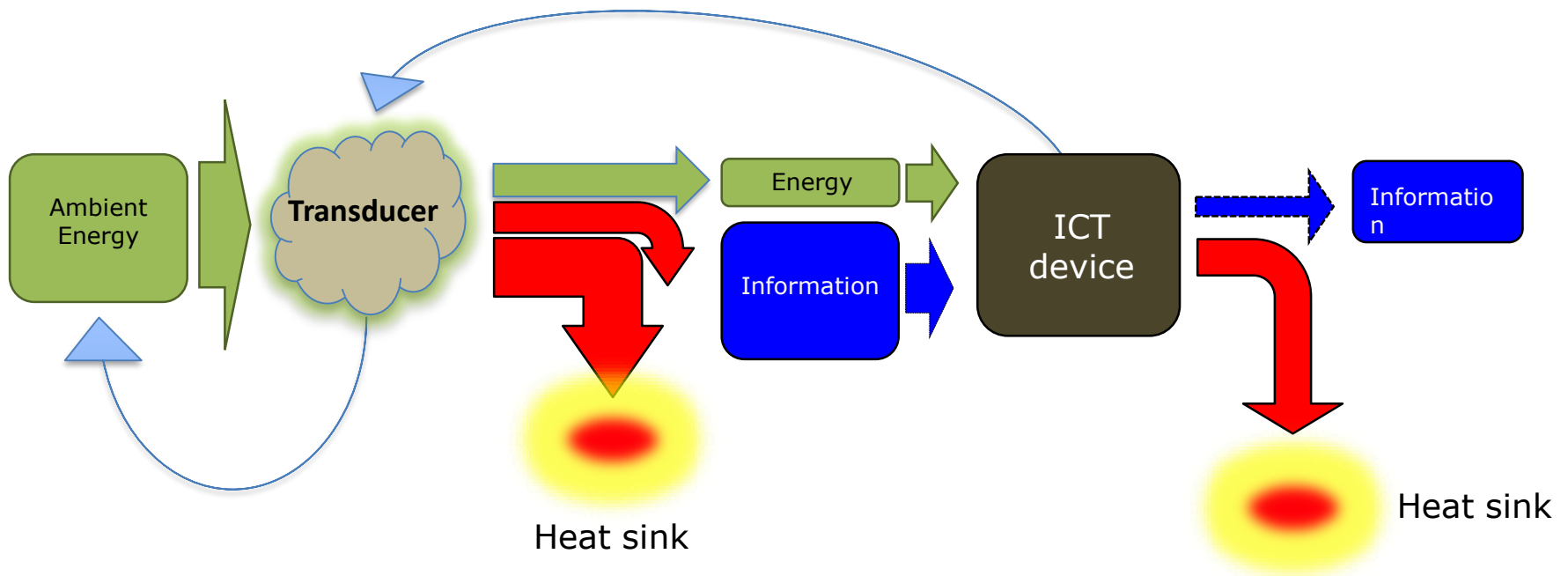
Some modeling

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

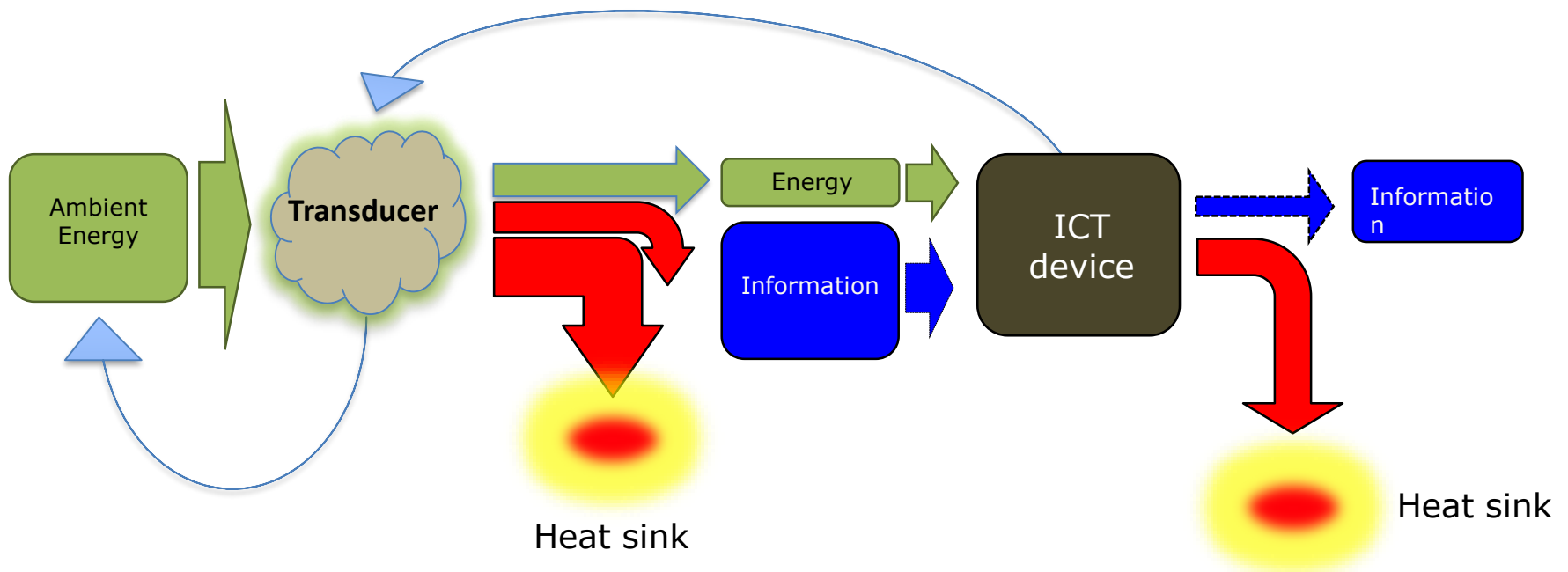


An **ICT device** is an info-thermal machine that inputs **information** and **energy** (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

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

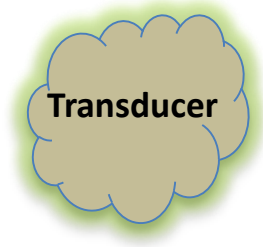
They have many d.o.f. (presence of fluctuations)

They are operated in a changing environment

~~Thermodynamics~~

~~Statistical mechanics~~

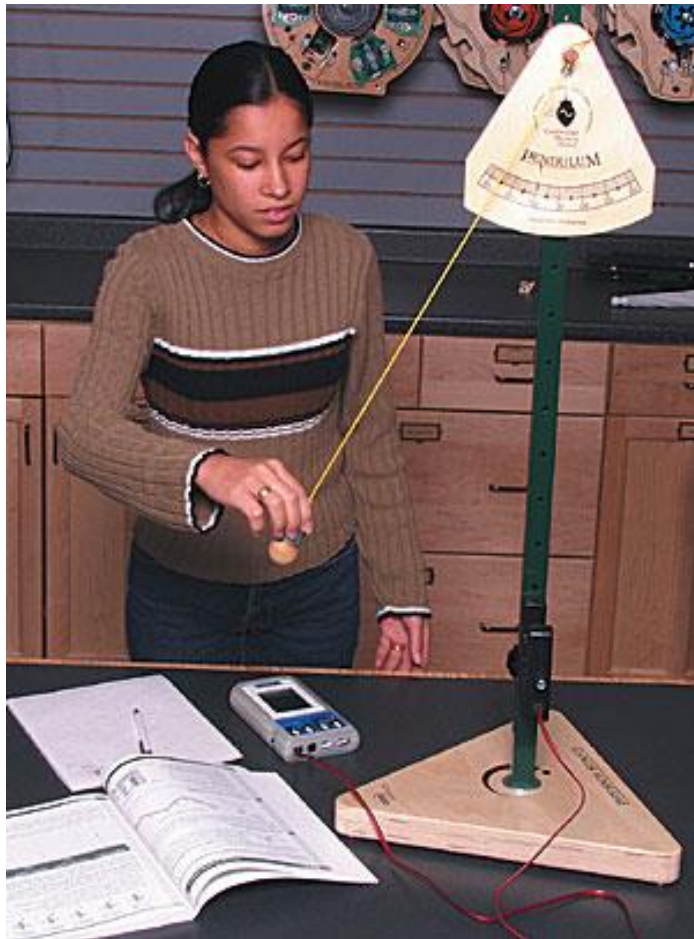
Non-equilibrium statistical mechanics



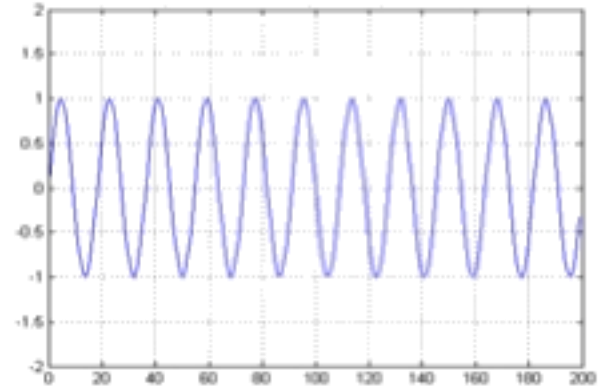
In this framework we can describe the device behavior in terms of few relevant d.o.f. via a procedure called “adiabatic elimination” or “coarse graining approach”: we exchange the dynamics of a *not small isolated system* with *small not isolated system*.

Let’s see an example...

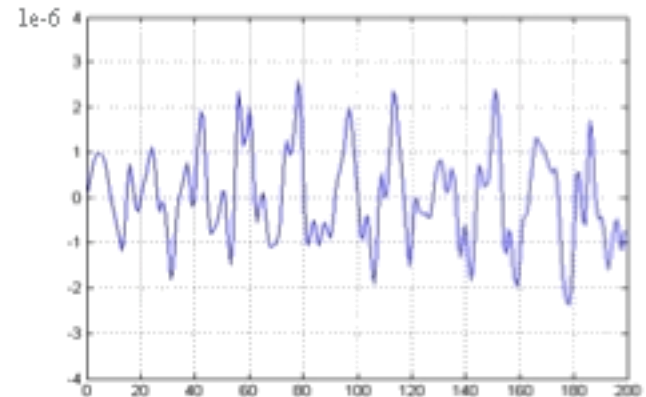
Example: physical system pendulum



Focus on the pendulum angle

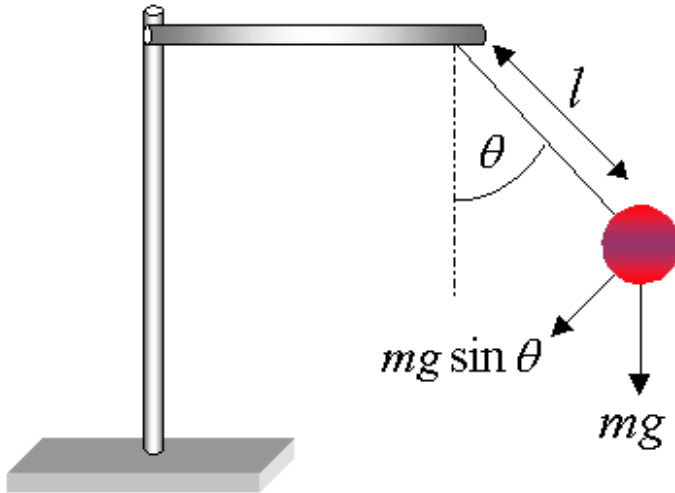


If we come back after a while..



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

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 $m l^2 \ddot{\theta} - \gamma \dot{\theta} + mgl \sin \theta + \zeta(t) = 0$

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

$$\langle \zeta(t) \zeta(0) \rangle = 2 K_B T \gamma \delta(t)$$

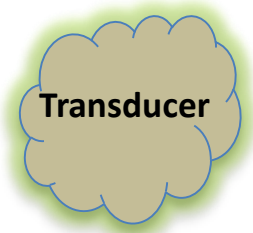
The viscous drag expression can be generalized in order to describe a wider class of damping functions

$$-\int_{-\infty}^t \gamma(t - \tau) \dot{x} d\tau \quad \longrightarrow \quad \langle z(t)z(0) \rangle = kT g(|t|)$$

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

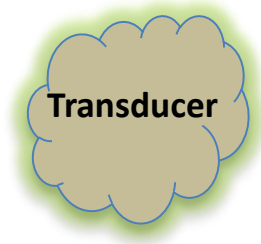
Random force
depending on t

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

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

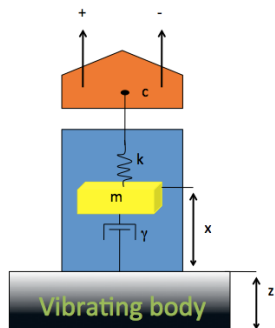
Two physical systems whose dynamical behavior can be described in the framework of non-equilibrium statistical mechanics.

Langevin equation approach



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Langevin equation approach



ICT device

(example from vibration harvester)

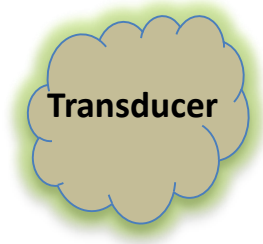
$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - c(x, V) + \zeta_z + \zeta$$

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

$$\langle \zeta(t) \zeta(0) \rangle = 2 K_B T \gamma \delta(t)$$

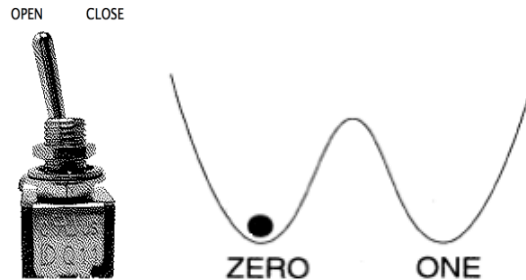
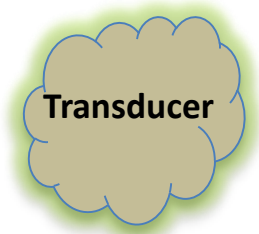
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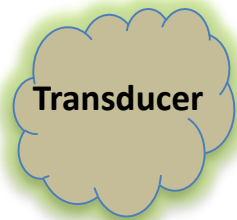
Two physical systems whose dynamical behavior can be described in the framework of non-equilibrium statistical mechanics.

Langevin equation approach



(example from a digital binary switch)

$$m\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} + F_{sw} + \zeta$$
$$\langle \zeta(t) \zeta(0) \rangle = 2 K_B T \gamma \delta(t)$$



Langevin equation approach

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

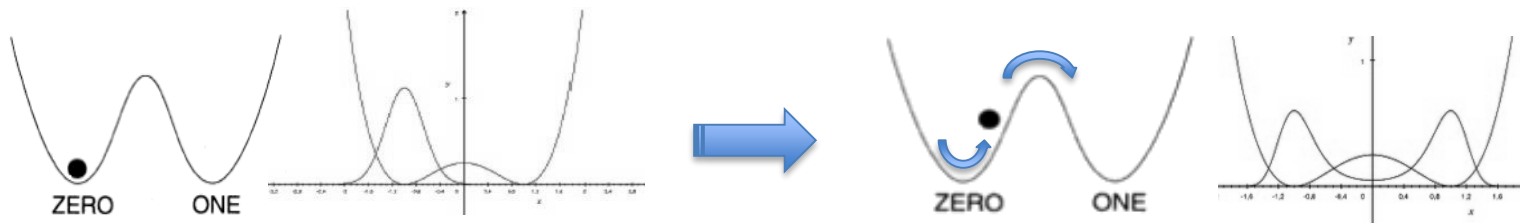


This is a stochastic dynamics whose solution $x(t)$ appears like



Probability density $P(x,t)$.

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

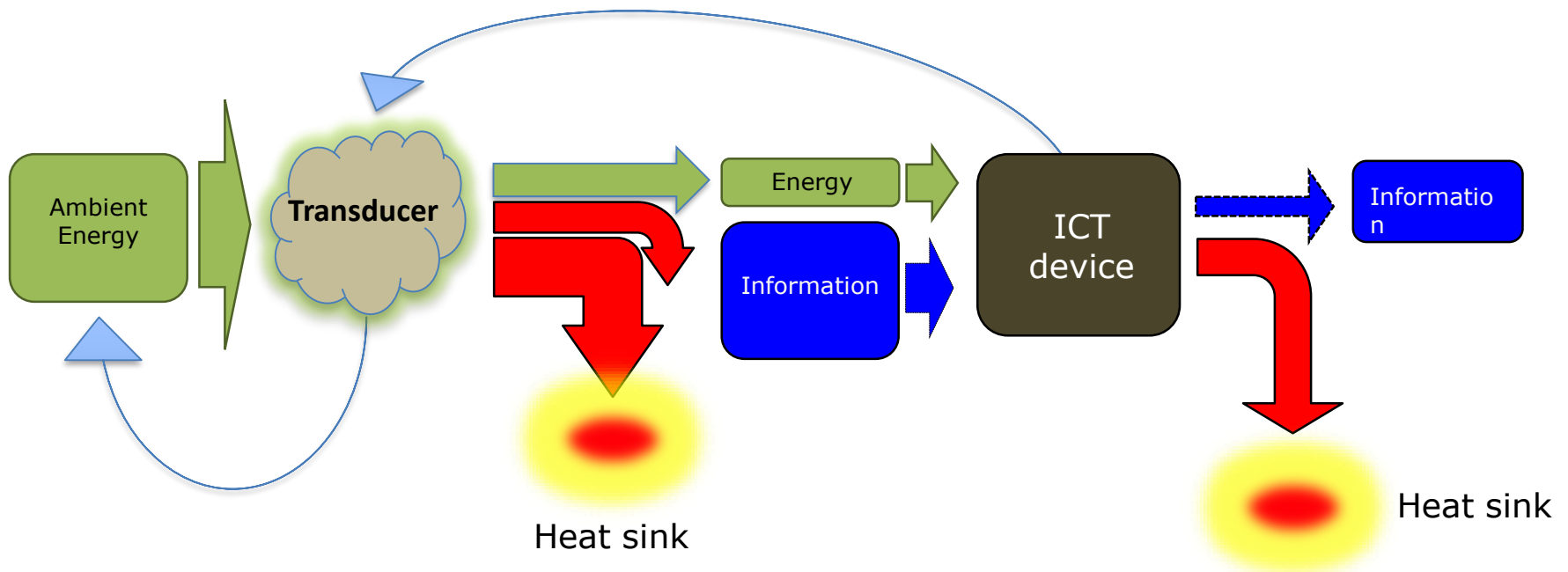


$P(x,t)$ is a deterministic quantity and its time evolution of can be described in terms of the associated Fokker-Planck equation.

Some considerations

The device powering issue:

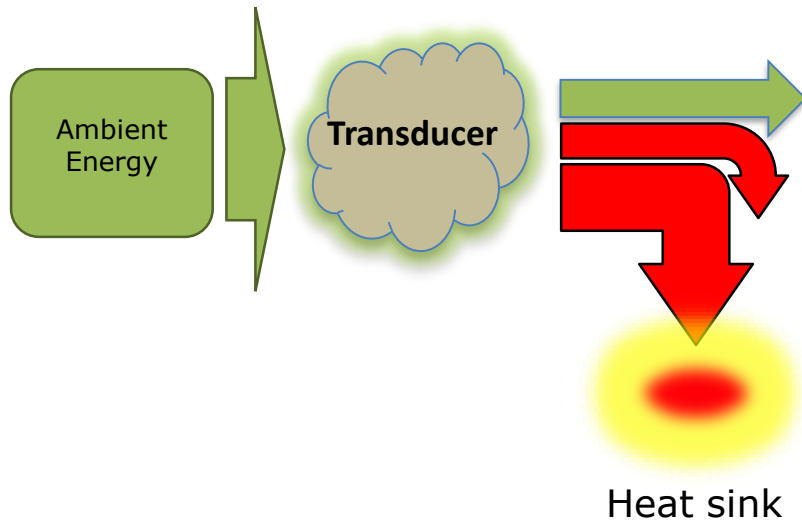
- 1) How much energy is needed to power a device ?
- 2) Where does the device get the needed energy ?



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).

The device powering issue:

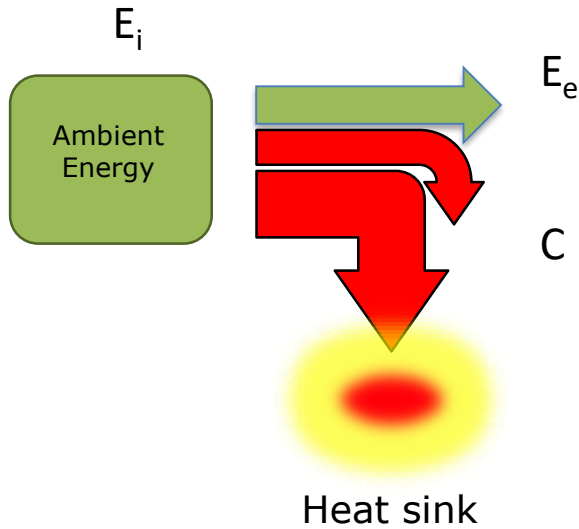
- 1) How much energy is needed to power a device ?
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Clearly this energy is obtained from the ambient...

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

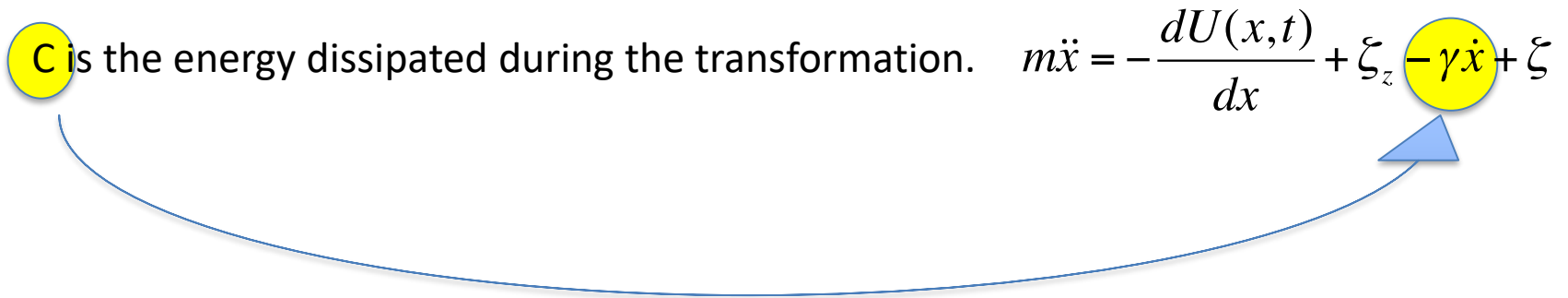
The diagram shows a yellow circle containing the letter 'C'. A blue arrow originates from the right side of the equation, specifically from the term $-\gamma\dot{x}$, and points back to the yellow circle.

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



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

$C=C(\gamma)$ can be a function of time and change with the dissipation process.
Viscous damping, thermo-elastic damping, structural damping, ...

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

The device powering issue:

- 1) How much energy is needed to power a device ?
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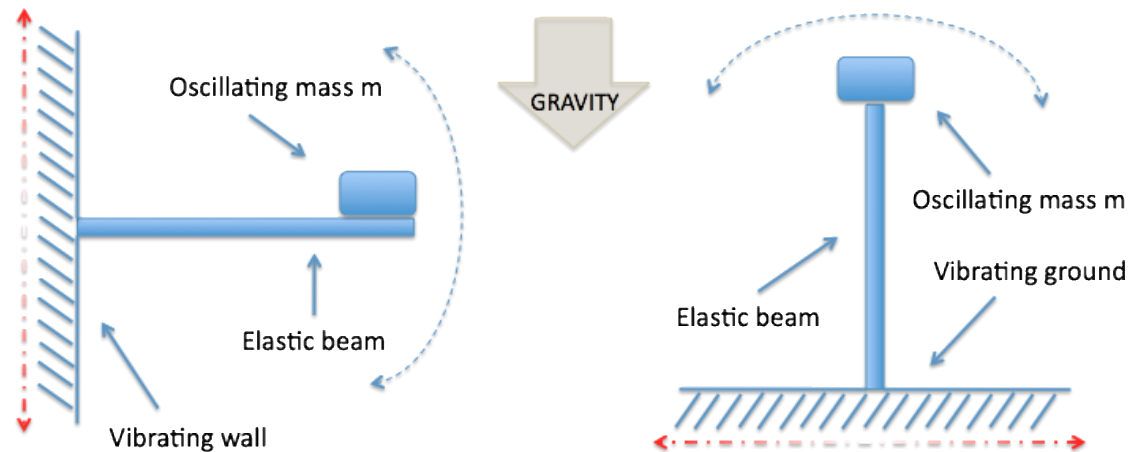
$$m\ddot{x} = -\frac{dU(x,t)}{dx} + \xi_z - \gamma\dot{x} + \zeta$$

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.

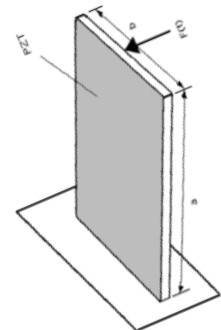
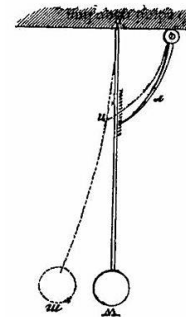
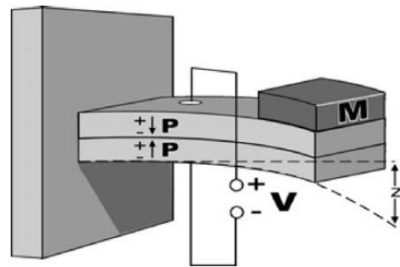
Right: configuration for harvesting horizontal vibrations.

Linear systems

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

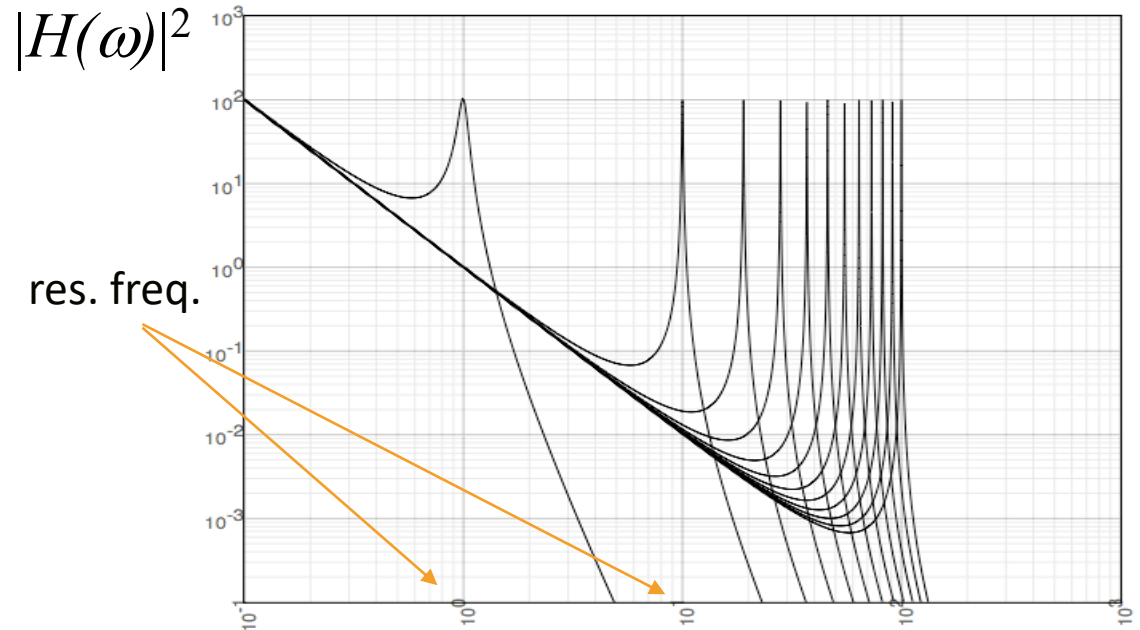


Transfer Function $H(\omega)$

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.

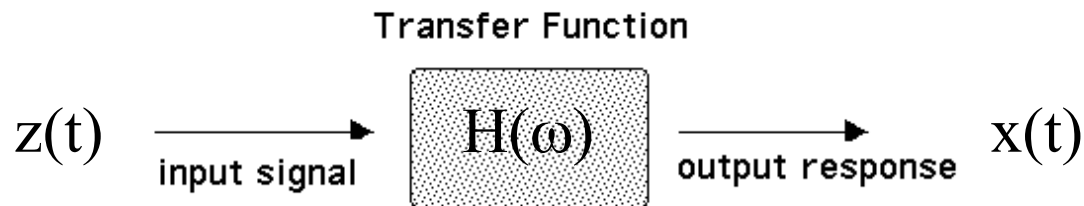
$$H(\omega) = H^{\Re}(\omega) + i H^{\Im}(\omega) = |H(\omega)| e^{i\phi(\omega)}$$



Vibrations energy harvesting

Linear systems

In a linear system, thanks to the transfer function $H(\omega)$, the output spectrum can be obtained from the input spectrum through a simple multiplication...



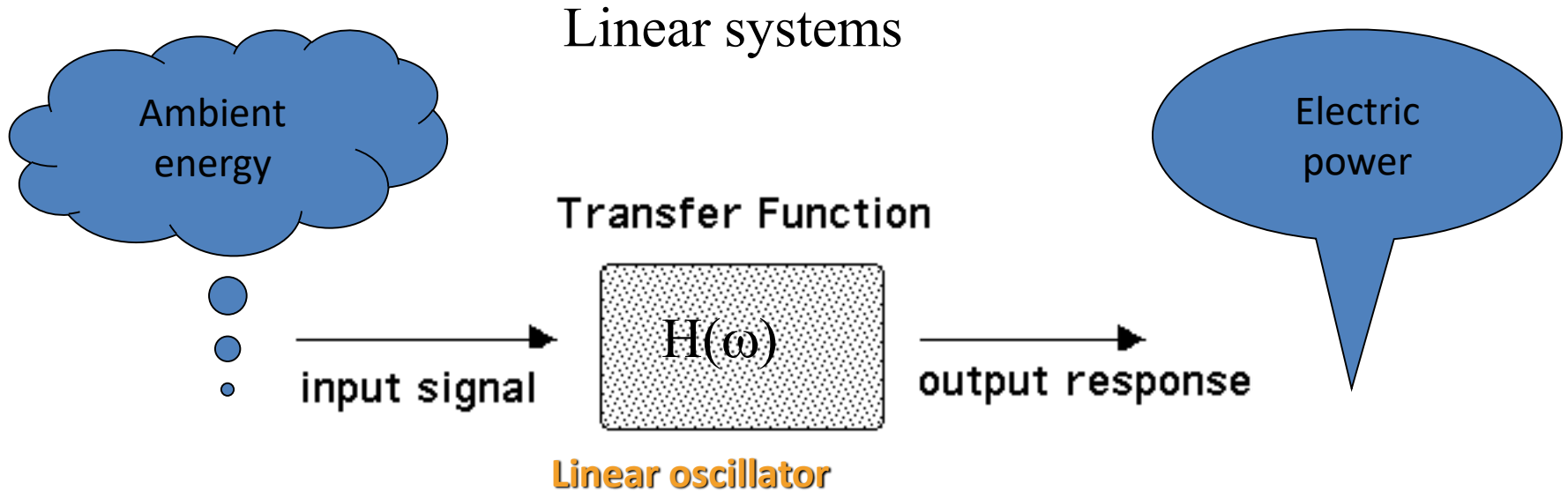
$$S_x(\omega) = |H(\omega)|^2 S_z(\omega)$$

Output power spectrum

Input power spectrum



Vibrations energy harvesting

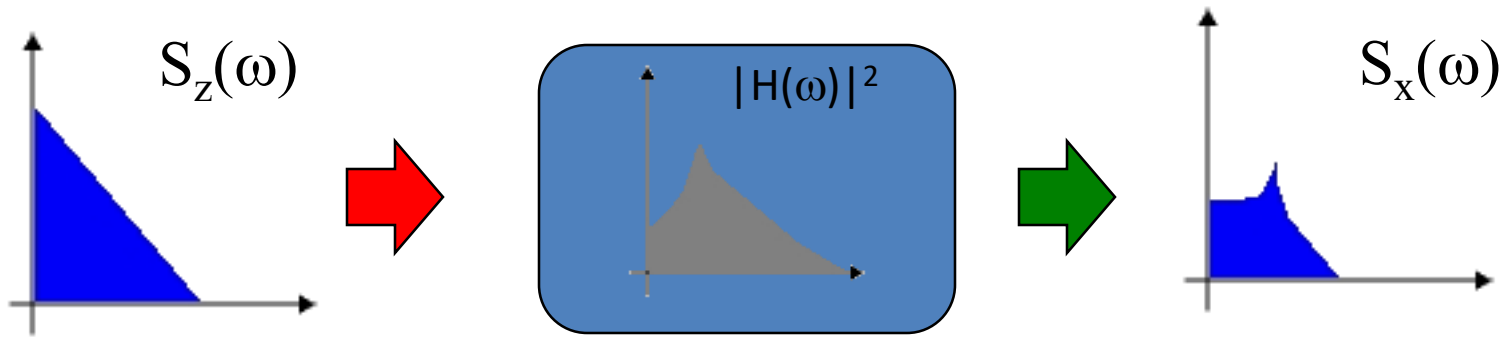


The transfer function is a math function of the frequency, in the complex domain, that can be used to represent the performance of a linear system

For a linear system the transfer function presents one or more peaks corresponding to the resonance 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.

Home | Real Vibrations

realvibrations.nipslab.org

Promised land

Home | Real Vibrations

you are here

thejawshabite

Più visitati | ResearchItaly | Blog più letti | ASN | Abilitazio... | MIUR - loginmiu... | PP Participant Portal | ROARS - Return ... | ResearcherID Ga... | Segnalibri

Real Vibrations

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Home

Welcome to the Real Vibrations web site.

What is Real Vibrations ?

This web site is home to a digital database containing numerical time series and spectral representations of experimentally acquired vibration signals. Most importantly, Real Vibrations is a participatory research project that aims at creating the world largest repository of vibrations recorded from everyday life objects and people movements.

Cars, trains, airplanes, and even human beings, constantly vibrate and these vibrations can be recorded with various devices and stored in such a way that they are readily available and easily usable both by researchers and non expert visitors.



There's a vibrating world around us

What are these data for?

A database of vibration data is a map of the moving world. To many this is of no meaning and little use. To us this is a map of potentially useful energy. In fact vibrations can be efficiently transformed in electrical energy that can be employed to power electronic devices such as wireless sensors: a way to improve the microelectronic world and make a better use of energy. In a near future we believe that this micro-generators that transform vibrations into electric energy will be able to integrate and/or substitute the existing batteries for a better and healthier planet.

How to take part in the project ?

If you are a scientist or a professional in the energy world, please contact the NiPS Laboratory at the Department of Physics, University of Perugia in order to become a professional partner of the Real Vibrations project.

If you are a student and/or a volunteer you can still contribute to this project simply by acquiring vibration data with your smartphone and uploading them to the database. Please find the iPhone app [here](#).

Nanopower

Real Vibrations is developed under the Nanopower project, that acknowledges the financial support of the Future and Emerging Technologies (FET) nanosystems within the ICT theme of the Seventh Framework Programme for Research of the European Commission (Grant Agreement n

WISEPOWER

NiPS Laboratory
Noise in Physical Systems



www.nipslab.org

Signal presentation:

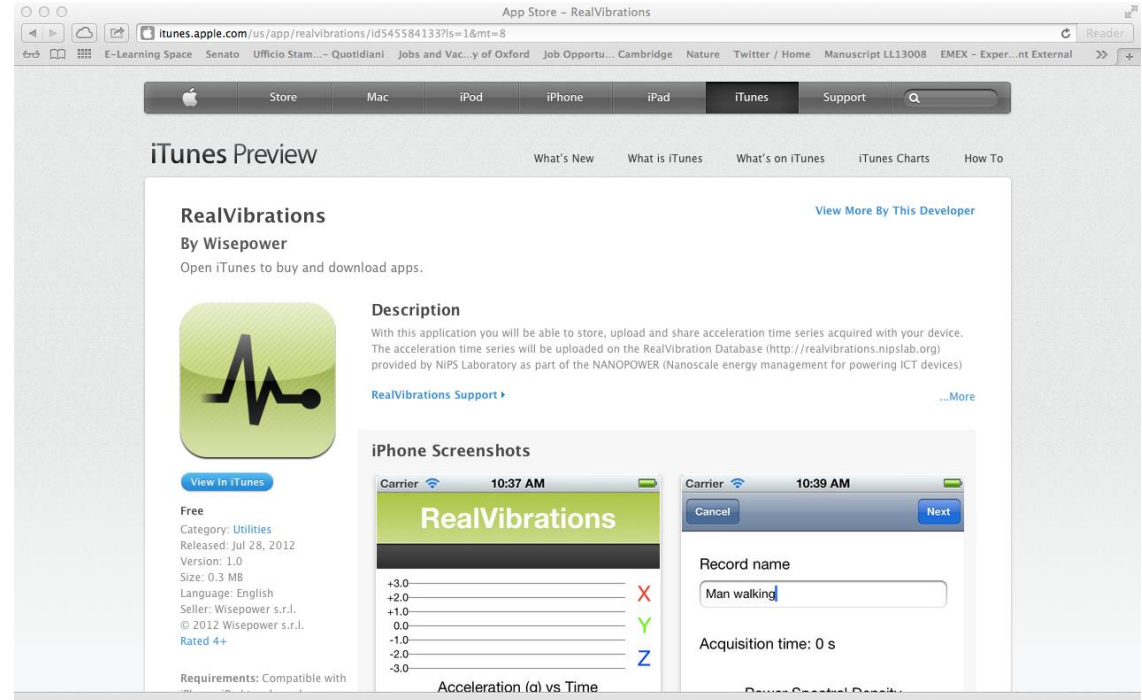
- Description
- Power spectrum
- Statistical data
- Time series download (authorized users)

realvibrations.nipslab.org

NiPS Laboratory
Noise in Physical Systems



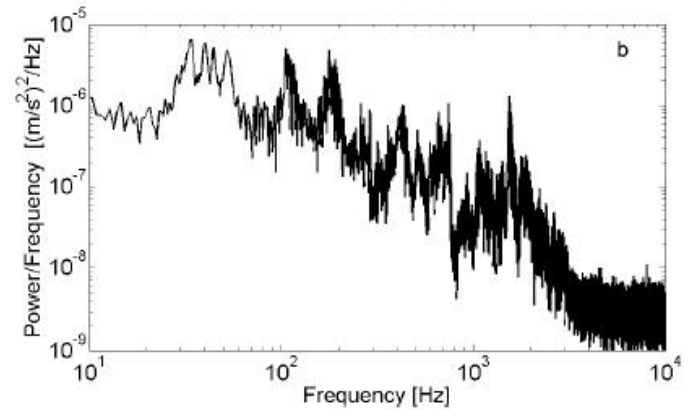
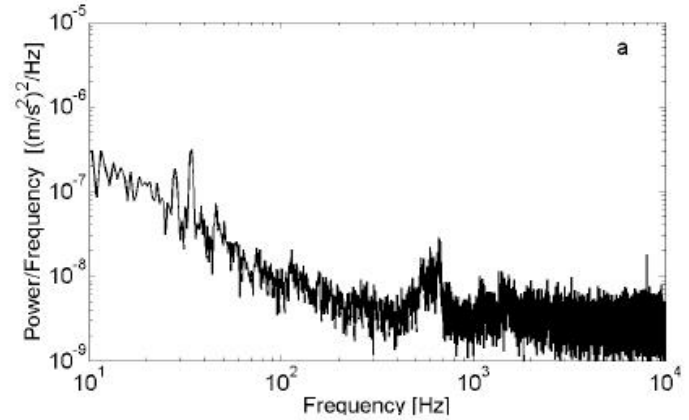
New App for contributing to the database



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



Bridge vibrations



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](#)

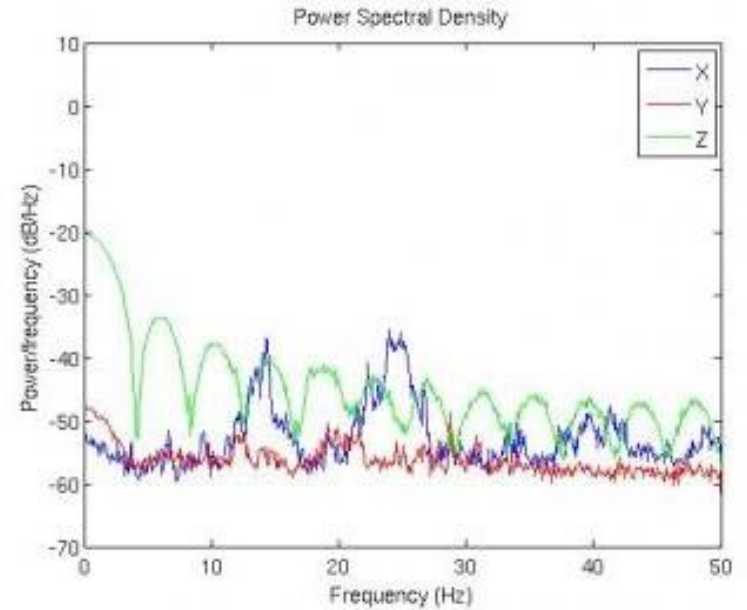
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Chicago North Bridge over Chicago River on Michigan Ave. 400 N
Michigan Ave, Chicago, IL 60611

Length: 358s

Sampling Rate: 100Hz

Acquisition Kit: EVAL-ADXL345Z



RMS

X: 0.03113800 g
Y: 0.03565100 g
Z: 0.89531800 g

STD

X: 0.02632800 g
Y: 0.01086900 g
Z: 0.01795200 g

Mean

X: 0.01662700 g
Y: -0.03395400 g
Z: 0.89513800 g

Woman walking

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

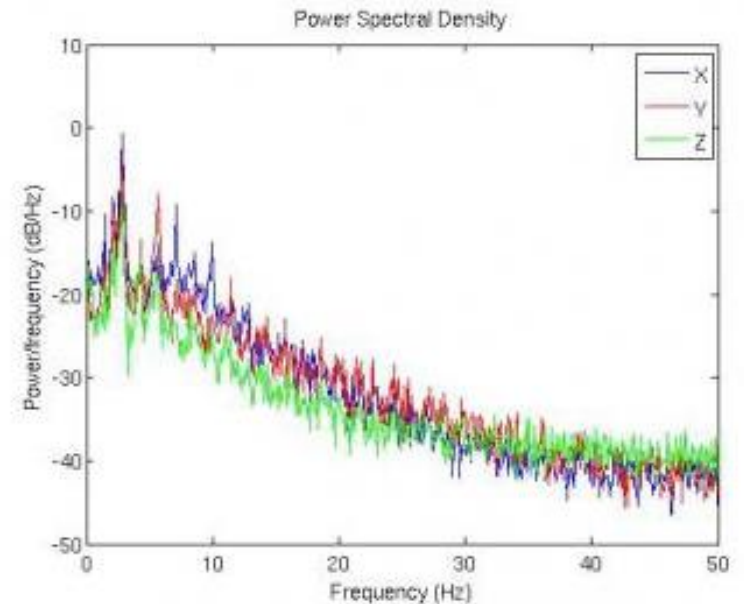
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Woman walking, accelerometer in the pocket

Length: 104s

Sampling Rate: 100Hz

Acquisition Kit: EVAL-ADXL345Z



RMS

X: 1.07838600 g

Y: 0.69502700 g

Z: 0.48628000 g

STD

X: 0.63895600 g

Y: 0.55951600 g

Z: 0.36751500 g

Mean

X: 0.86872900 g

Y: 0.41235300 g

Z: -0.31845600 g



Child walking

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

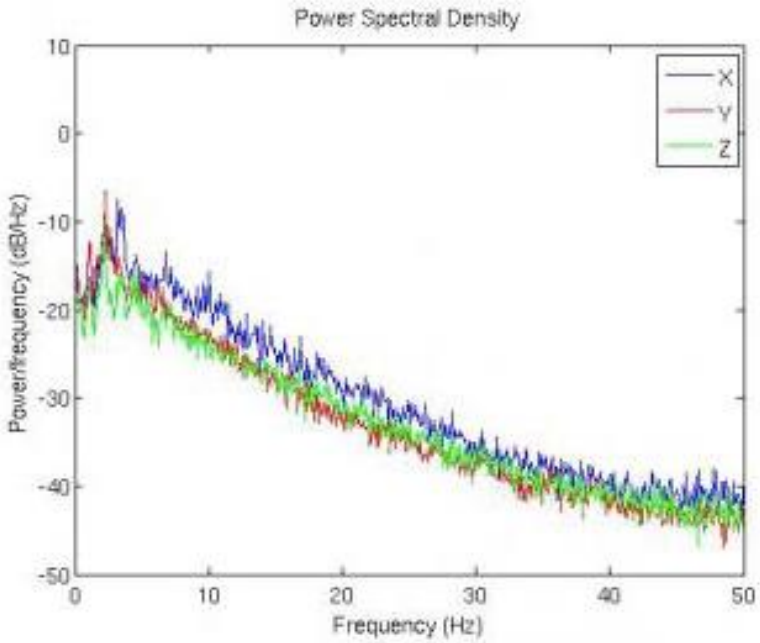
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Child walking, accelerometer in the pocket

Length: 192s

Sampling Rate: 100Hz

Acquisition Kit: EVAL-ADXL345Z



RMS	
X:	1.07091700 g
Y:	0.68002500 g
Z:	0.49744100 g

STD	
X:	0.66398100 g
Y:	0.57957400 g
Z:	0.37653900 g

Mean	
X:	0.84024700 g
Y:	0.35573300 g
Z:	-0.32507400 g



Running BMW X3

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

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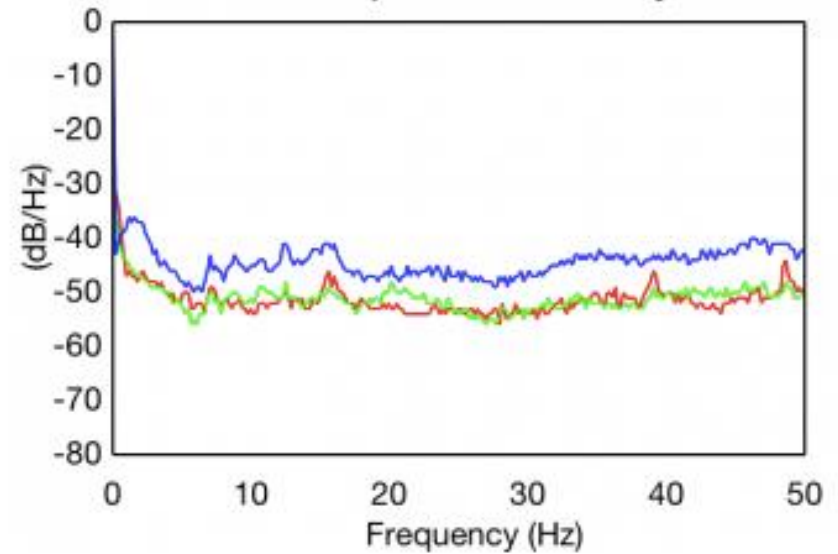
Ventura Freeway - CA, at the speed of 65 mi/hr. Sensor on the front dash.

Length: 308s

Sampling Rate: 100Hz

Acquisition Kit: iPhone

Power Spectral Density



RMS

X: 0.00567000 g
Y: 0.00901000 g
Z: 0.99528000 g

STD

X: 0.00292000 g
Y: 0.00252000 g
Z: 0.00488000 g

Mean

X: -0.05242000 g
Y: -0.08053000 g
Z: -0.99519000 g



Some conclusions




The screenshot shows a web browser window displaying the homepage of the ICT-Energy project website. The browser's address bar shows the URL www.ict-energy.eu. The website features a navigation menu with links for Home, Project, Consortium, News, Events, Publications, Contacts, and Login. The main content area includes the ICTenergy logo, a search bar, and several featured sections: a banner for the NiPS Summer School 2014, a call for submissions for the ICT-ENERGY PHD FORUM, and a subscription link for NANOENERGY LETTERS. A welcome message is displayed in a box at the bottom left, and an upcoming events section is visible at the bottom right.

Home | ICT-Energy

www.ict-energy.eu

Home Project Consortium News Events Publications Contacts Login

 ICTenergy

SEARCH

Search

NiPS Summer School 2014 "ICT-Energy: Energy management at micro and nanoscales for future ICT"

ICT-ENERGY PHD FORUM
Call for Submissions

NANOENERGY LETTERS
Subscribe to the NANOENERGY newsletter to be informed on our latest news!

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Previous issues

UPCOMING EVENTS

Welcome to the ICT-Energy project website!

The goal of the project is to create a coordination activity among consortia involved in the ICT-Energy

www.ict-energy.eu

ICT-ENERGY

L E T T E R S

www.ict-energyletters.eu

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”.