The future of powering for small mobile electronic devices

(2)

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NiPS Laboratory
Noise in Physical Systems

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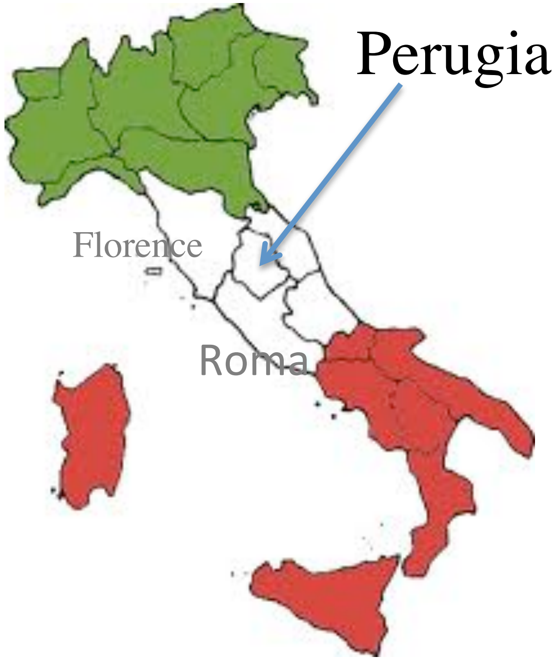

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Noise in Physical Systems

WISEPOWER

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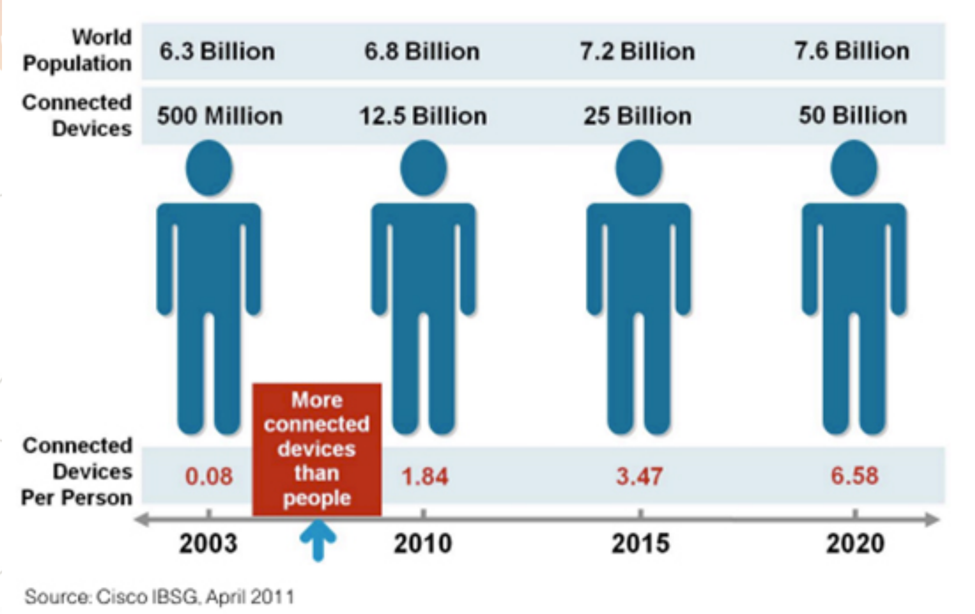
A growing number of people accepted to join the so-called internet-of-things scenario



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 required to operate the portable devices

We need to bridge the gap by acting on both arrows

Energy available from portable sources

Some modeling

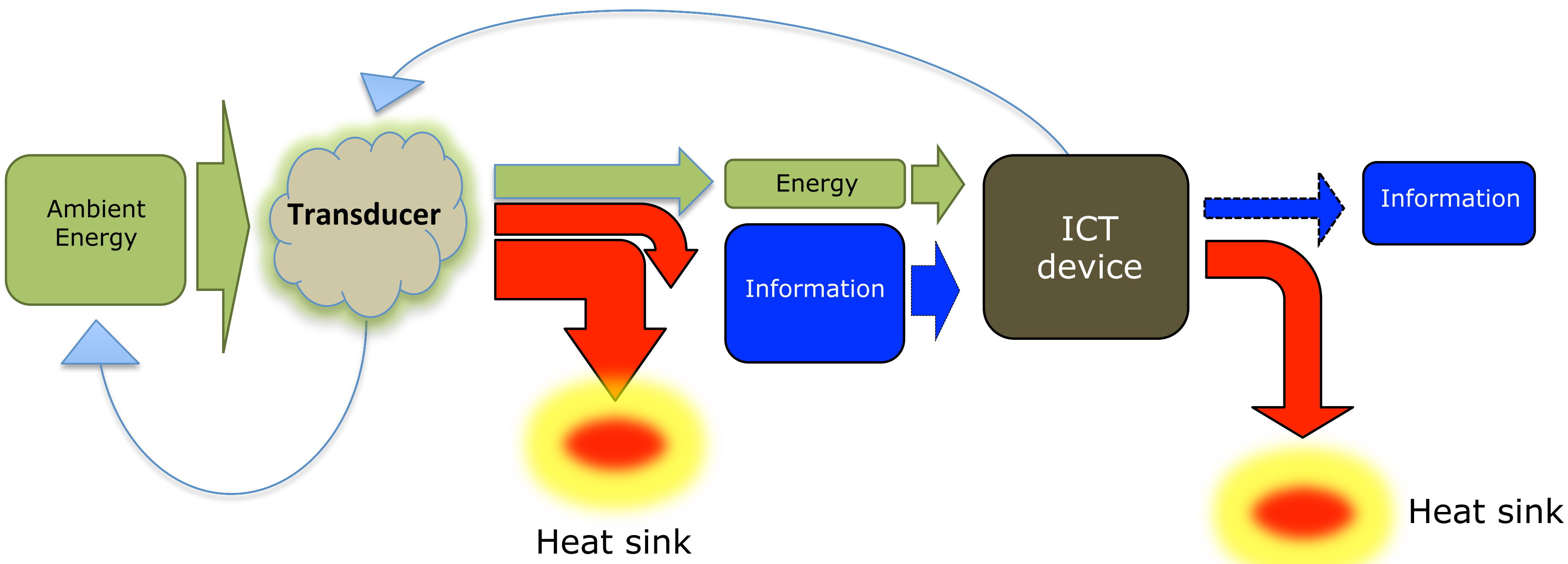
The device powering issue:

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

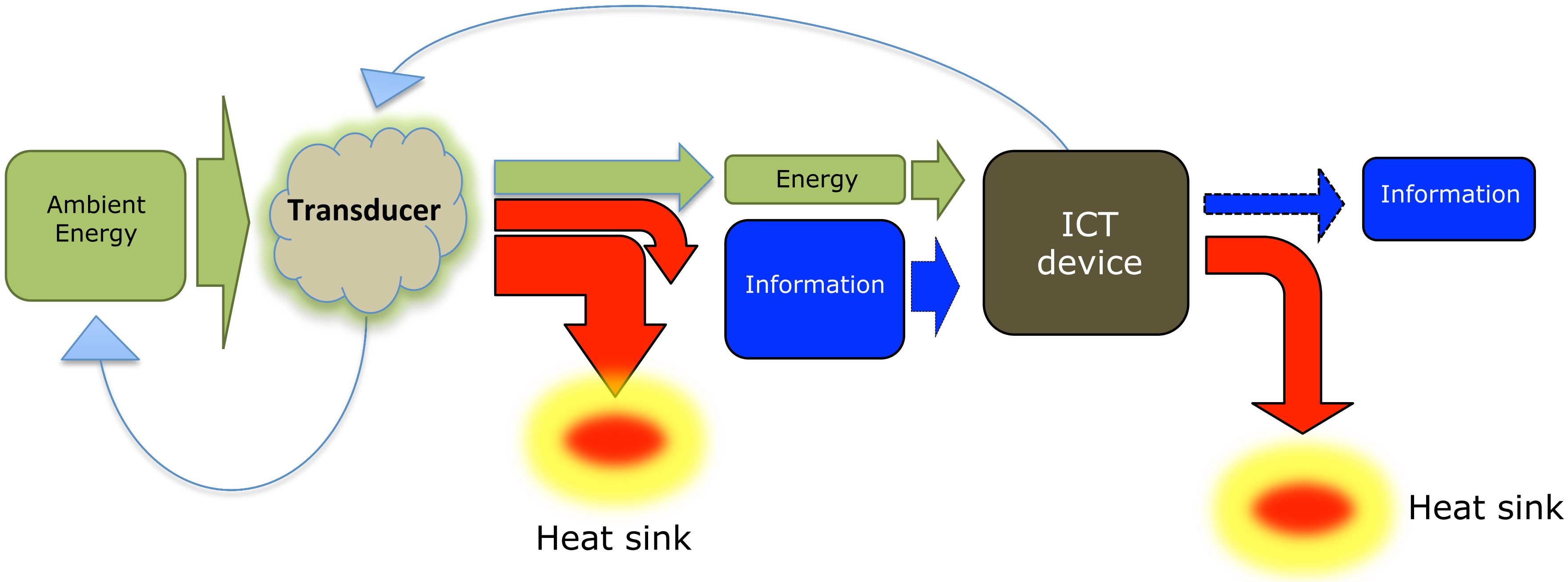


An ICT device is an info-thermal machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

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…

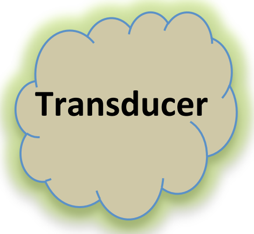
Two physical systems:

They transform energy

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

They are operated in a changing environment

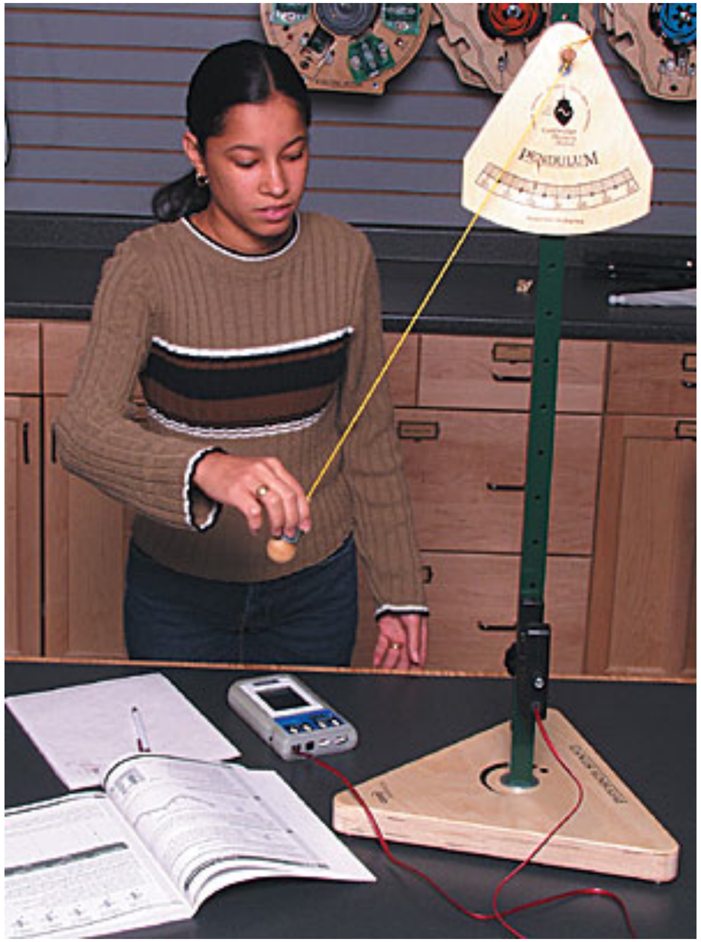
~~Thermodynamics~~ ~~Statistical mechanics~~ Non-equilibrium statistical mechanics



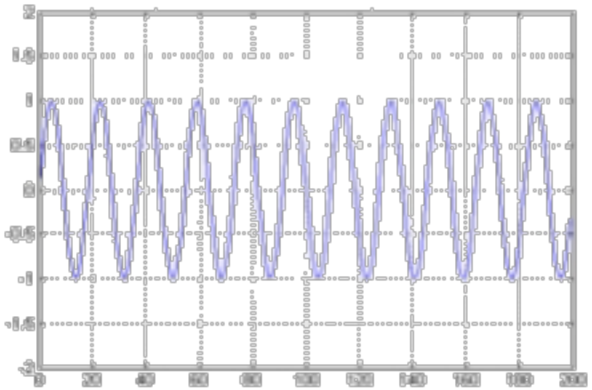
In this framework we can describe the device behavior in terms of few relevant d.o.f. via a procedure called "adiabatic elimination" or "coarse graining approach": we exchange the dynamics of a *not small isolated system* with *small not isolated system.*

Let's see an example…

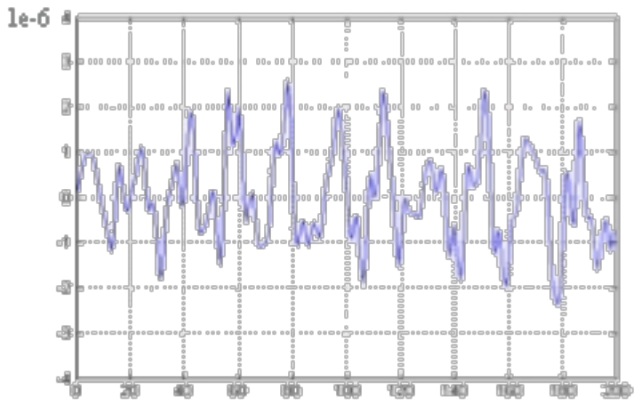
Example: physical system pendulum



Focus on the pendulum angle

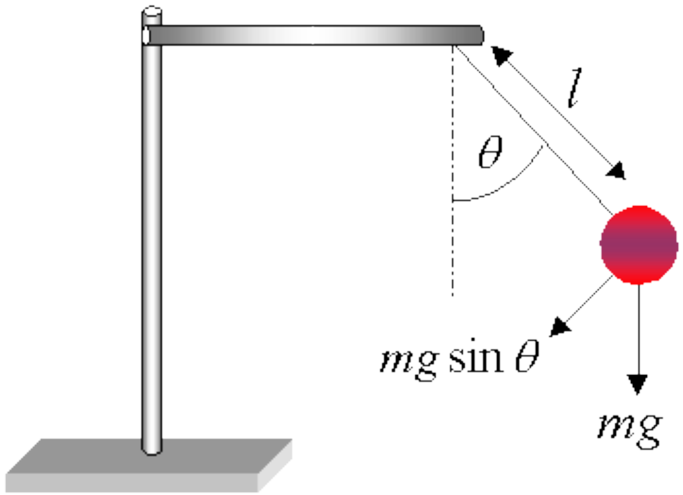


If we come back after a while..



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

$$-\int_{-\infty}^{t} \gamma(t-\tau)\,\dot{x}\,d\tau \quad \Rightarrow \quad \langle \zeta(t)\zeta(0) \rangle = kT\,\gamma(|t|)$$

Fluctuation – Dissipation theorem

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

Langevin equation approach

Transducer

ICT device

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

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

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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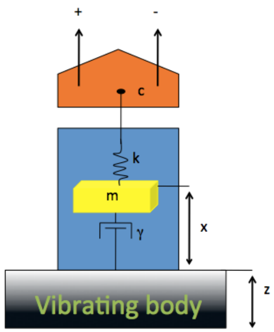
Langevin equation approach



(example from vibration harvester)

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

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

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

See e.g. Halvorsen, E. Energy Harvesters Driven by Broadband Random Vibrations, Microelectromechanical Systems, Journal of (Volume:17 , Issue: 5), 2008.

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Langevin equation approach

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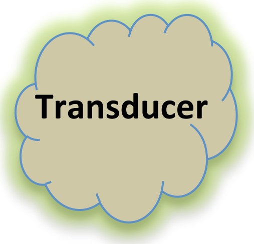
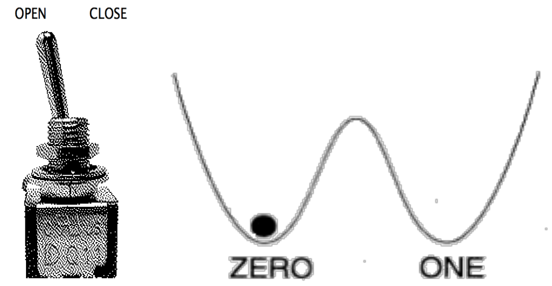




(example from a digital binary switch)

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

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

Transducer

Langevin equation approach

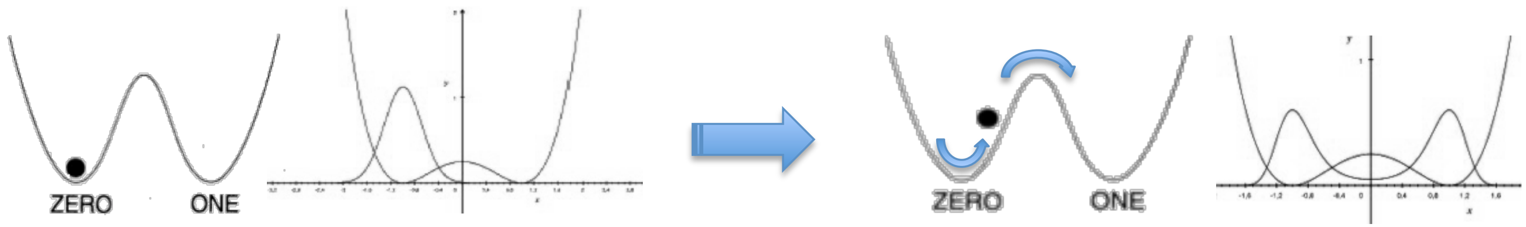
ICT device

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

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 $(x , x+dx)$.



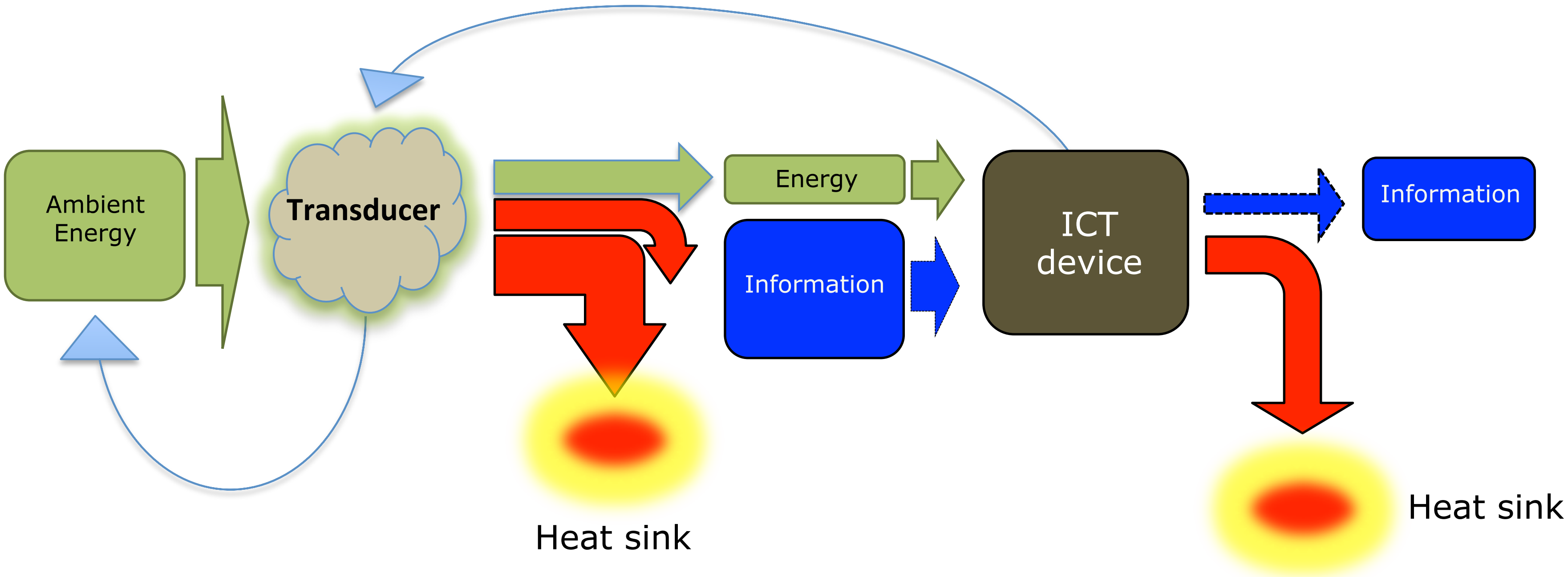
$P(x,t)$ is a deterministic quantity and its time evolution of can be described in terms of the associated Fokker-Planck equation.

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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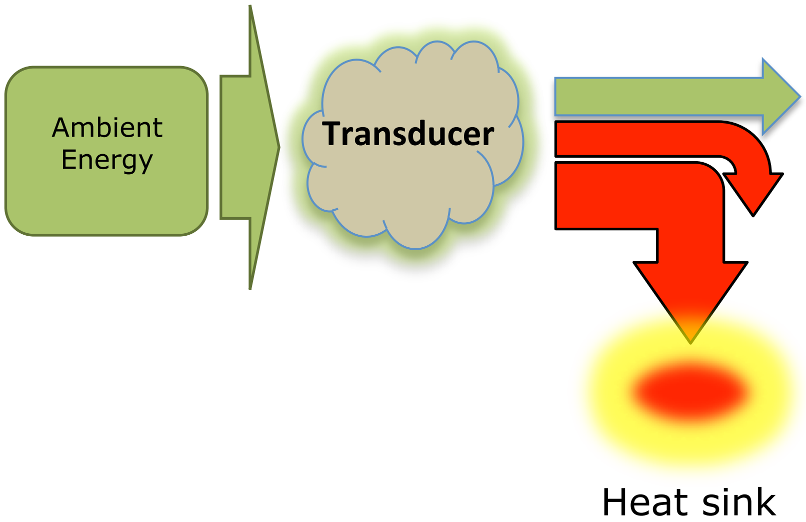

Clearly this energy is obtained from the ambient…

The device powering issue:

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

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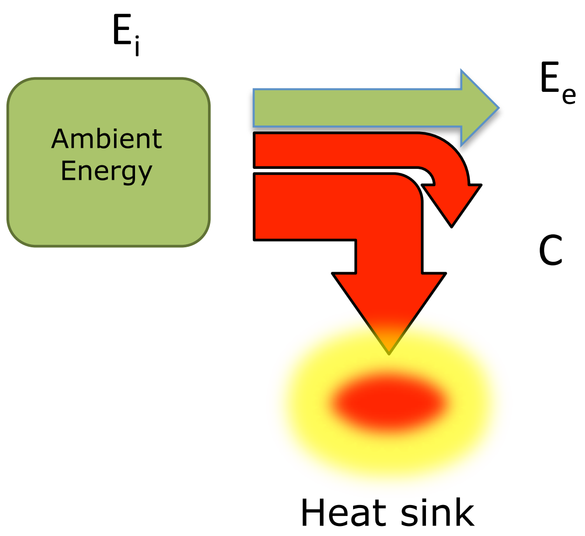


Energy is conserved....

$E_e = E_i - C$

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 ?

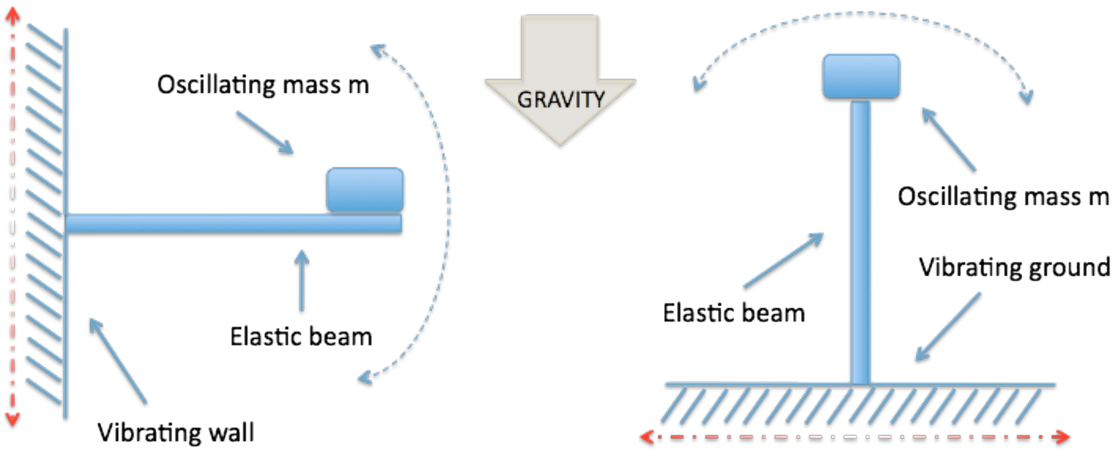
$$m\ddot{x} = -\frac{dU(x,t)}{dx} + \zeta_z - \gamma\dot{x} + \zeta$$

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

linear oscillator approach

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

cantilever



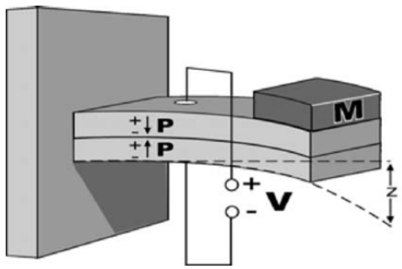
Left: configuration for harvesting vertical vibrations.
Right: configuration for harvesting horizontal vibrations.

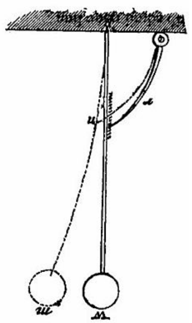
Linear systems

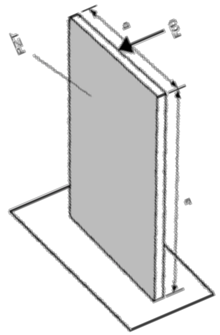
When $U(x) = \frac{1}{2} k x^2$ it is called a linear system

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





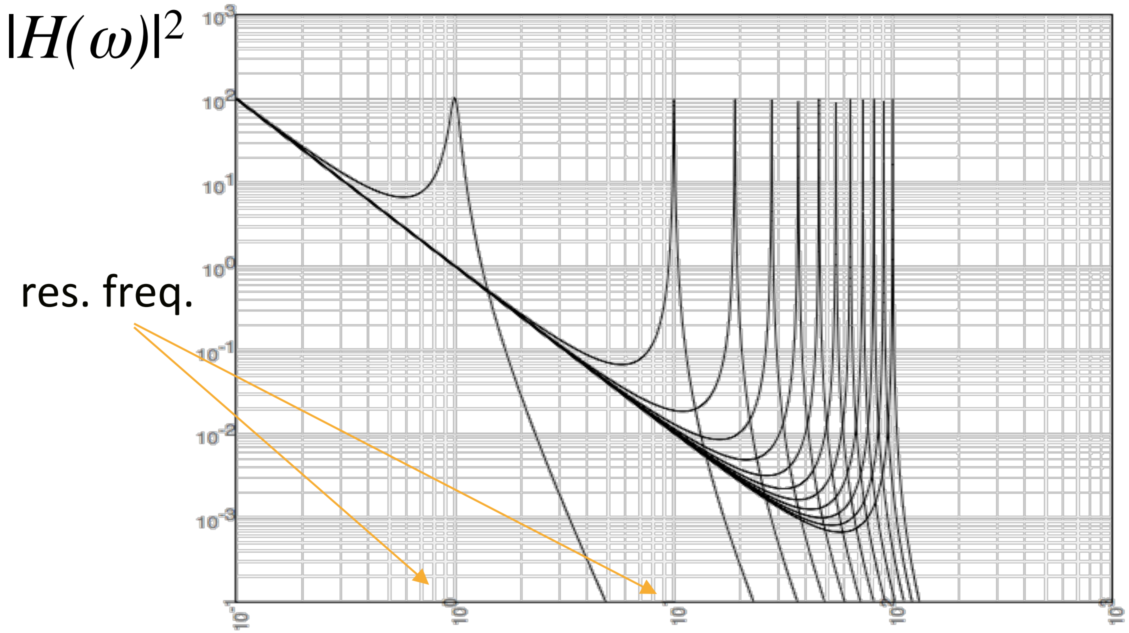


Transfer Function $H(\omega)$

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.

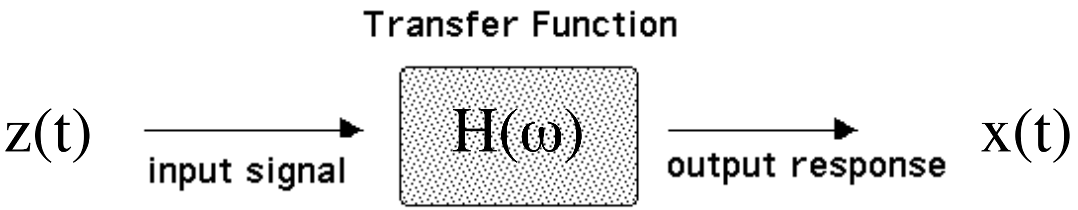
$$H(\omega) = H'(\omega) + i\,H''(\omega) = \left|H(\omega)\right| e^{i\phi(\omega)}$$



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…

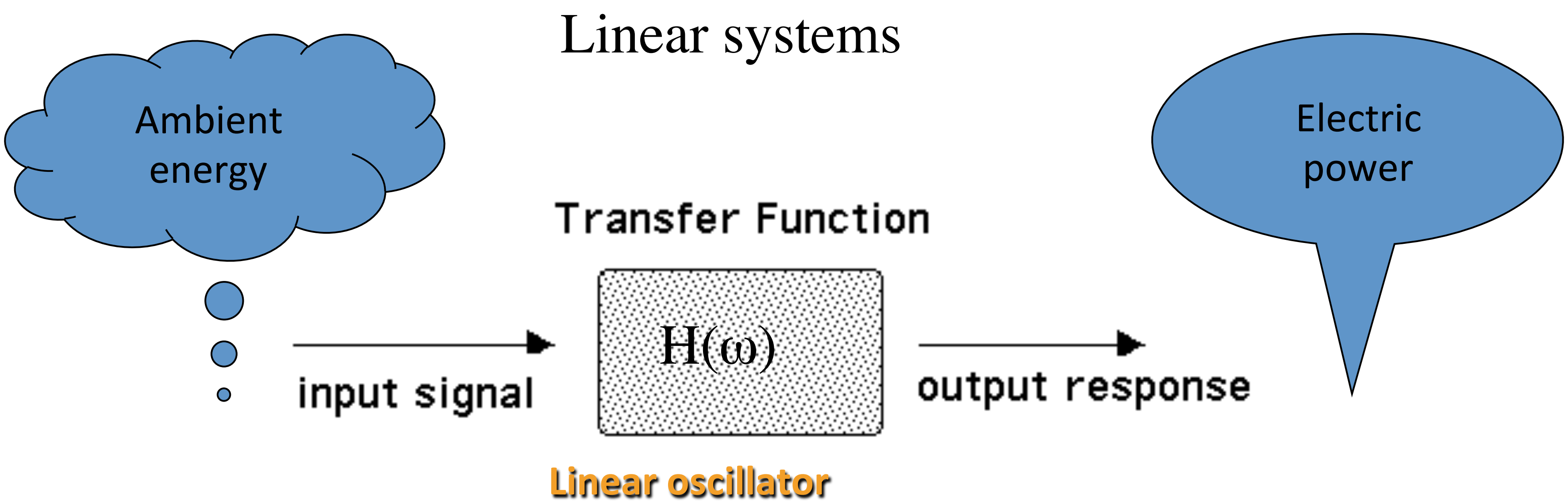


$$S_x(\omega) = |H(\omega)|^2 \, S_z(\omega)$$

Output power spectrum

Input power spectrum

Vibrations energy harvesting

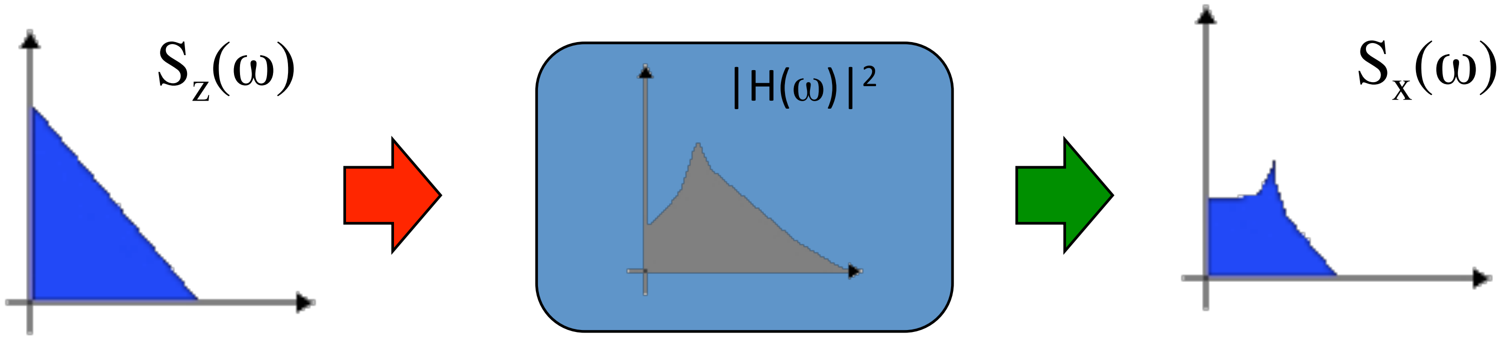


The transfer function is a math function of the frequency, in the complex domain, that can be used to represent the performance of a linear system

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.

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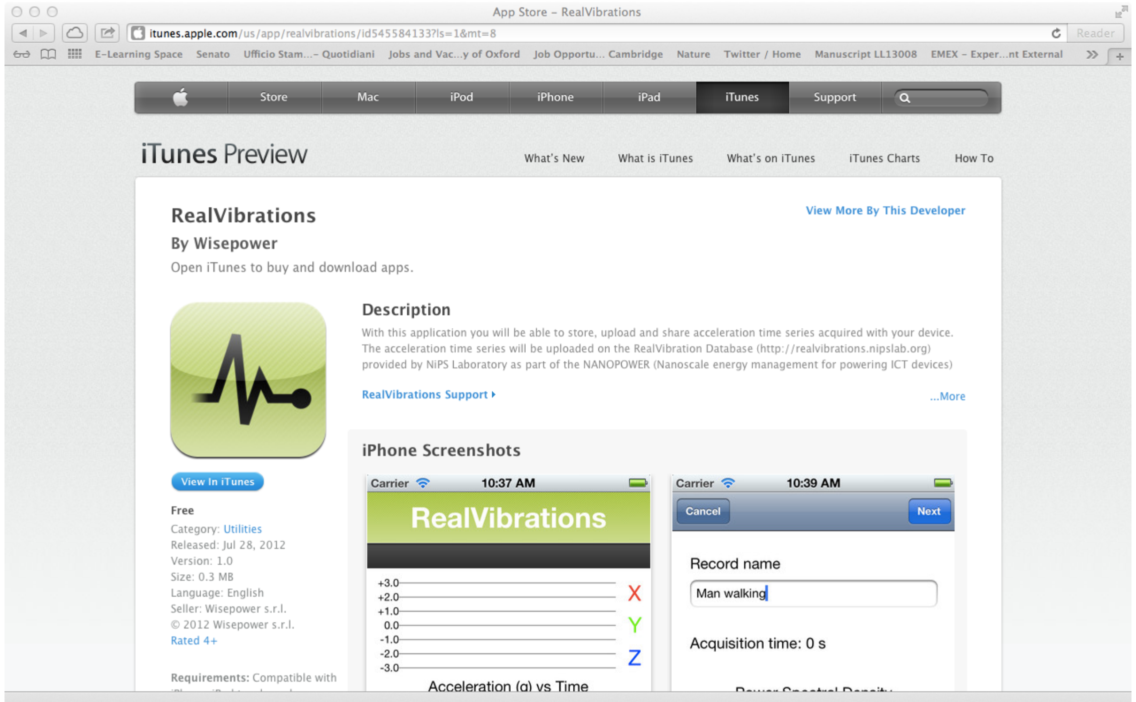
www.nipslab.org

Signal presentation:

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

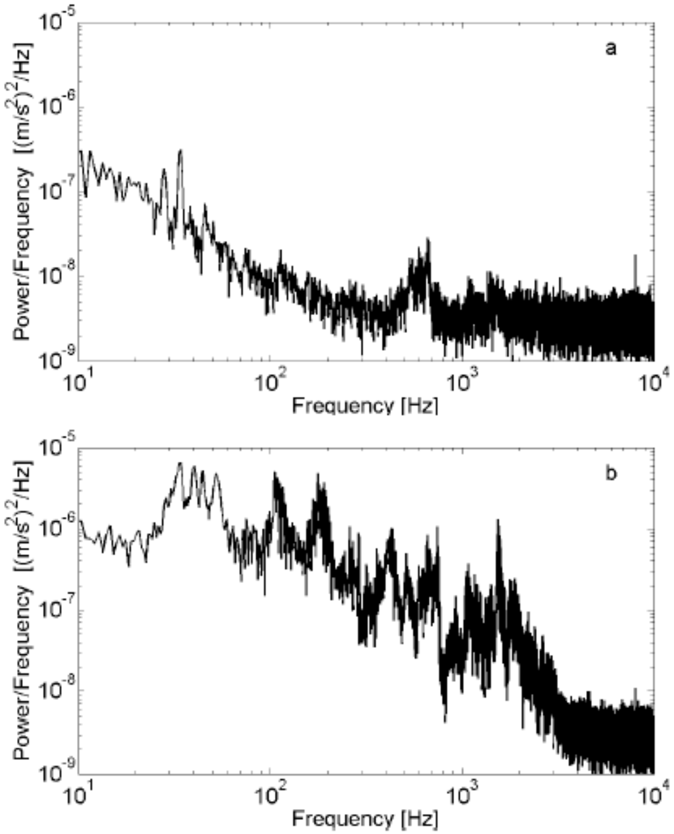
realvibrations.nipslab.org

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

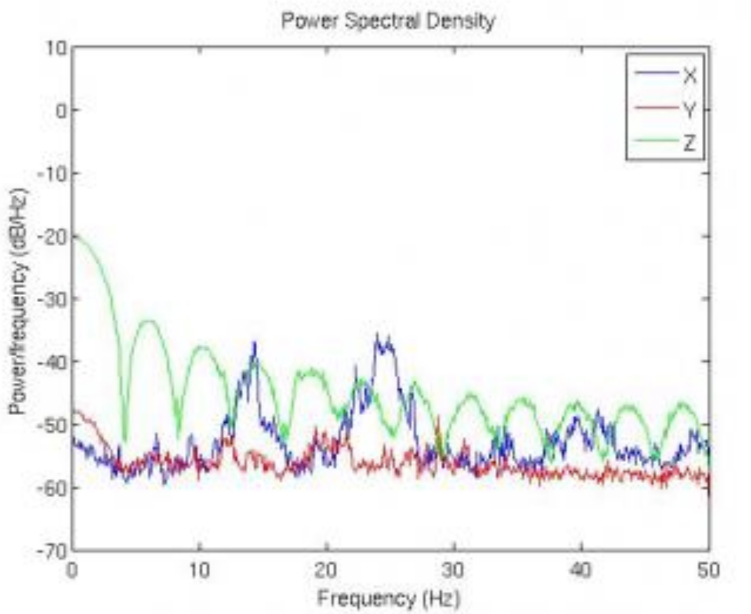
‹ previous 147 of 313 next ›

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

Woman walking

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

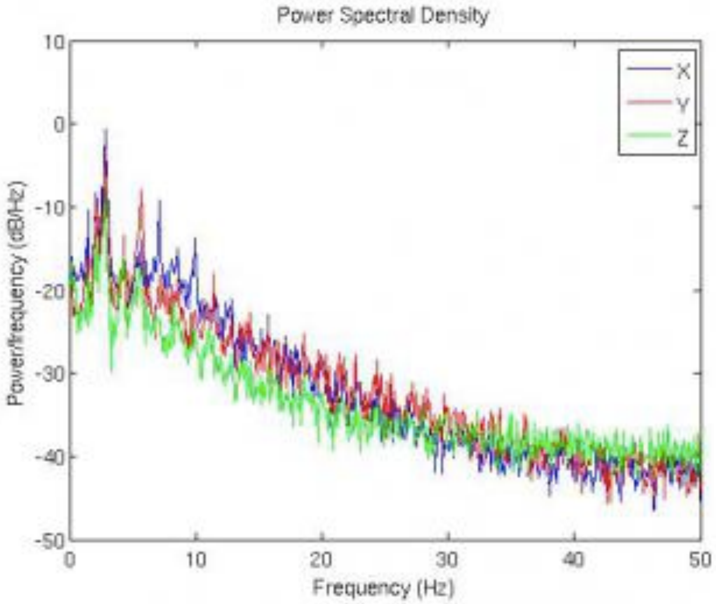
‹ previous 4 of 313 next ›

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

Child walking

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

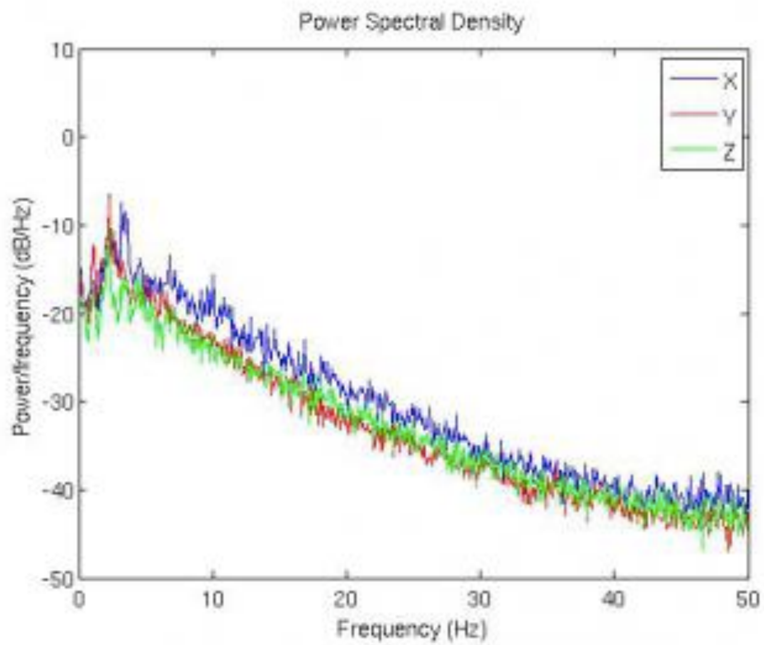
‹ previous 6 of 313 next ›

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

Running BMW X3

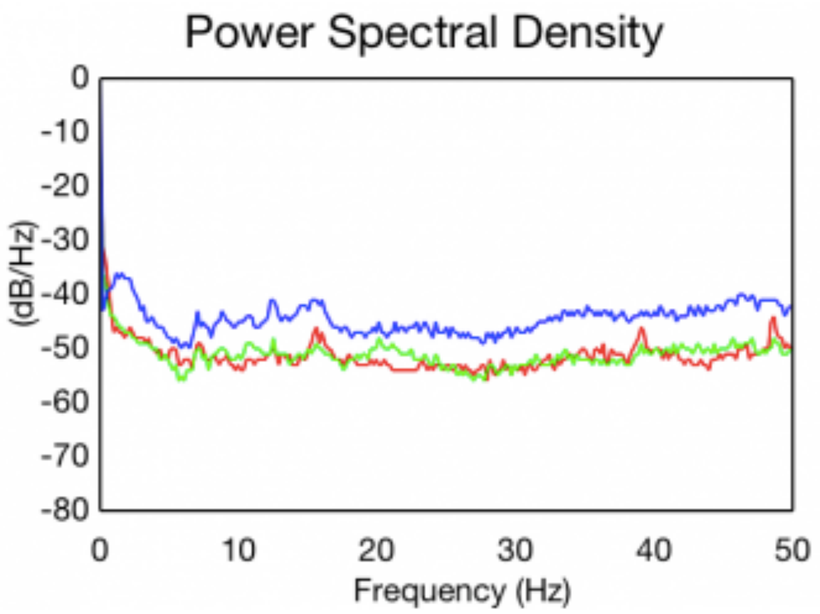
Submitted by igor.neri on Thu, 05/02/2013 - 15:57

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

Length: 308s

Sampling Rate: 100Hz

Acquisition Kit: iPhone



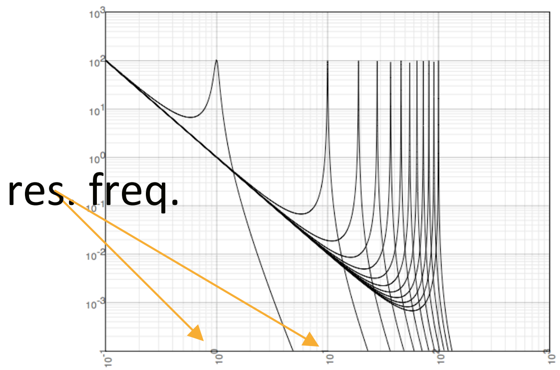
RMS	STD	Mean
X: 0.00567000 g	**X:** 0.00292000 g	**X:** -0.05242000 g
Y: 0.00901000 g	**Y:** 0.00252000 g	**Y:** -0.08053000 g
Z: 0.99528000 g	**Z:** 0.00488000 g	**Z:** -0.99519000 g

Vibrations energy harvesting

Linear systems

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…

This is a serious limitation when you want to build a small energy harvesting system…



Limitations of linear energy harvesters

$$S_y(\omega) = \mid H(\omega) \mid^2 S_x(\omega)$$

- Transfer function: one or more peaks corresponding to the resonance frequencies

- Difficult, if not impossible, to build small low-frequency resonant systems

- The frequency spectrum of available vibrations not sharply peaked.

Vibrations energy harvesting

Whish list for the perfect vibration harvester

1) Capable of harvesting energy on a broad-band
2) No need for frequency tuning
3) Capable of harvesting energy at low frequency

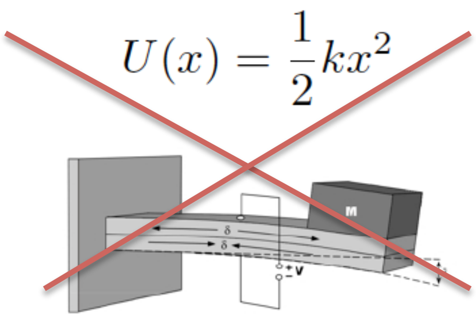
1) Non-resonant system
2) "Transfer function" with wide frequency resp.
3) Low frequency operated

Vibrations energy harvesting

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z \\ \dot{V} = K_c \dot{x} - \dfrac{1}{\tau_p} V \end{cases}$$

The oscillator dynamics

$U(x)$ Represents the Energy stored



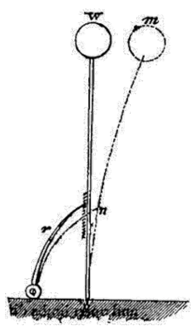
$$U(x) \neq \frac{1}{2}kx^2$$

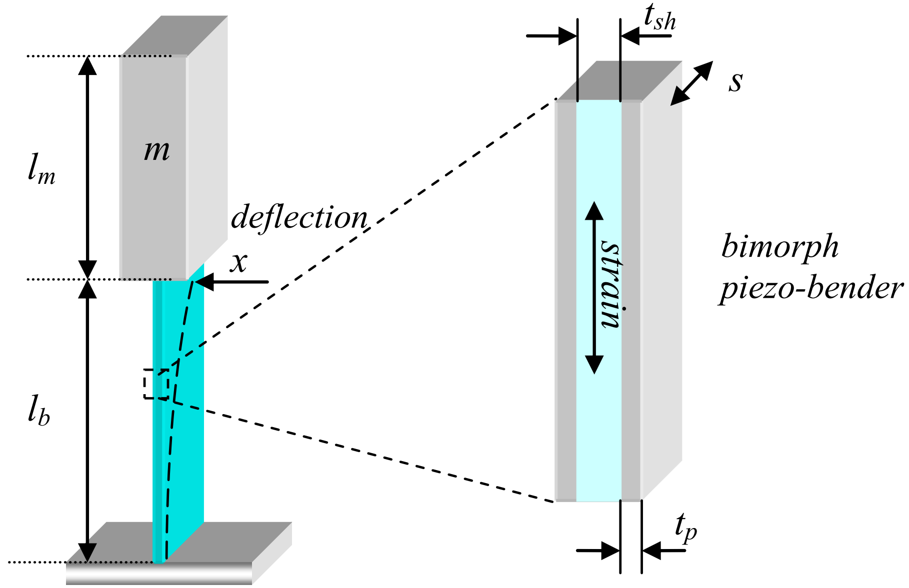
NON-Linear mechanical oscillators

1) Non-resonant system
2) "Transfer function" with wide frequency resp.
3) Low frequency operated

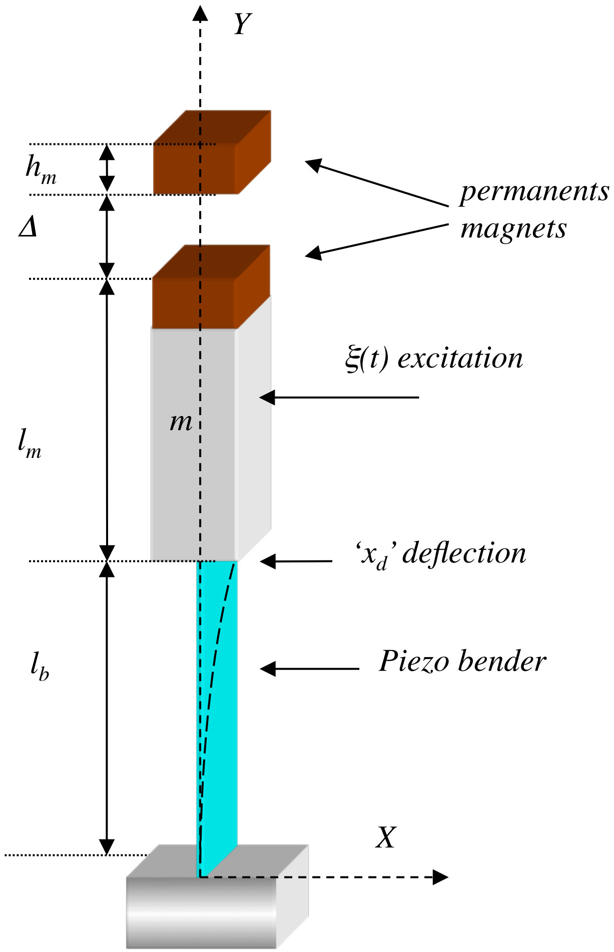
Example…

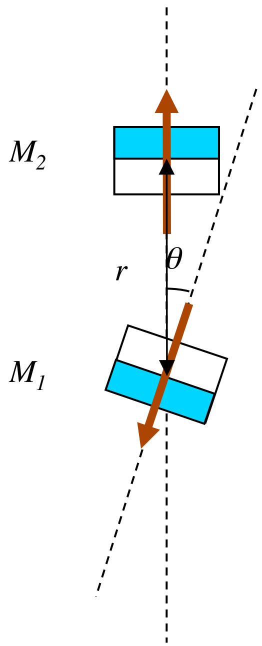
Inverted pendulum

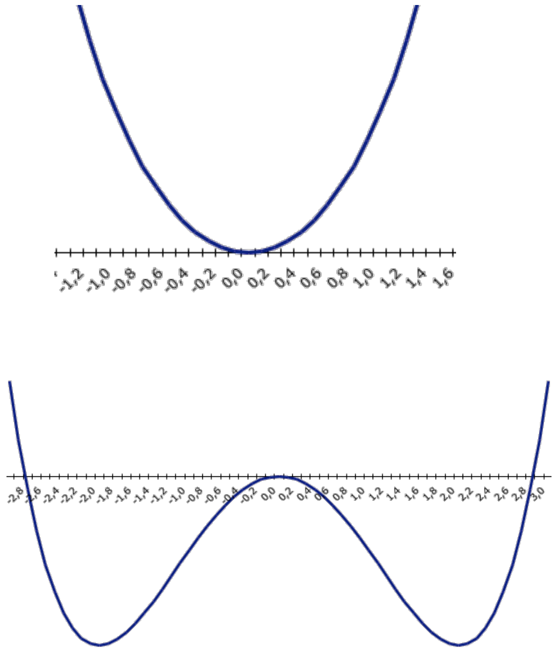




NON-Linear Inverted pendulum

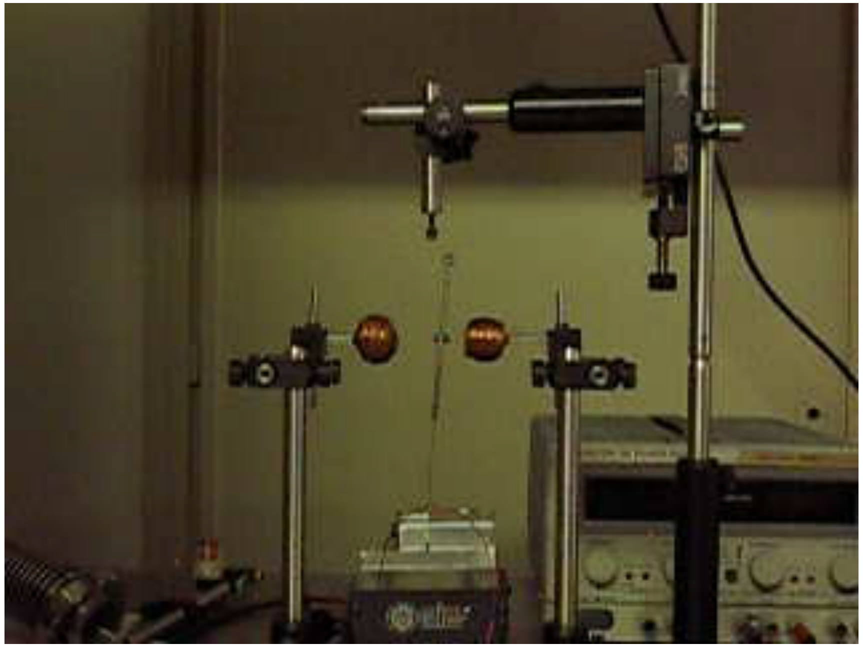


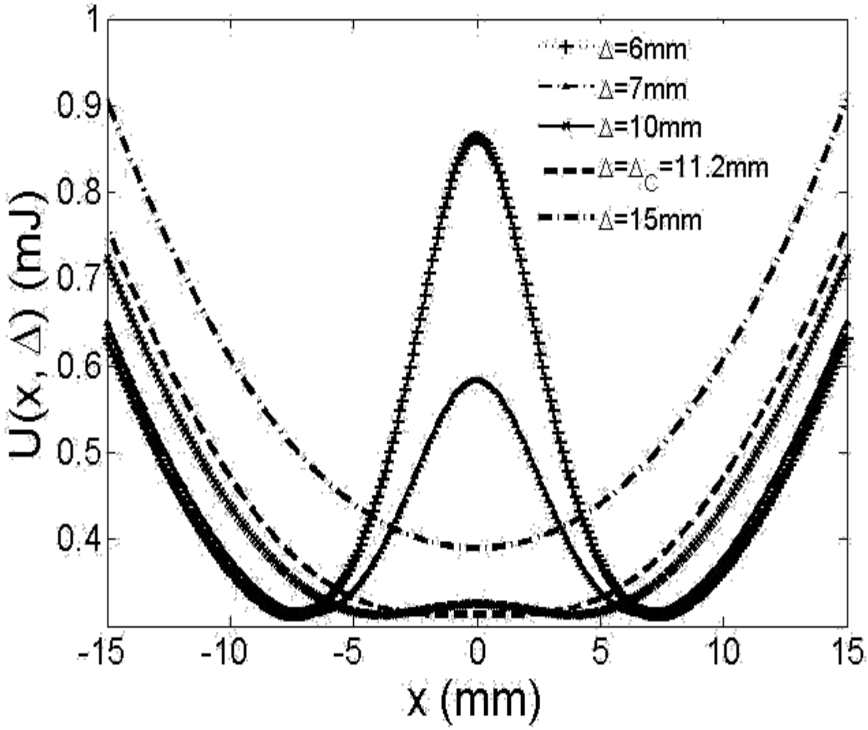




b)

NON-Linear mechanical oscillators

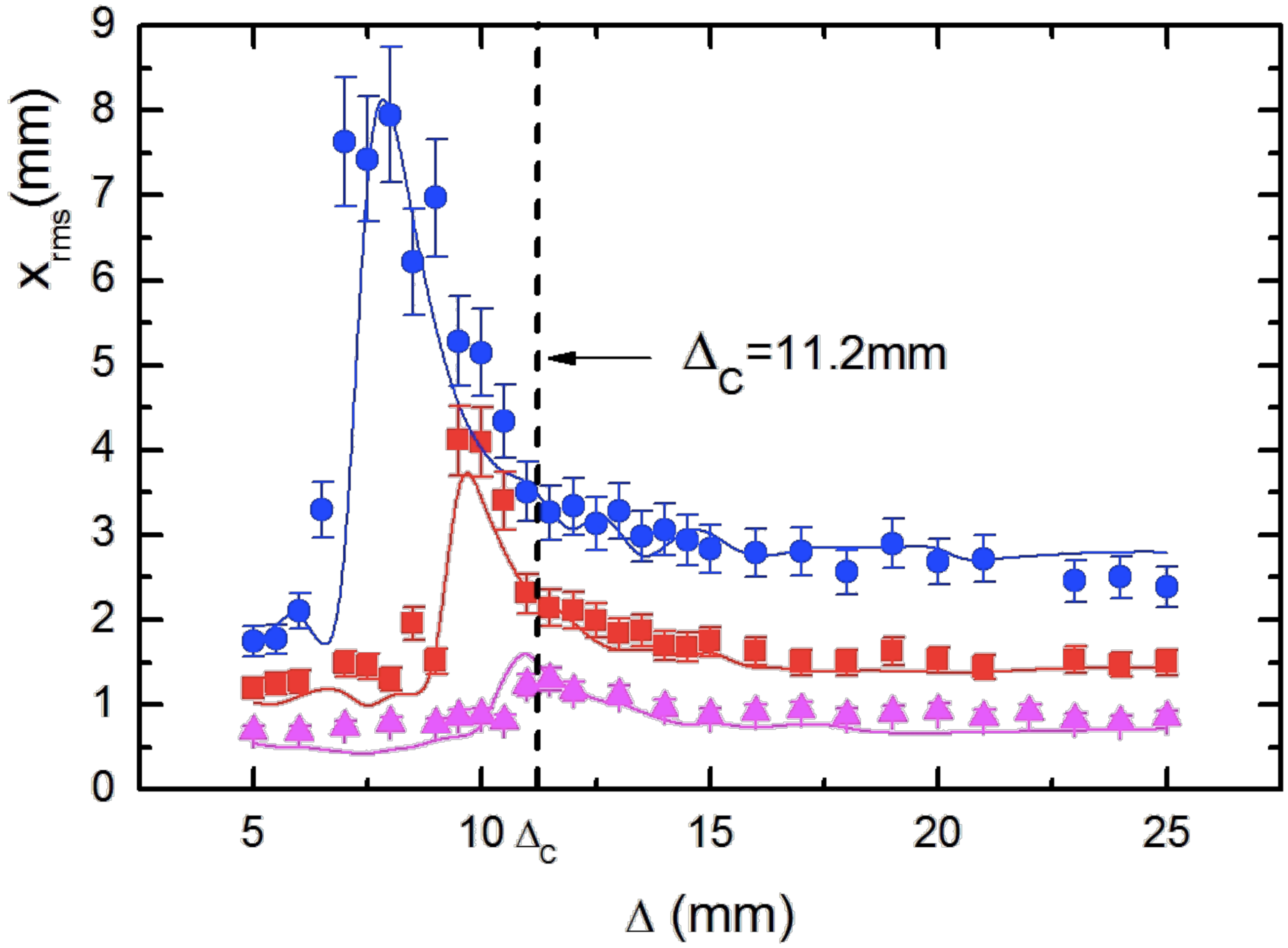




http://www.nipslab.org/node/1676

Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni
Physical Review Letters, 102, 080601 (2009)

NON-Linear mechanical oscillators



Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni , Physical Review Letters, 102, 080601 (2009)

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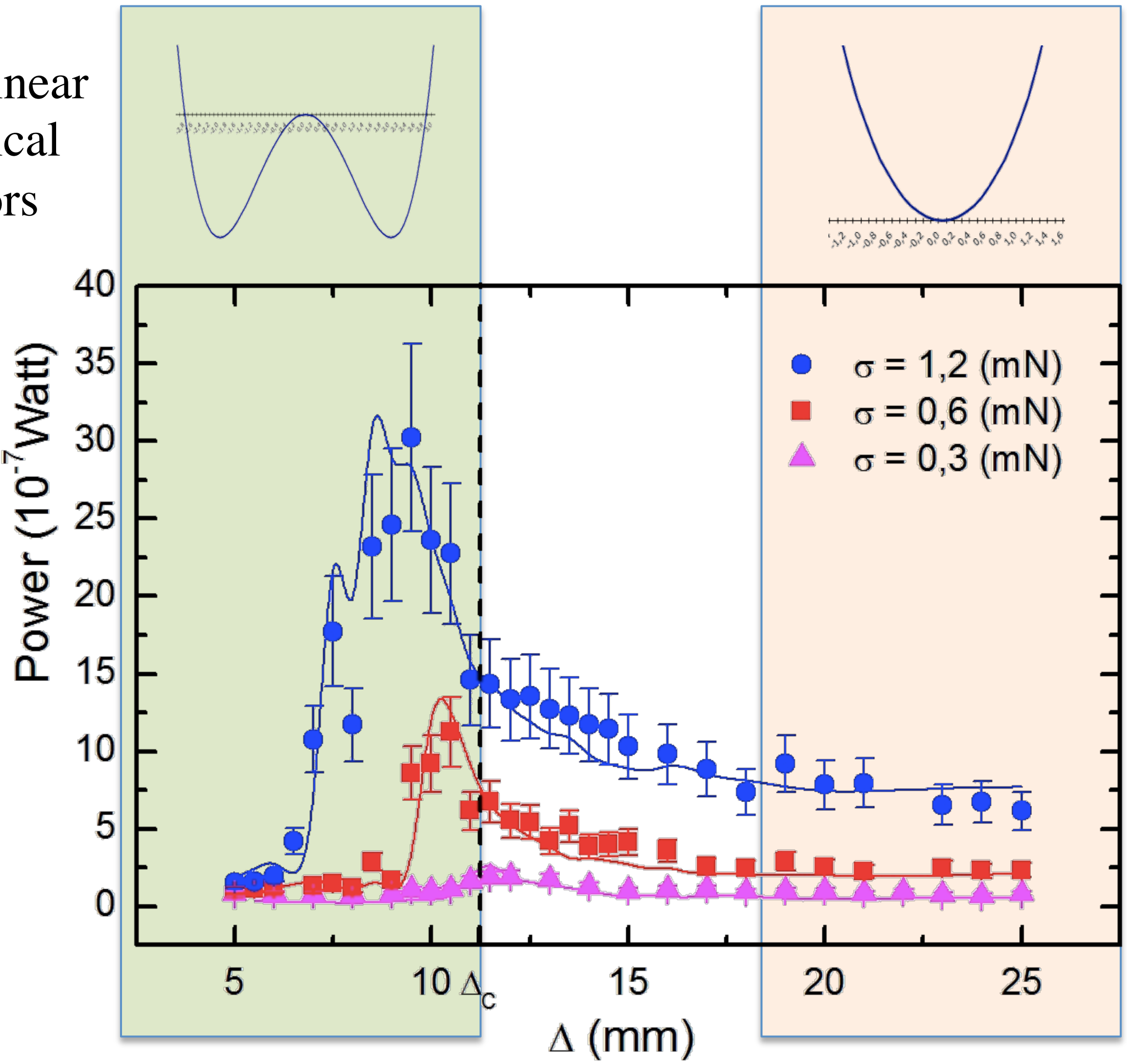
Power response

NON-Linear mechanical oscillators

Linear mechanical oscillators

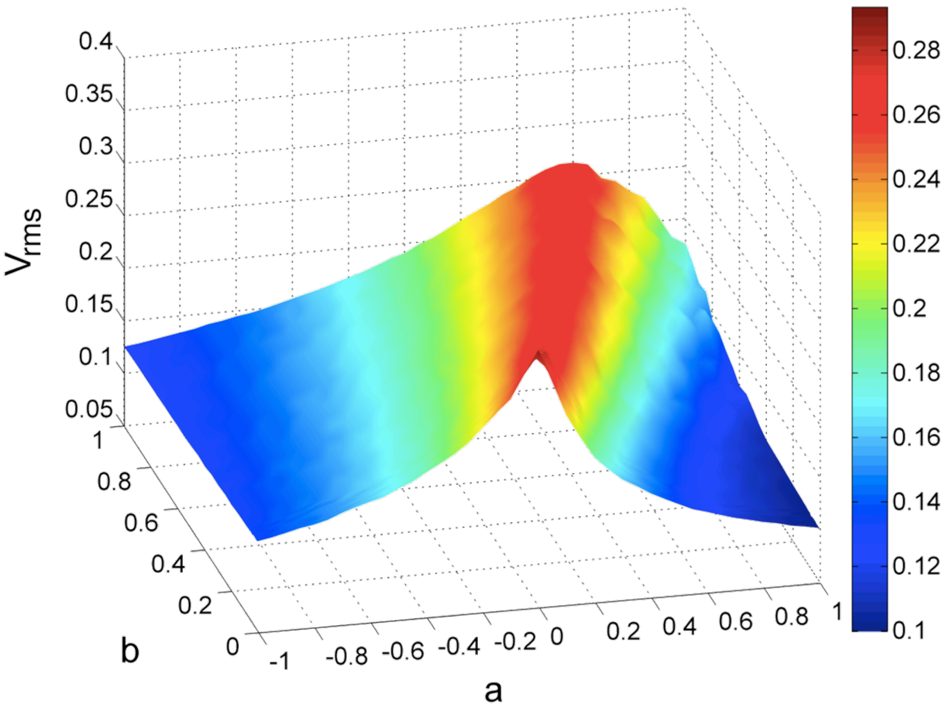


Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni , Physical Review Letters, 102, 080601 (2009)

NiPS Laboratory
Noise in Physical Systems

Non-linear systems

$$U(x) = -\frac{1}{2}ax^2 + \frac{1}{4}ax^4$$ Duffing potential



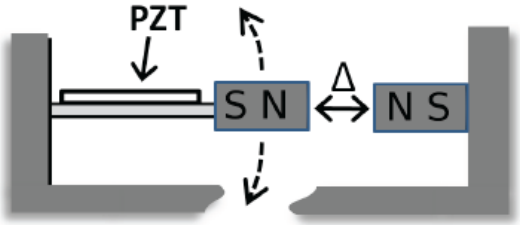
L. Gammaitoni, I. Neri, H. Vocca, Appl. Phys. Lett. 94, 164102 (2009)

NiPS Laboratory
Noise in Physical Systems

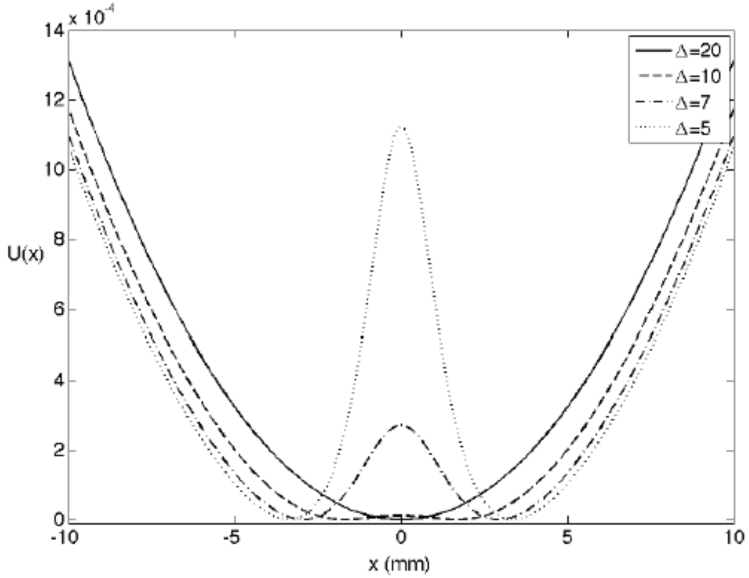
Field tests

Nonlinear energy harvesters: $U(x) \neq \frac{1}{2}kx^2$

Bistable kinetic energy harvester

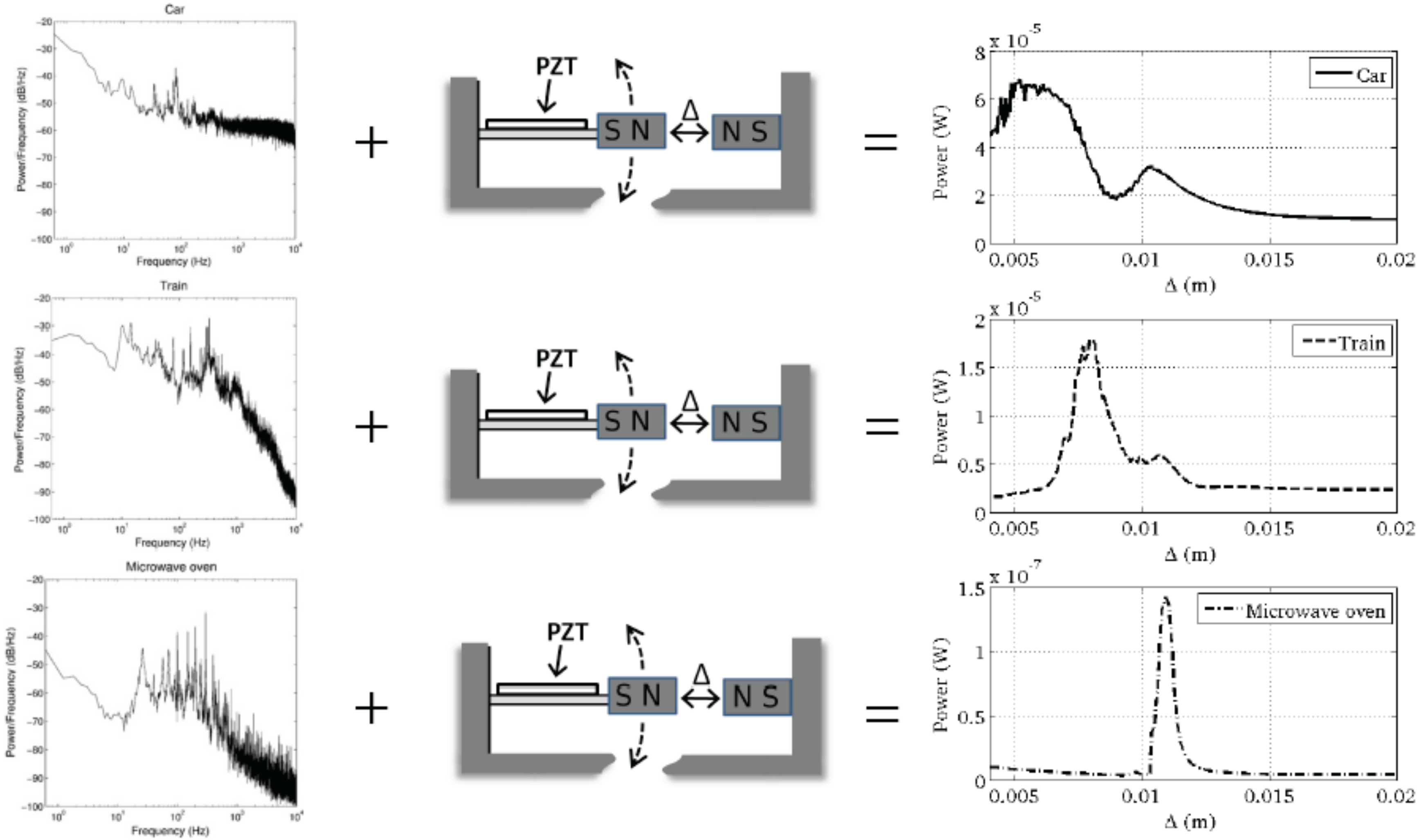


$$U(x) = \frac{1}{2}K_{eff}x^2 + \frac{\mu_0}{2\pi}\frac{M_1 M_2}{(x^2 + \Delta^2)^{3/2}}$$



| F. Cottone, PhD Thesis, Perugia 2007

Simulation of power harvested using various vibrations sources



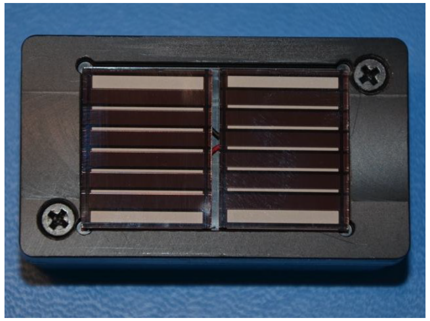
[5] Kinetic energy harvesting with bistable oscillators, H. Vocca et al., Applied Energy 2012

Shrinking size

HAT (Hybrid Autonomous Transceiver)

(Courtesy of Wisepower srl, www.wisepower.it)

50 mm



35 mm

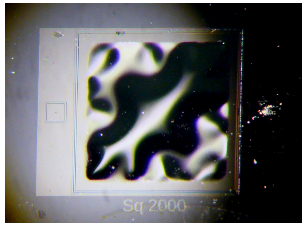
20 mm

Few mW range

Prototype Vibration Harvester

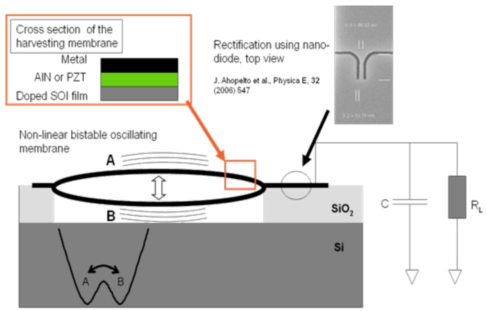
(NANOPOWER FET Proactive – G.A. 256959, www.nanopwr.eu)

0.5 mm



0.5 mm

800 nm

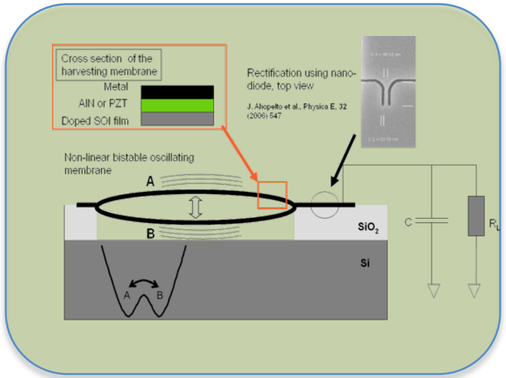


Few 0.1 µW range

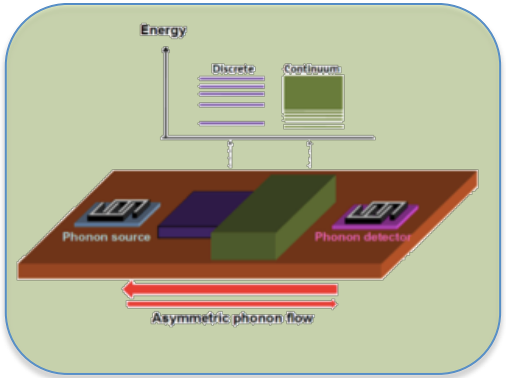
This research has been developed in the framework of the project

NANOPOWER

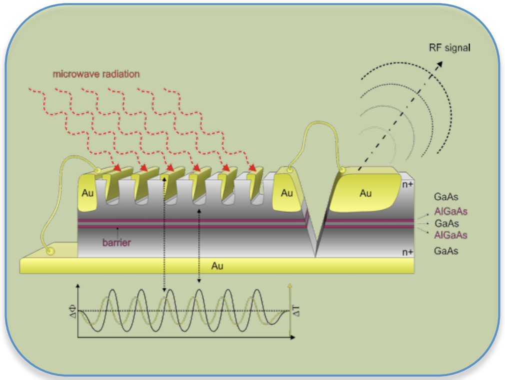
Three classes of potential nanoscale energy harvester devices have been studied.



Nonlinear nano oscillators



Heat rectification harvester



Quantum harvester

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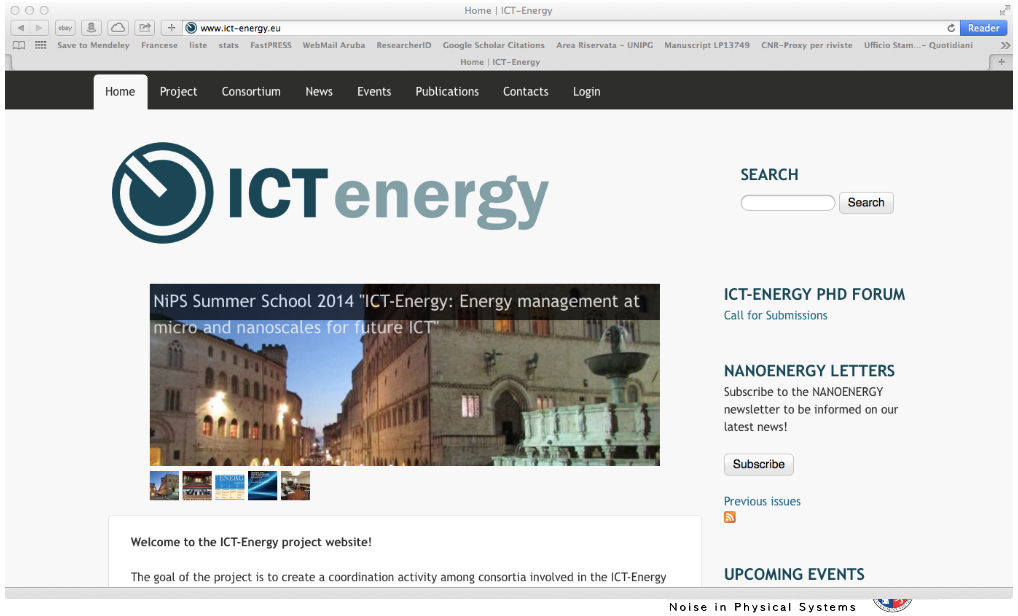
Some conclusions

ICT-Energy consortium/community

Participant no.	Participant organisation name	Part. short name	Country
1 (Coordinator)	Università di Perugia	UNIPG	IT
2	Roskilde University	RUC	DK
3	Karlsruher Institut fuer Technologie	KIT	DE
4	Barcelona Supercomputing Center	BSC	SP
5	Ecole Polytechnique Federale de Lausanne	EPFL	CH
6	Aalborg University - Denmark	AAU	DK
7	Hitachi Europe Limited	HCL	UK
8	University of Bristol	UNIVBRIS	UK
9	University of Glasgow	UGLA	UK
10	University College Cork, National University of Ireland	TNI-UCC	IR



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In the last three issues 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 15th 2015

The future of powering for small mobile electronic devices

Present solution: - ~~disposable batteries~~

- rechargeable batteries **energy storage issue**

Future solution: - energy harvesting + storage

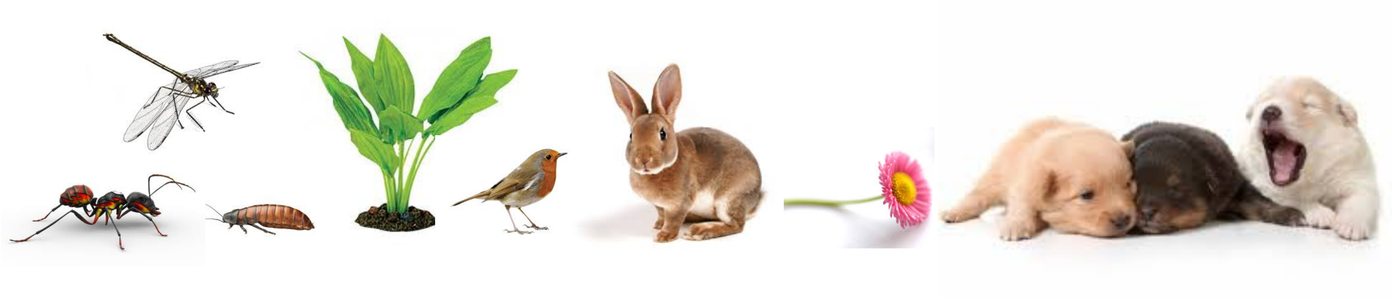
Take-home message:

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

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