ICT-Energy

(Energy extraction from noise…)

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Noise in Physical Systems

5th SINANO Summer School

Aug 28, 2012 - Bertinoro

The starting point

1) To deal with the problem of PORTABLE POWER for Autonomous ICT Devices

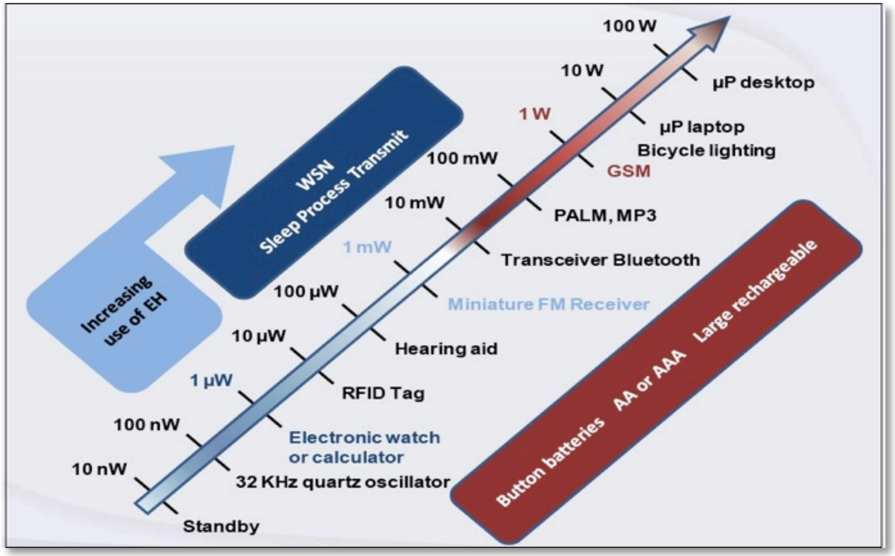
2) To deal with the problem of ENERGY EFFICIENCY in ICT

To date these two problems have been addressed only independently and by different communities

We will show that these tow problems sits on a common scientific background and thus can be addressed within a unified framework

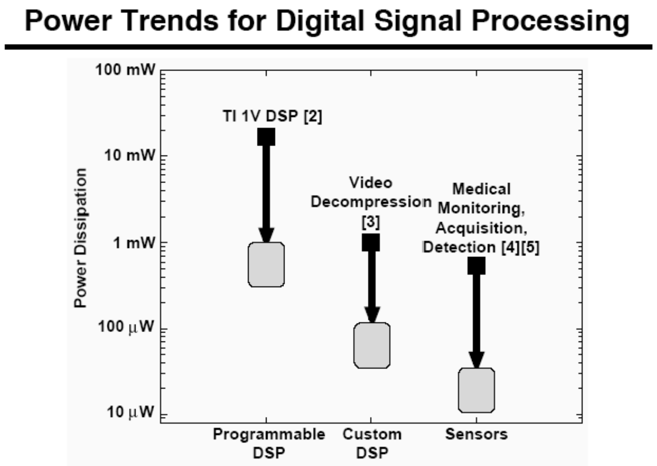
1) To deal with the problem of PORTABLE POWER for Autonomous ICT Devices

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

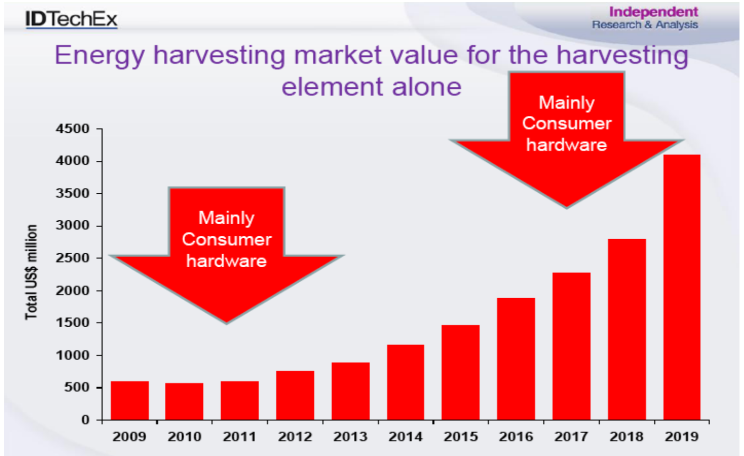


Source: IDTechEx, "Energy Harvesting and Storage 2009-2019", Cambridge 2009. EH: Energy Harvesting; WSN: Wireless Sensors Network

Future ICT will be characterized by pervasive computing



Decreses the power demand for ICT devices



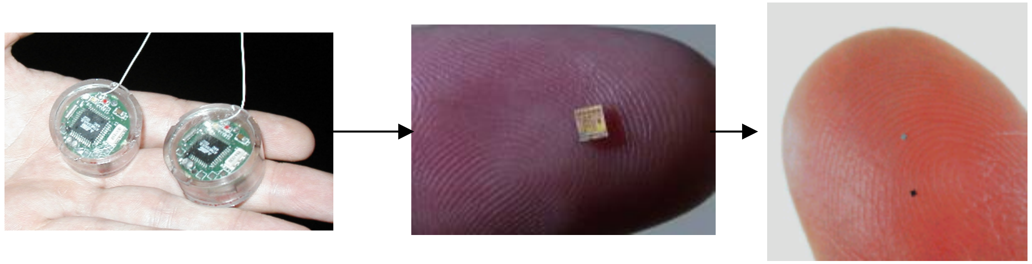
Increases the market for portable micro-to-nano power generators

Guardian Angels (GA's) are zero-power smart autonomous systems featuring sensing, computation and communication. They can harvest different kinds of energy.

From Florin Udrea presentation at Scientific Session
Sustainable ICT: Micro and Nanoscale Energy Management
Budapest, May 2011

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: 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

What is Energy Harvesting ?

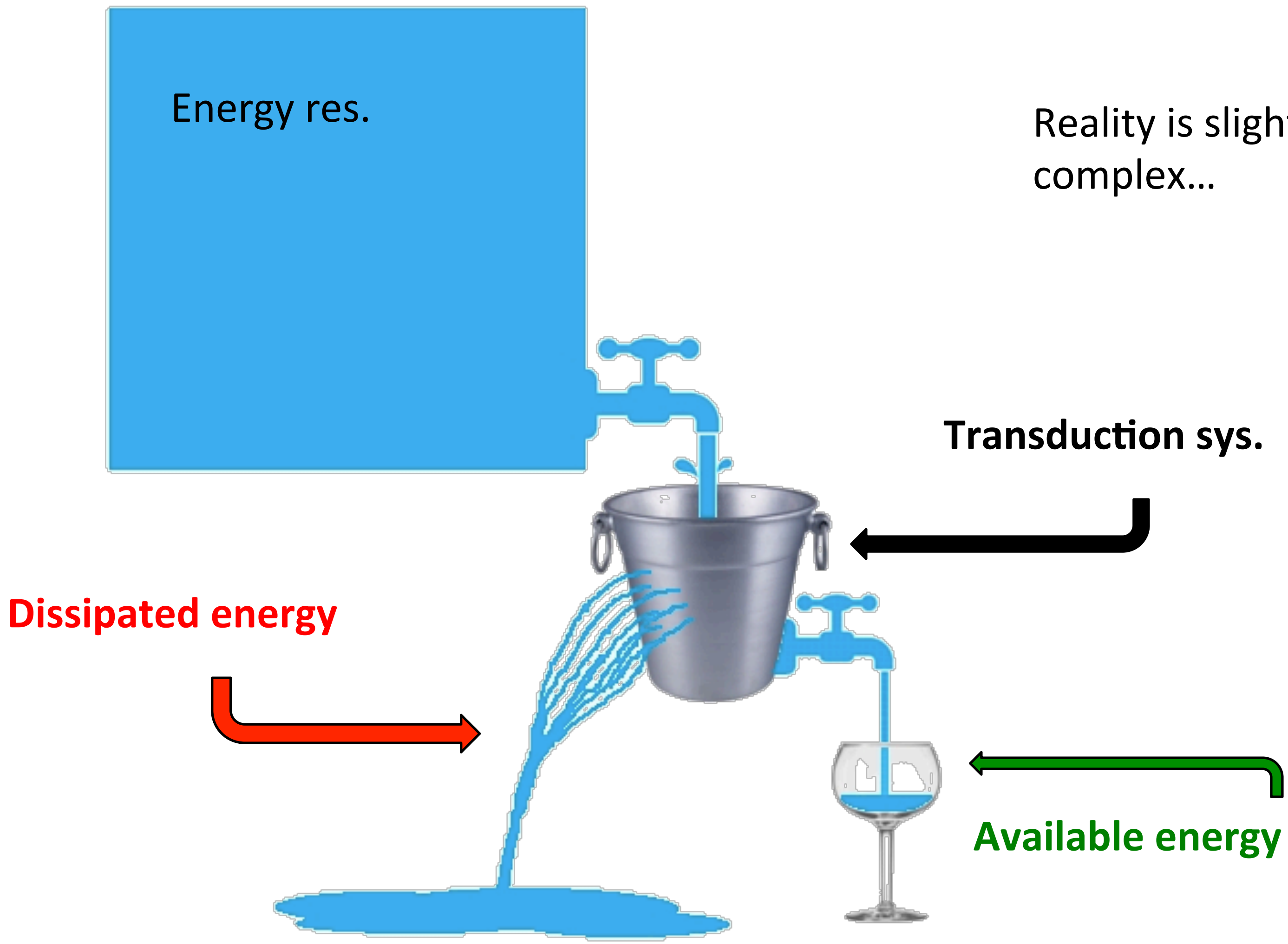
Energy harvesting basic ideas

ENERGY

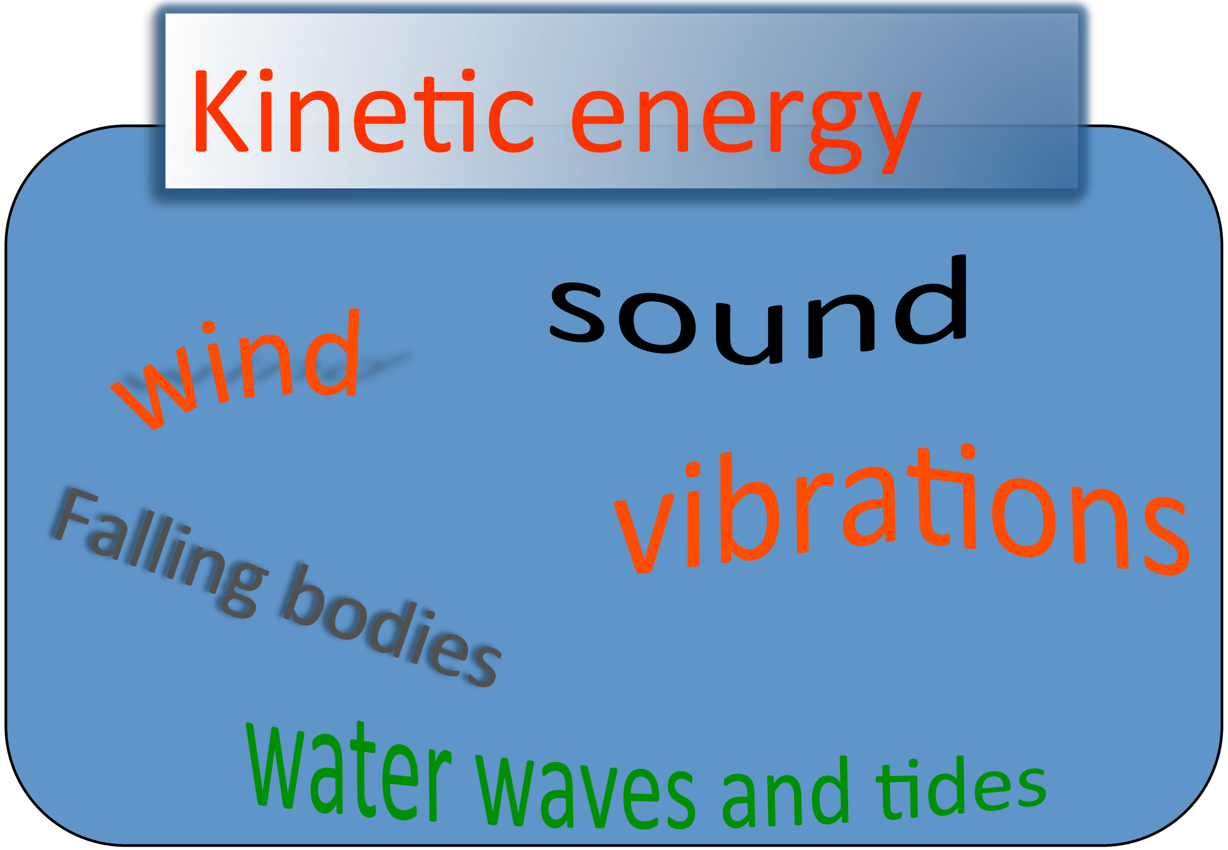
Unlimited source of free energy, readily available for multiple uses…

Energy harvesting basic ideas

Reality is slightly more complex…



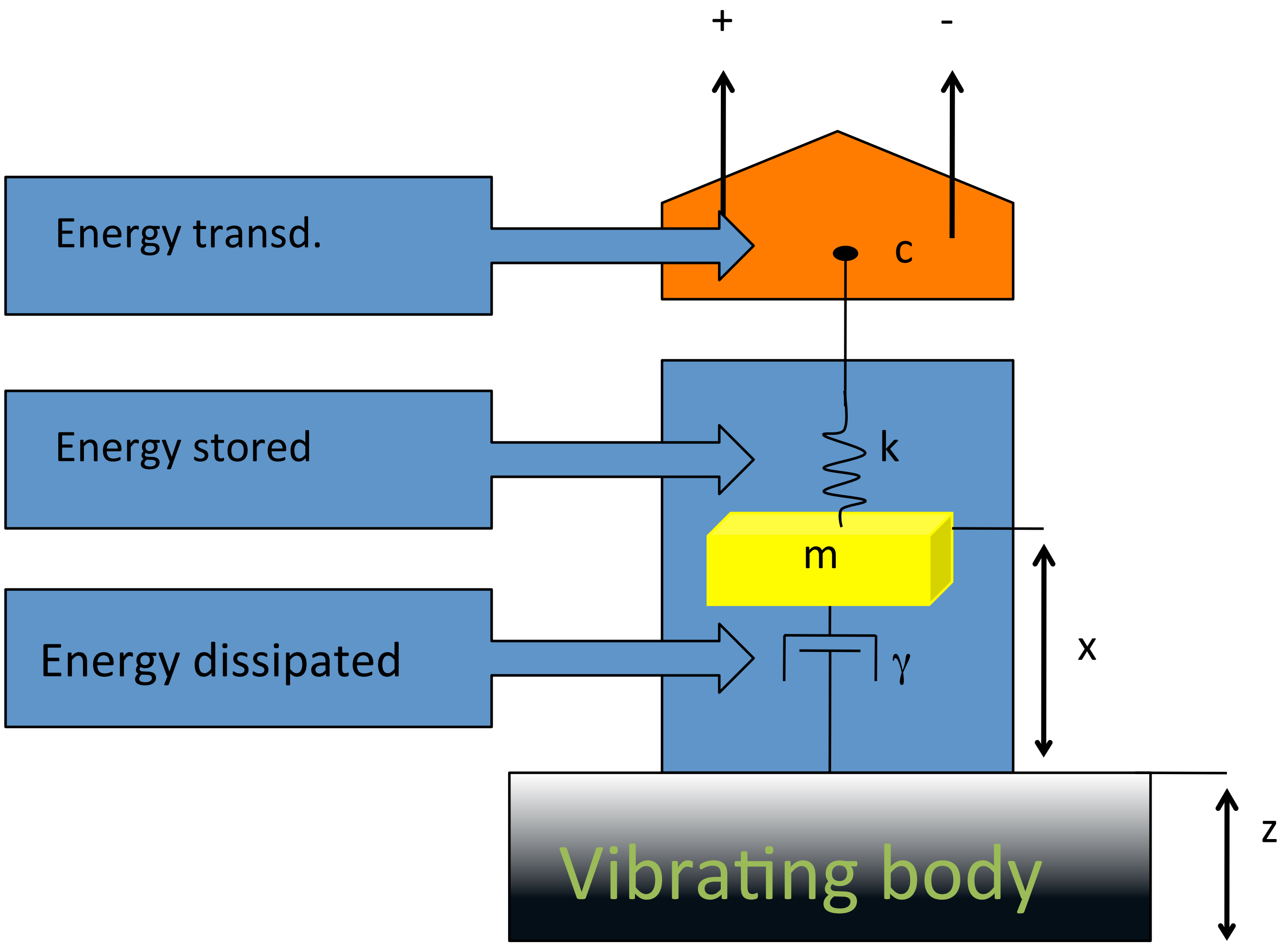
Energy harvesting basic ideas



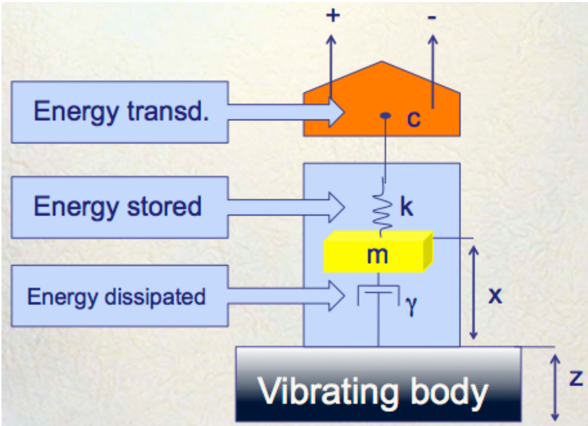
Focus on vibrations of solid bodies….

Vibrations energy harvesting

Dynamical model



Vibrations energy harvesting



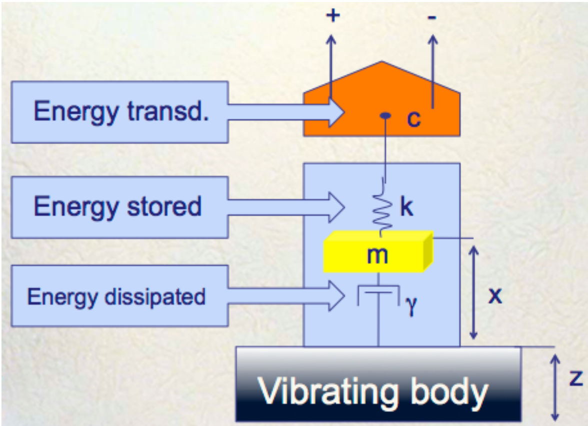
Dynamical model

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

Where:

$U(x)$	Represents the Energy stored
$\gamma\dot{x}$	Accounts for the Energy dissipated
$c(x,V)$	Accounts for the Energy transduced
ζ_z	Accounts for the input Energy

Vibrations energy harvesting

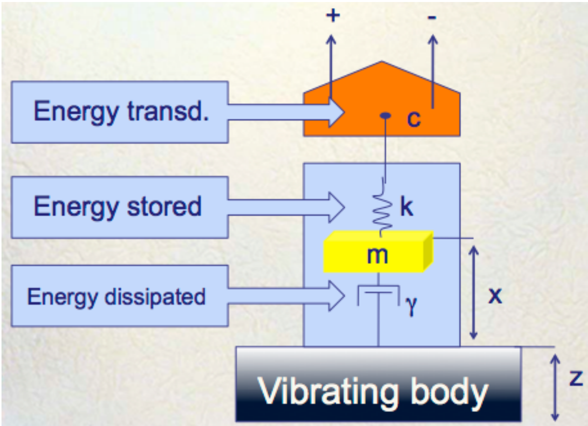


Dynamical model

$$
\begin{cases}
m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - c(x,V) + \zeta_z \\
\dot{V} = F(\dot{x},V)
\end{cases}
$$

Equations that link the vibration-induced displacement with the Voltage

Vibrations energy harvesting



Dynamical model

Equations that link the vibration-induced displacement with the Voltage

$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - c(x,V) + \zeta_z \\ \dot{V} = F(\dot{x},V) \end{cases}$$

Details depend on the physics of the conversion principles…

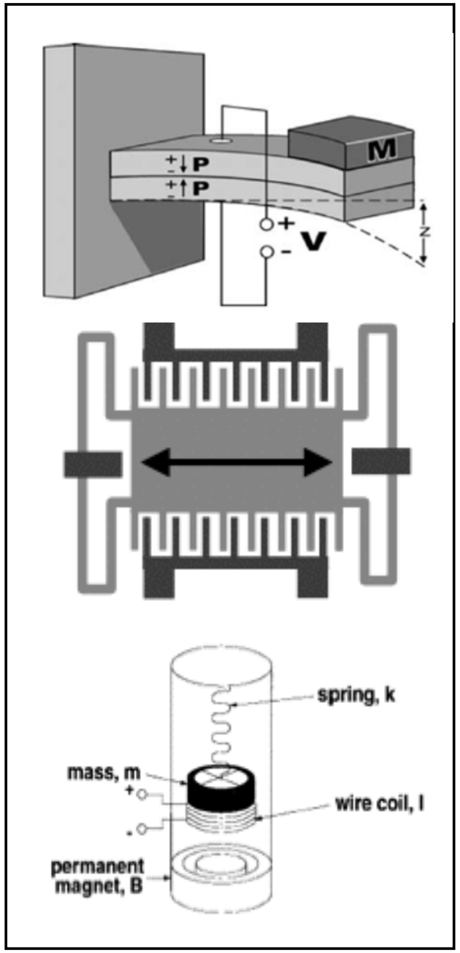
Vibrations energy harvesting

Transduction mechanisms

1. Piezoelectric: dynamical strain is converted into voltage difference.

2. Capacitive: geometrical variations induce voltage difference

3. Inductive: dynamical oscillations of magnets induce electric current in coils



Vibrations energy harvesting

1 Piezoelectric: dynamical strain is converted into voltage difference.

$$
\begin{cases}
m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \sigma\zeta_z \\[2ex]
\dot{V} = K_c\dot{x} - \dfrac{1}{\tau_p} V
\end{cases}
$$

The available power is proportional to V^2

Vibrations energy harvesting

1 Piezoelectric: dynamical strain is converted into voltage difference.

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

The Physics of piezo materials

K_c and K_v depends on **materials**

Vibrations energy harvesting

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

The oscillator dynamics

U(x) is the "elastic" potential mechanical energy of the oscillator

Vibrations energy harvesting

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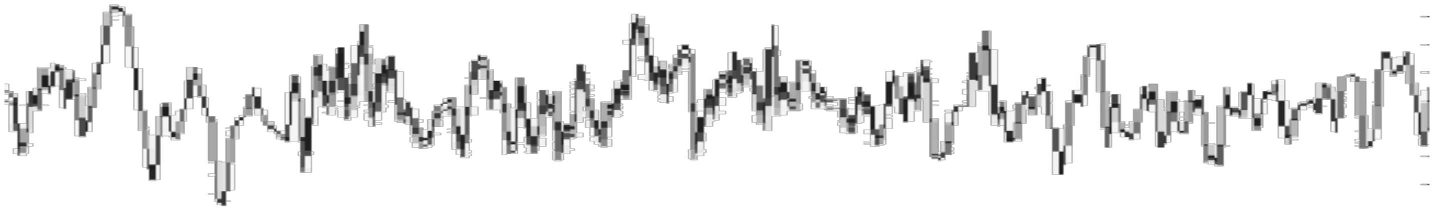
The environmental energy available

What are fluctuations and how can we harvest them ?

The random character of kinetic energy

ζ_z Represents the vibration (force)

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**.

Thus the challenge is to:

use the noise to power nano-scale devices aimed at Sensing/computing/acting and communicating.

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,…)

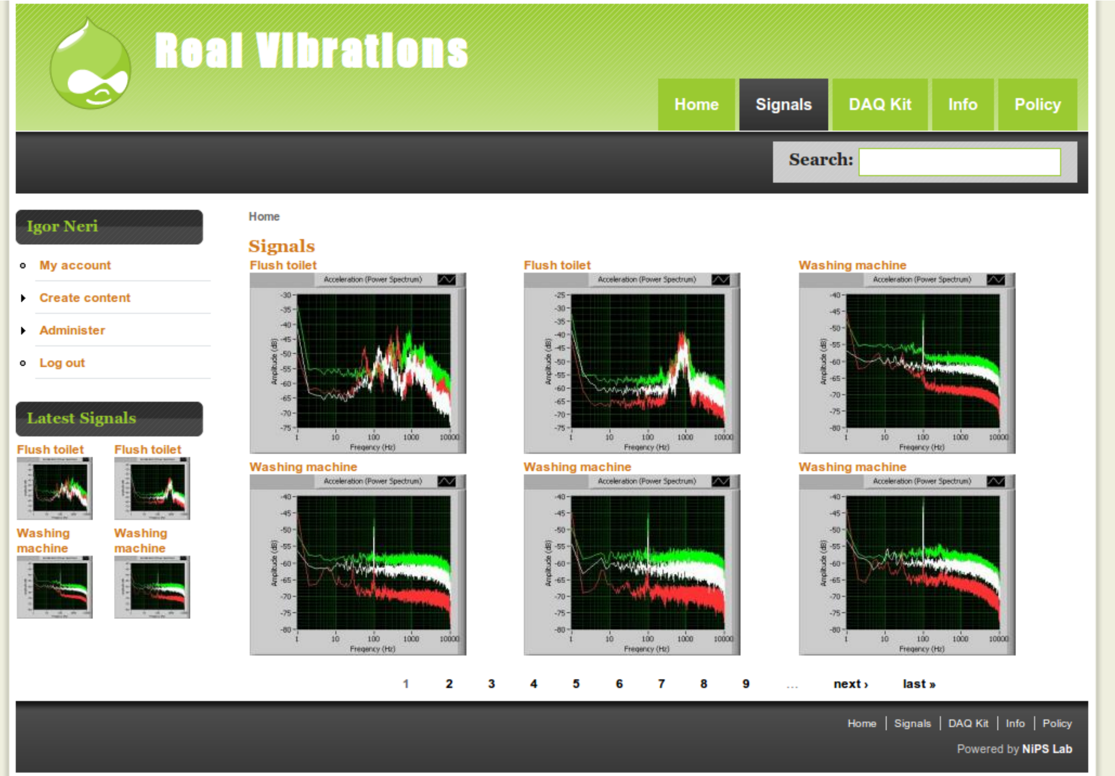
All different for intensity, spectrum, statistics

The random character of kinetic energy

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

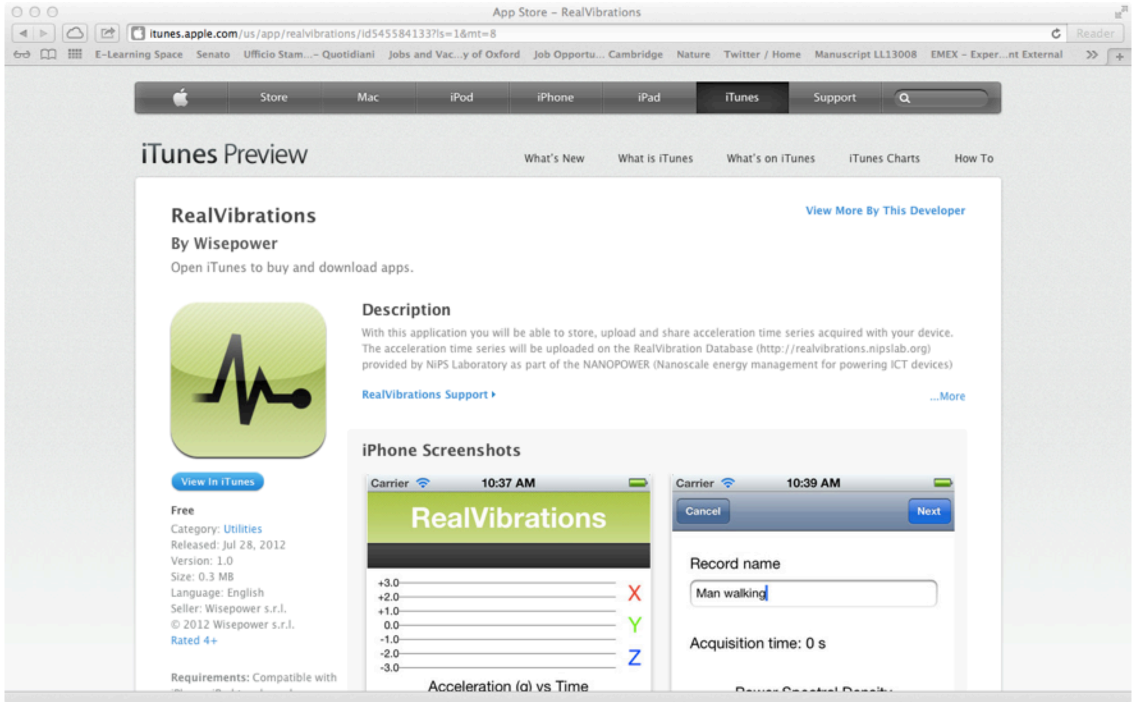
NiPS Laboratory
Noise in Physical Systems

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 on the App Store: **RealVibrations**

Vibrations energy harvesting

1. Piezoelectric: dynamical strain is converted into voltage difference.

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

The environmental energy available

Vibrations energy harvesting

U(x) is the "elastic" potential mechanical energy of the oscillator.
How does it look like?

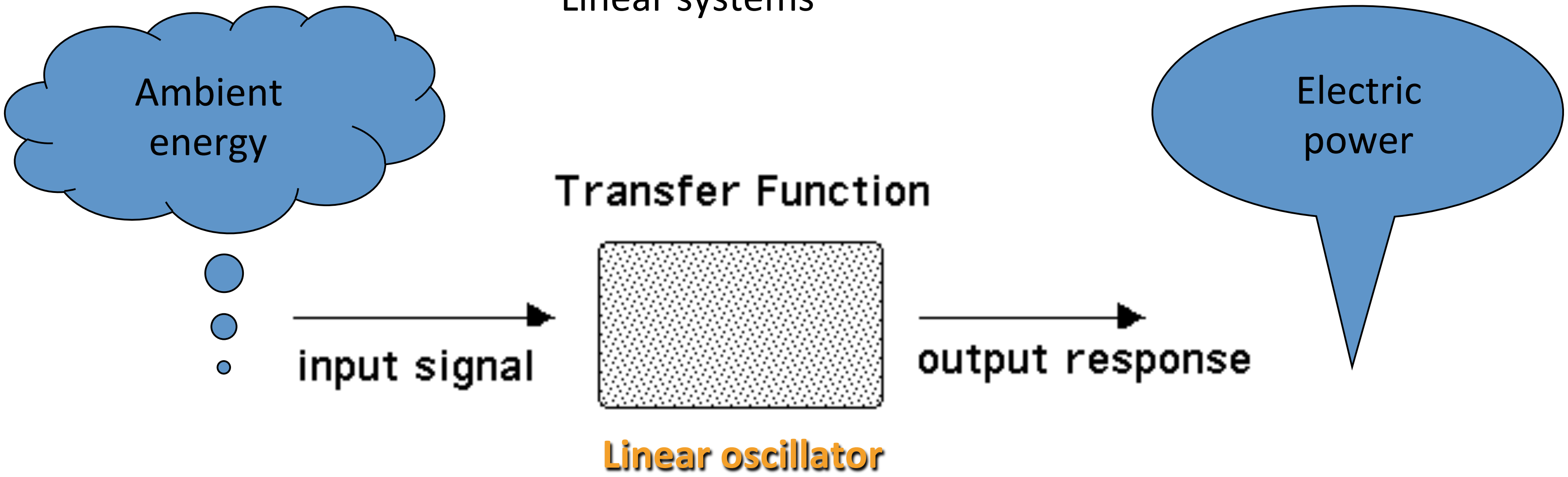
$$\begin{cases} m\ddot{x} = -\dfrac{dU(x)}{dx} - \gamma\dot{x} - K_V V + \zeta_z \\[2ex] \dot{V} = K_c\dot{x} - \dfrac{1}{\tau_p}V \end{cases}$$

The oscillator dynamics

If $U(x) = \frac{1}{2} Kx^2$ then we have a LINEAR SYSTEM

Vibrations energy harvesting

Linear systems



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…

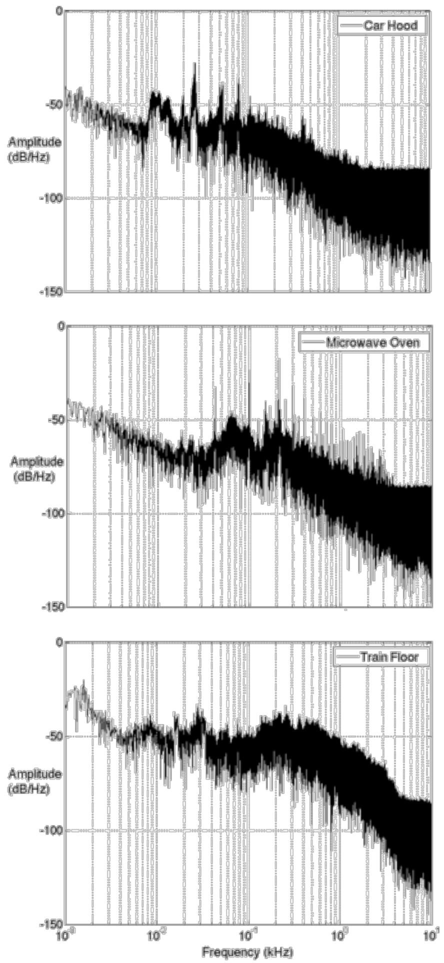
This is a serious limitation when you want to build a small energy harvesting system…

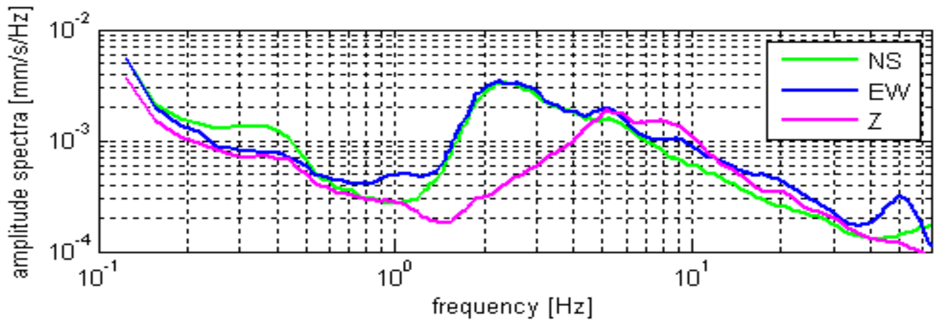
Vibrations energy harvesting

For two main reasons…

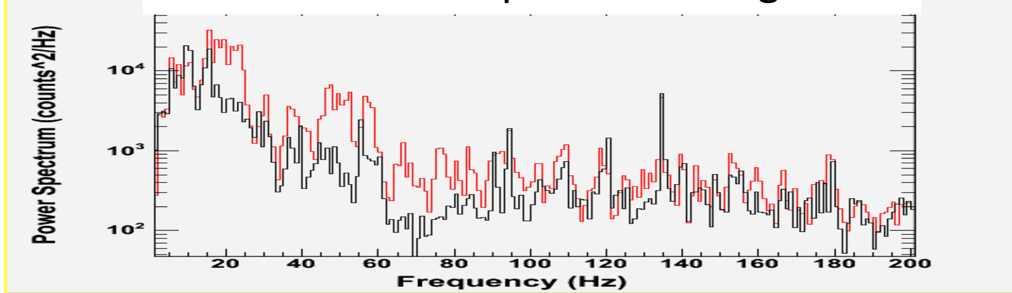
(1) the frequency spectrum of available vibrations instead of being sharply peaked at some frequency is usually very broad.

(2) The frequency spectrum of available vibrations is particularly rich in energy in the low frequency part… and it is very difficult, if not impossible, to build small low-frequency resonant systems…

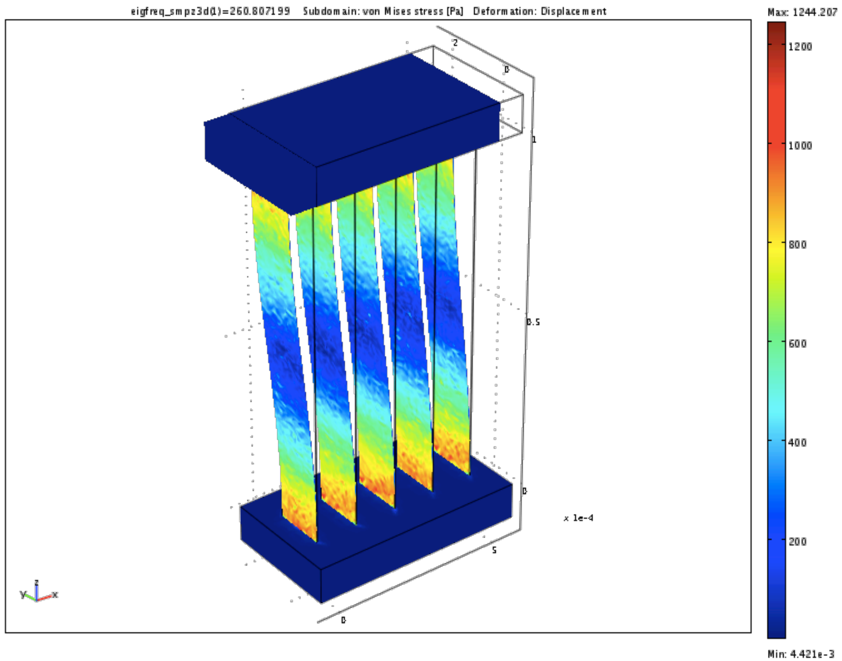




Acoustic noise – quiete working env.

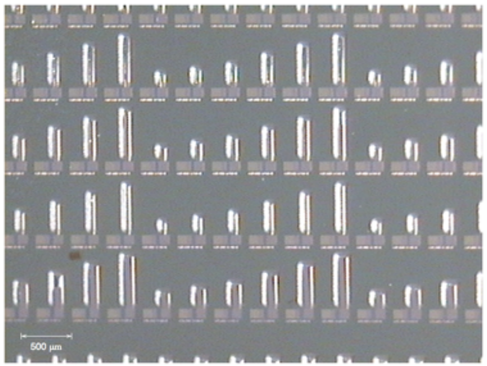


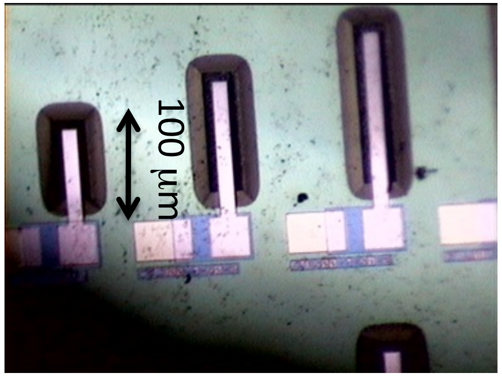
Micro energy harvesting system…

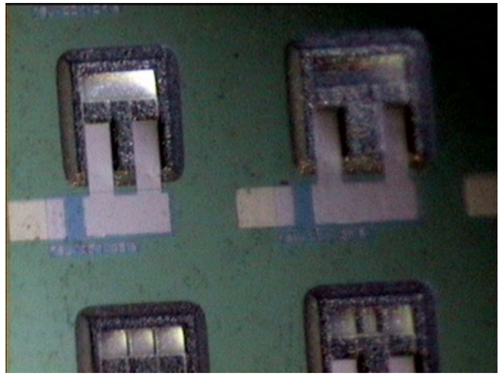


25 μm thick
1 mm high

Freq. 10 KHz







Collaboration with CEA-LETI Grenoble (FR)

Vibrations energy harvesting

Whish list for the perfect vibration harvester

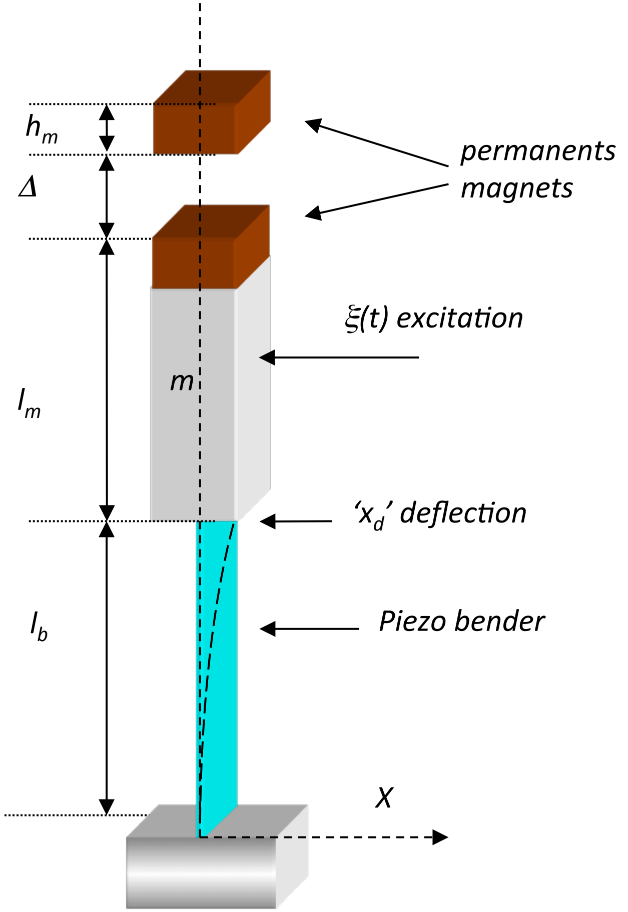
1) Capable of harvesting energy on a broad-band
2) No need for frequency tuning
3) Capable of harvesting energy at low frequency

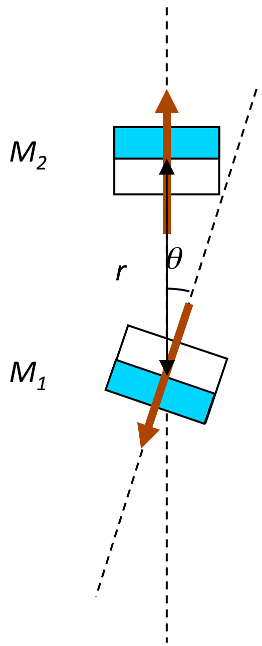
1) Non-resonant system
2) “Transfer function” with wide frequency resp.
3) Low frequency operated

Noise energy harvesting

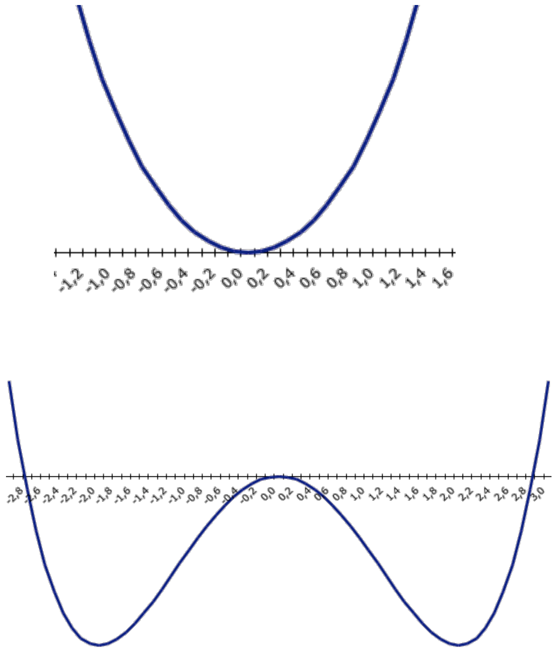
NON-Linear mechanical oscillators

NON-Linear Inverted pendulum



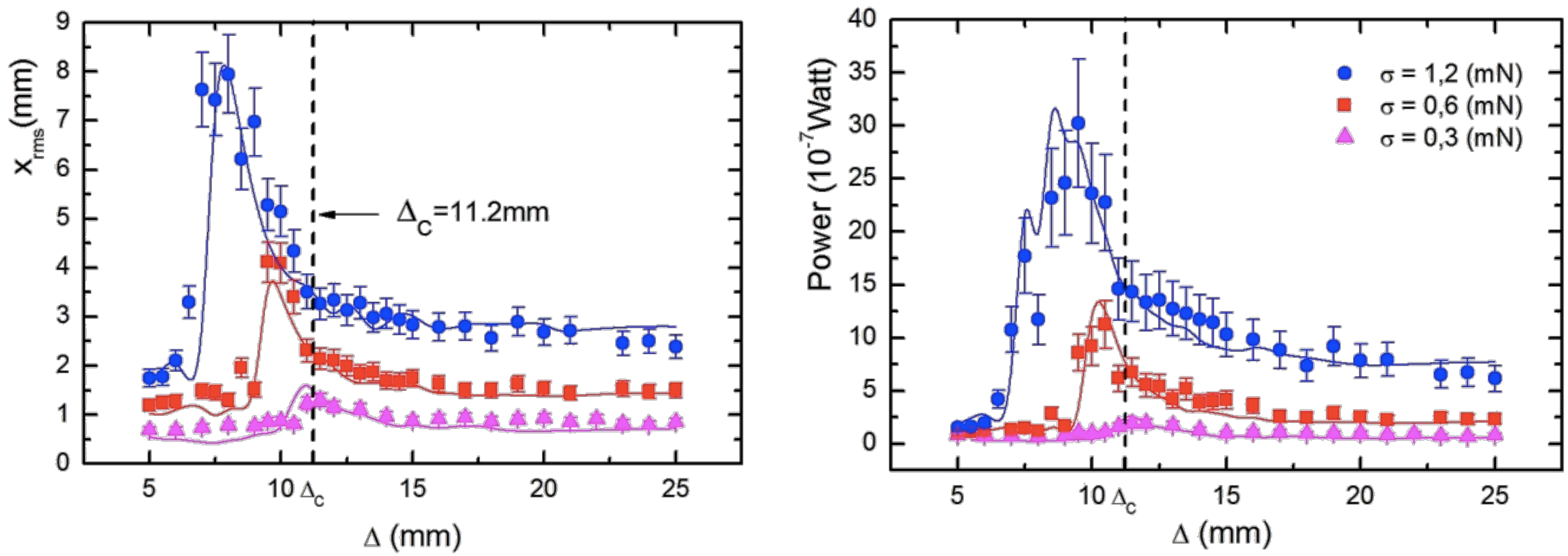


b)



Noises energy harvesting

NON-Linear mechanical oscillators



Nonlinear Energy Harvesting, F. Cottone; H. Vocca; L. Gammaitoni **Phys. Rev. Lett.**, 102, 080601 (2009)

ICT related initiatives funded by EC (coordinated by NiPS Lab)

NANOPOWER

-Univ. Wurzburg (Ger),
- ICN (Sp),
- VTT (Fi),
- Univ Geneva (Ch),
- Unicam (It)

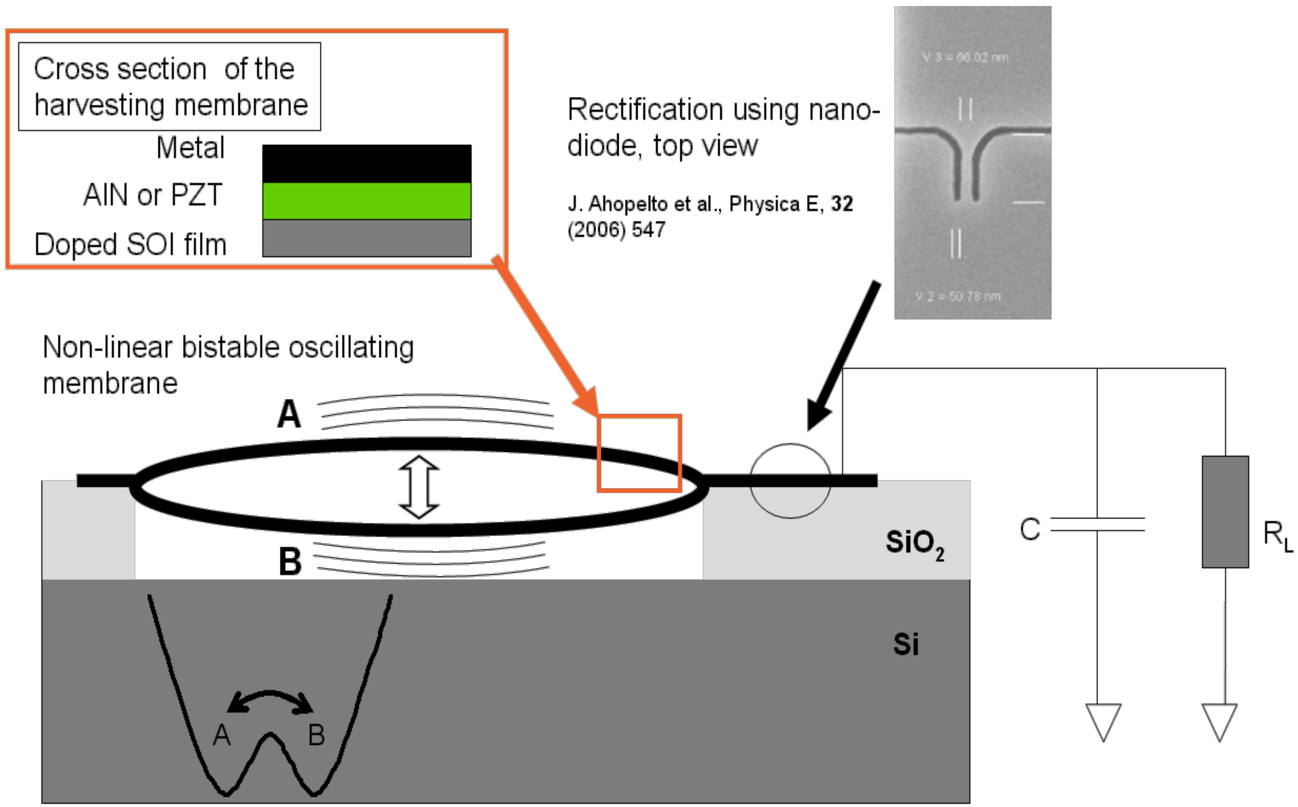
2.6 M€, 3 years, lead by NiPS
www.nanopwr.eu

ZEROPOWER

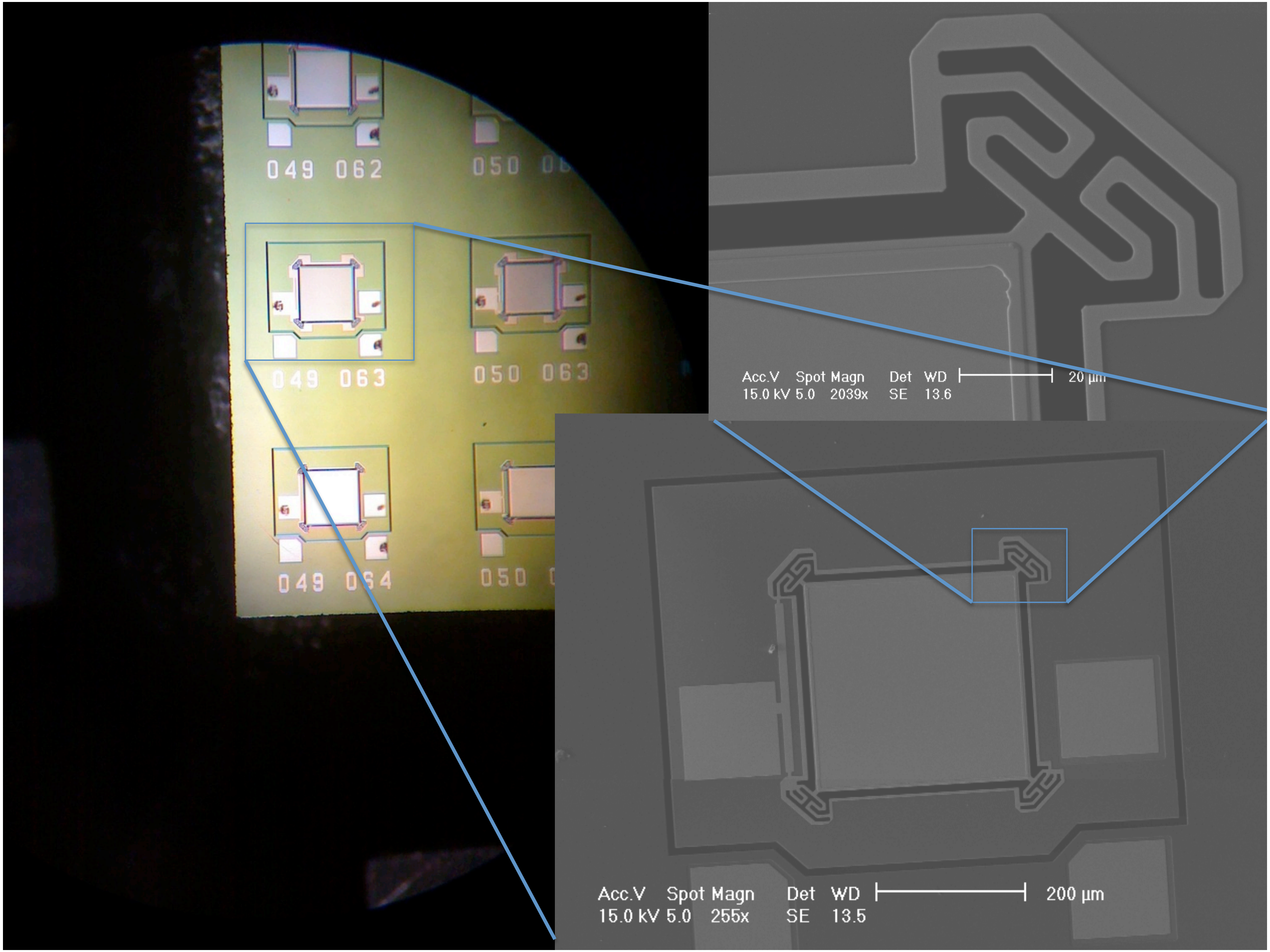
Coordinated Action – 2zeroP
UAC (Sp),
Tyndal (Ir),
Univ Glasgow (UK)
0.6 M€, 3 years, lead by NiPS
www.zero-power.eu

NANOPOWER

Nanomechanical nonlinear oscillators



Sketch of a multi-stable oscillator based on clamped membranes. The kinetic energy of the nonlinear vibration is converted into electric energy by either AlN or PZT membrane sandwiched between the electrodes. The voltage is then rectified by a nanodiode integrated to the SOI film


049 062
050
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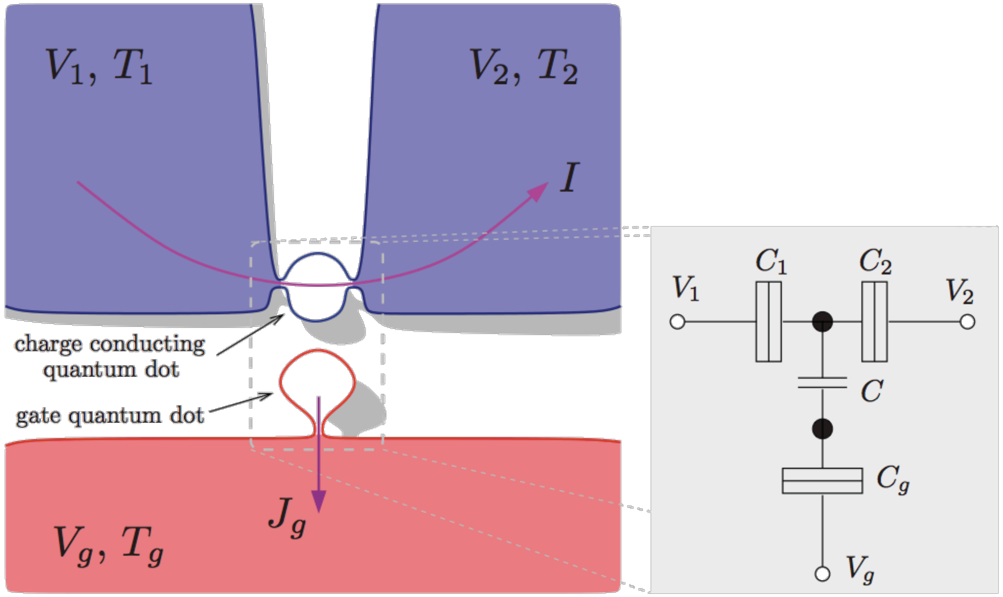
050 063
049 064
050
Acc.V Spot Magn Det WD 20 µm
15.0 kV 5.0 2039x SE 13.6
Acc.V Spot Magn Det WD 200 µm
15.0 kV 5.0 255x SE 13.5

NANO|POWER

Quantum Harvester



There is a relation between the charge current flowing through the two terminals of the conductor, and the heat current flowing through the gate terminal at temperature Tg > T.

What the Geneva group has found is that, in proper conditions, an electron that tunnels into the conductor quantum dot from left can only be transmitted to right after absorbing a quantized amount of energy from the gate. This process allows a heat-to-charge current conversion allowing the design of a new class of solid-state thermal-energy to current converters of high efficiency.

R. Sánchez and M. Büttiker, Phys. Rev. B 83, 085428 (2011)

The starting point

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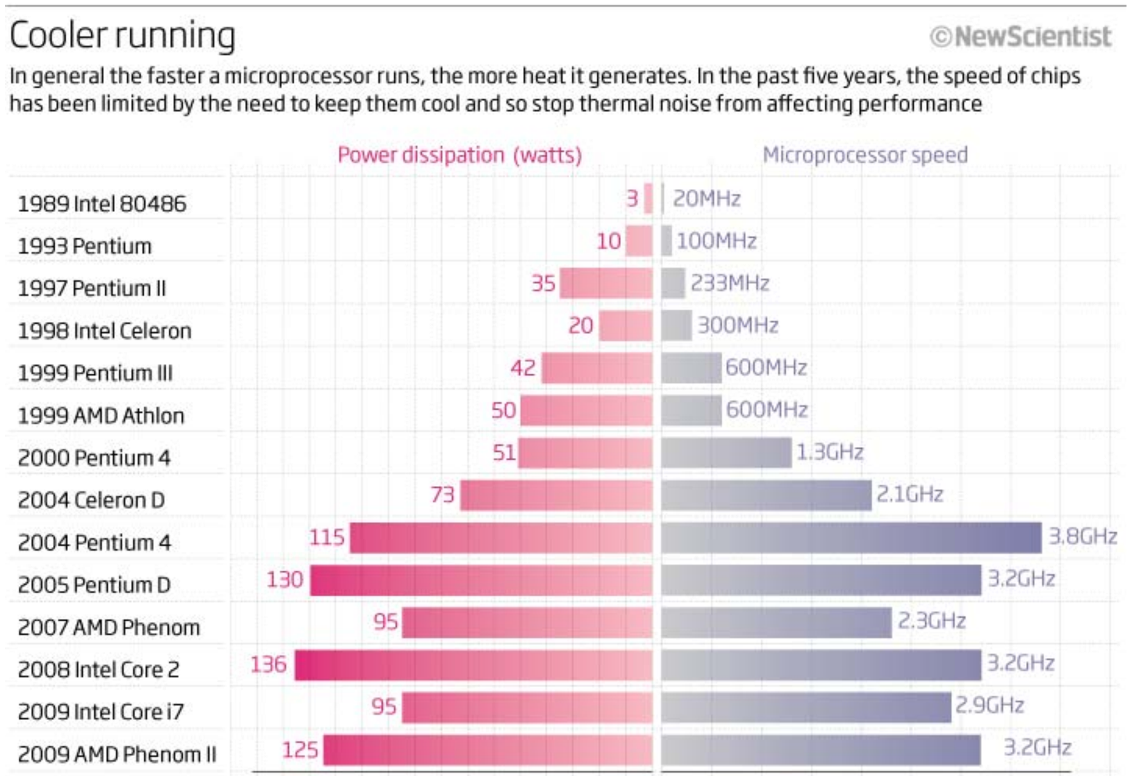
2) To deal with the problem of ENERGY EFFICIENCY in ICT

To date these two problems have been addressed only independently and by different communities

We will show that these tow problems sits on a common scientific background and thus can be addressed within a unified framework

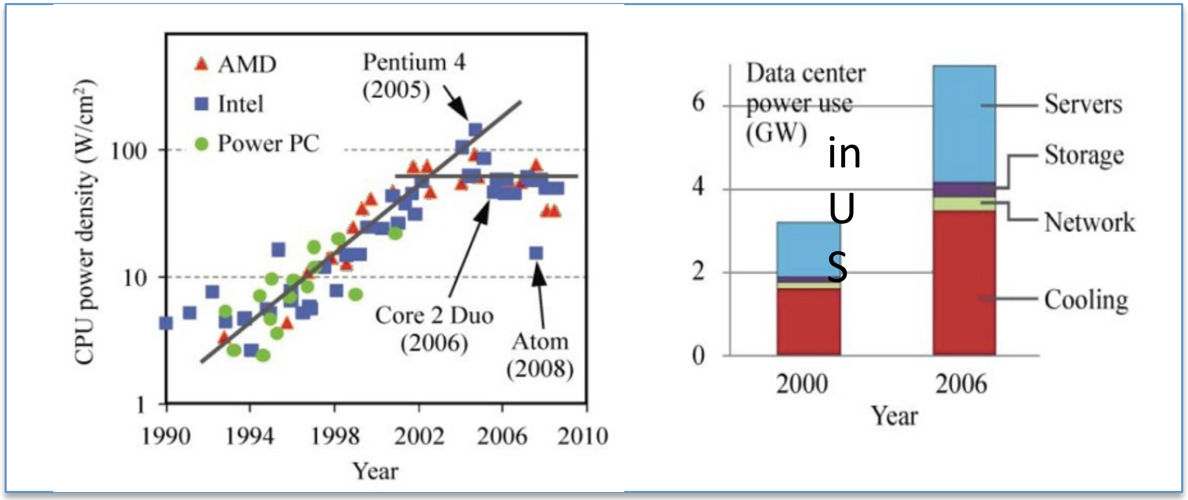
2) To deal with the problem of ENERGY EFFICIENCY in ICT

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

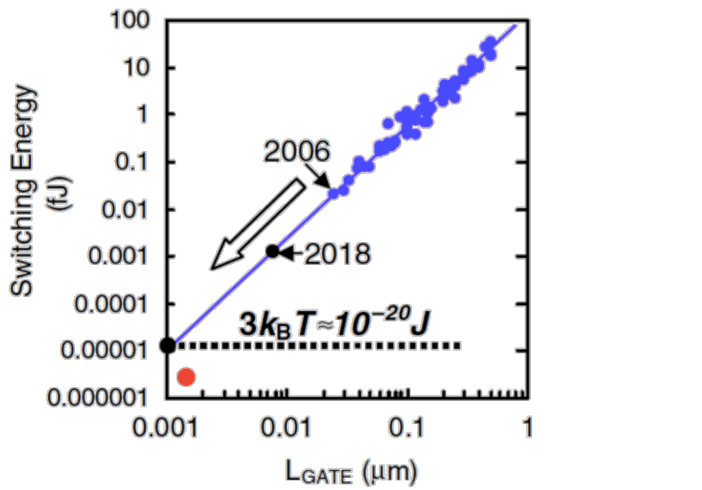


ICT - Energy

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



Research directions and challenges in nanoelectronics
R. K. Cavin1, V. V. Zhirnov, D. J. C. Herr1, Alba Avila and J. Hutchby, 2006

Present status

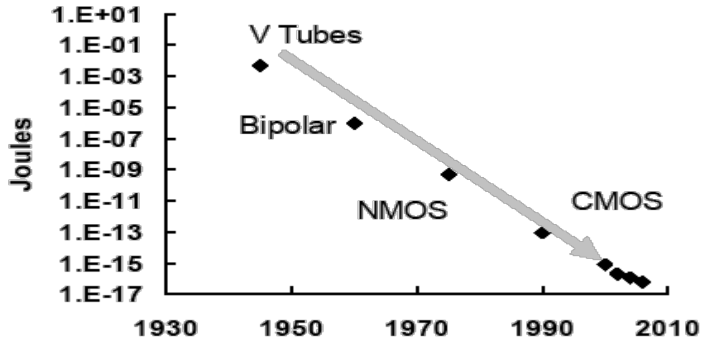


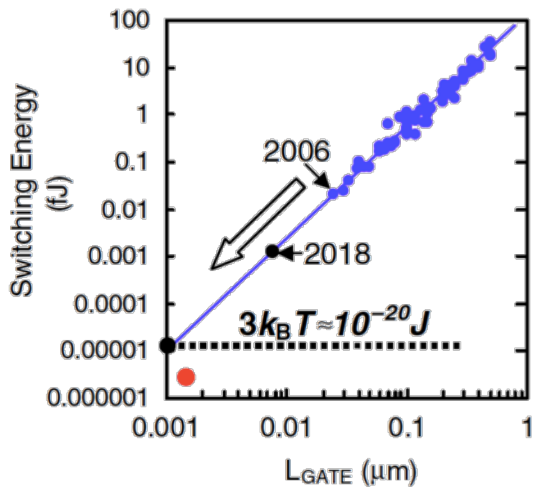
Figure 3: Energy per logic operation

Electronics Beyond Nano-scale CMOS, Shekhar Borkar

ICT - Energy

…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**



The search for alternative switches is presently very active*, however, even if a new information vector will be found that overcomes the limitation of charge driven FET switches a more fundamental energy limit stands in the path toward zero-power dissipation: the **Landauer**'s limit.

*To take on this grand challenge, the Nanoelectronics Research Initiative (NRI) (nri.src.org) was formed in 2004 as a consortium of Semiconductor Industry Association (SIA) (www.sia-online.org) companies to manage a university-based research program as part of the Semiconductor Research Corporation (SRC) (www.src.org). The NRI was founded by six U.S. semiconductor companies (AMD, Freescale, IBM, Intel, Micron, and TI), and partners with the National Science Foundation (NSF), the National Institute of Standards and Technology (NIST), and state governments, sponsoring research currently at 35 U.S. universities in 20 states.

Energy inpact of ICT is under discussion

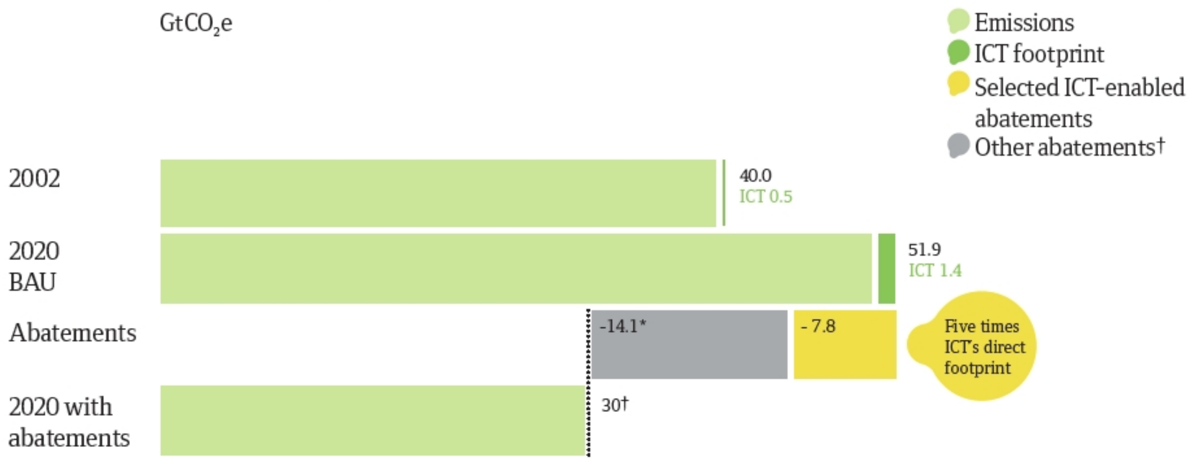
Objectives of the Consultation Workshop (Brussels, 8-9 February 2010**):**
Disruptive Solutions for Energy Efficient ICT

It will be **a clear future priority** world wide to decrease mankind's carbon footprint.

According to the SMART2020 study, the share of ICT on the world wide energy consumption today is in the range of 2-5%.

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, and **we must start to search for those ideas already now**.

Fig. 1 ICT impact: The global footprint and the enabling effect



* For example, avoided deforestation, wind power or biofuels.
† 21.9 $GtCO_2e$ abatements were identified in the McKinsey abatement cost curve and from estimates in this study. Source: Enkvist P., T. Naucler and J. Rosander (2007), *'A Cost Curve for Greenhouse Gas Reduction'*, The McKinsey Quarterly, Number 1.

http://cordis.europa.eu/fp7/ict/fet-proactive/docs/shapefetip-wp2011-12-10_en.pdf

1) To deal with the problem of PORTABLE POWER for Autonomous ICT Devices

2) To deal with the problem of ENERGY EFFICIENCY in ICT

What these two problems have in common?

They both sits on a common scientific ground:

Micro and nano scale energy management

Questions like:

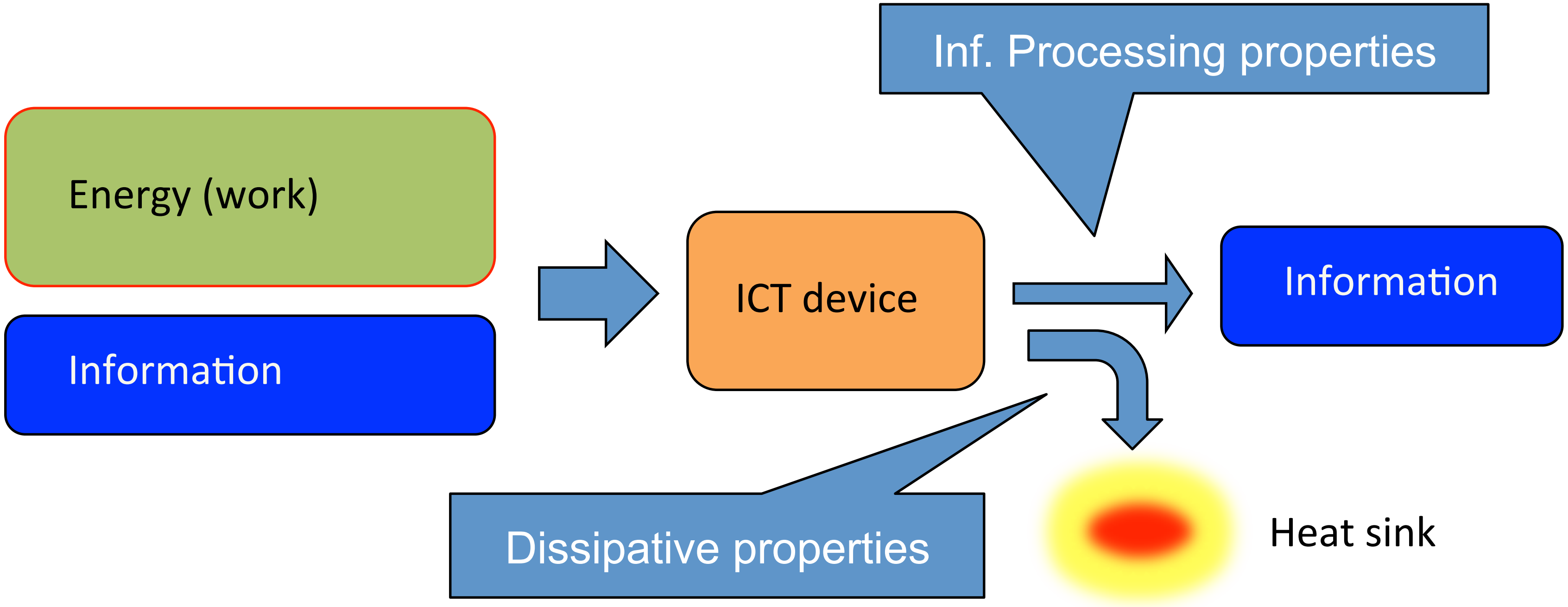
-How does electric energy get converted into heat at nanoscale
-How can we find an information transport solution that does not add to dissipation
-How can we harvest thermal vibrations to power nanoscale devices
-…

Could be asked and answered within this framwork.

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

How to turn problemS… INTO an opportunity

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.

Target Outcome / Expected Impact

The specific outcome of research in this area will cover the following results:

- the significant decrease of the power needed by the most common ICT devices
- an extension of the laws of thermodynamics to nanoscale systems
- a fundamental physics description of the processes related to heat dissipation
- the growth of a novel field related to phonon engineering for ICT applications
- the experimental realization of reversible logic gates
- the realization of *ICT in-body, ICT in-civil system and transport vehicles*

10 The expected impact in 10 years would be the growth of the bases for a **new technology** based on nanoscale devices that **harness thermal fluctuations and process information with reduced power**.

The energy efficiency issue: some more clues…

There are fundamental physics **ISSUES** that are relevant

1. Nanoscale thermodynamics *vs* macroscale thermodynamics

   Hill, Terrell, L., (2001). "Nanothermodynamics", *Nanoletters,* 1, 111, 273

2. Non-equilibrium statistical mechanics *vs* standard statistical mechanics

3. Linear dynamics *vs* Nonlinear dynamics

At the nanoscale, in fact, thermal fluctuations, negligible at higher scale, become the most relevant factor and non-equilibrium thermodynamics approaches are required as opposed to the traditional concepts based on equilibrium energy balances. *Non-equilibrium work relations,* mainly in the form of "fluctuation theorems", have shown to provide valuable information on the role of *non-equilibrium* fluctuations.

- Bustamante, C., Liphardt, J. and Ritort, F., *The nonequilibrium thermodynamics of small systems*, PHYSICS TODAY, 2005, 58, p.43-48.
- F. Ritort, *Work fluctuations, transient violations of the second law and free-energy recovery methods: Perspectives in Theory and Experiments*, Poincare Sem. 2 (2003) 193.
- Gallavotti G., Cohen E.G.D., *Dynamical ensembles in nonequilibrium statistical mechanics*, Phys Rev Lett, 2694 (1995).

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

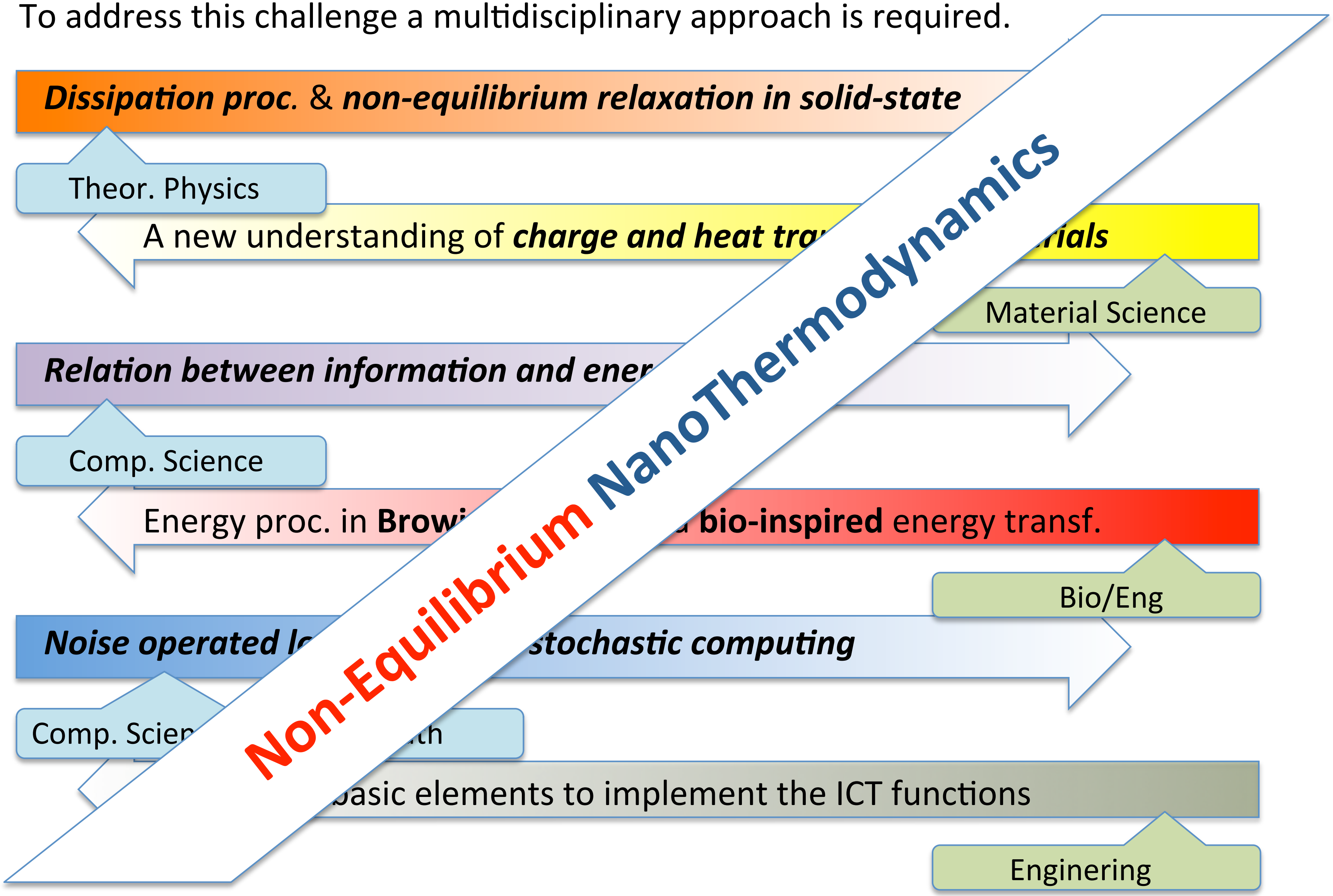
Information is physical !!!

CHALLENGE:

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

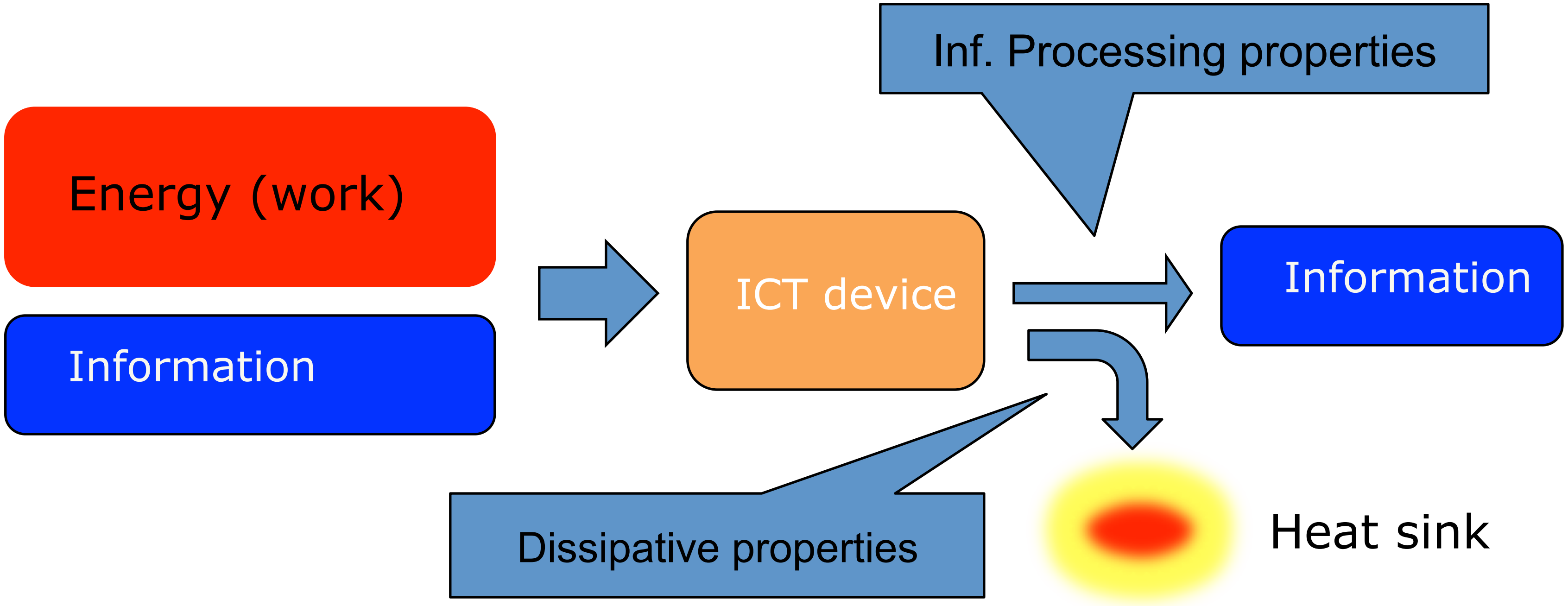
RESEARCH AGENDA

To address this challenge a multidisciplinary approach is required.



Key-point in our effort:
A general approach to ICT devices as micro/nano thermal machines

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, **however ...**

This is part of an ongoing effort at European level

- Jan 2008, Brussels. Expert Consultation on "Molecular-scale Information Systems"
- July 2009, Call FP7-ICT-2009-5 - ICT 2009.8.6 Towards Zero-Power ICT
- Feb 2010, Brussels. Consultation workshop on "Disruptive Solutions for Energy Efficient ICT"
- Aug.1st 2010 three project started (SiNAPS, GREEN SILICON, NANOPOWER)
- Jan 1st 2011 ZEROPOWER C.A. started
- 26 July 2011 FP7 CALL 8, ICT 9.8 FET Proactive: Minimising Energy Consumption of Computing to the Limit (MINECC) (deadline 17 January 2012)
- 12 Oct 2011 FET Proactive Information Day (MINECC) – Brussels
- 12 June 2012 MINECC Project coordination meeting – Brussels
- 1 Sept 2012 Starting of the 7 MINEC funded projects (Landauer, …)

NANOPOWER ZEROPOWER LANDAUER

and outside Europe…

- ONRG NiCOP Grant, in collab. with SPAWAR System Center, San Diego

With spin-off involvement:

- Wisepower srl, Fabro (TR), Italy
- Wisepower corp., Arcadia (CA), USA

Educational activities

2010

2011

2012

Summer School - 23-27 July 2012, Erice (Sicily)

Networking activity

ZEROPOWER

ZEROPOWER is aimed at creating a coordination activity among consortia involved in “Toward Zero-Power ICT” research projects (FET proactive call FP7-ICT-2009-5, Objective 8.6) and communities of scientists interested in energy harvesting and low power, energy efficient ICT.

NANOPOWER

NiPS Laboratory, Università degli Studi di Perugia, Italy
Julius-Maximilians Universität Würzburg, Würzburg, Germany
Valtion Teknillinen Tutkimuskeskus, VTT, Espoo, Finland
Catalan Institute of Nanotechnology, Bellaterra (Barcelona), Spain
Université de Genève, Genève, Switzerland
Universita degli Studi di Camerino, Camerino, Italy

Tyndall National Institute, University College Cork, Ireland
Institut für Photonische Technologien E.V., Jena, Germany
École Polytechnique Fédérale de Lausanne, Switzerland
Imperial College of Science, Technology and Medicine, London, U.K.
Aquamarijn Research B.V., Zutphen, The Netherlands

GREEN Silicon

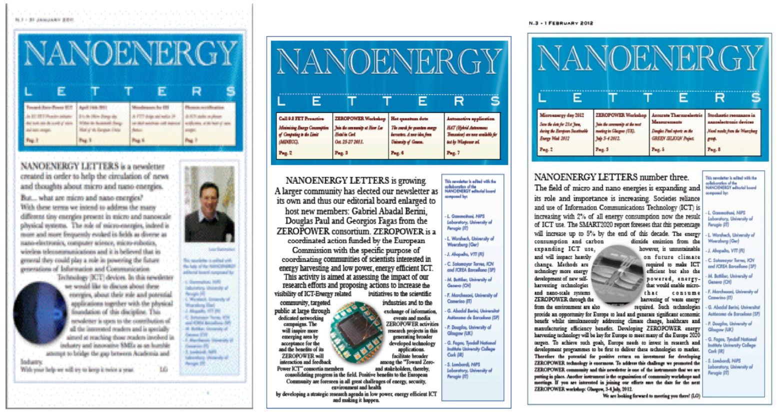
School of Engineering, University of Glasgow, U.K.
L-NESS, Politecnico di Milano, Como, Italy
Institute for Semiconductor and Solid State Physics, Universitaet Linz, Austria
Electron Microscopy, ETH Zürich, Switzerland

16 Groups

Communication is important !

Newsletter

www.nanoenergyletters.eu



A special section of the ZEROPOWER WEB site allows the registration for receiving a periodic Newsletter (NANOENERGY Letters) aimed at informing scientists and industrial players on advances related to ICT-Energy issues, together with scientific highlights from the research developed by the four consortia represented by the four partners of ZEROPOWER.

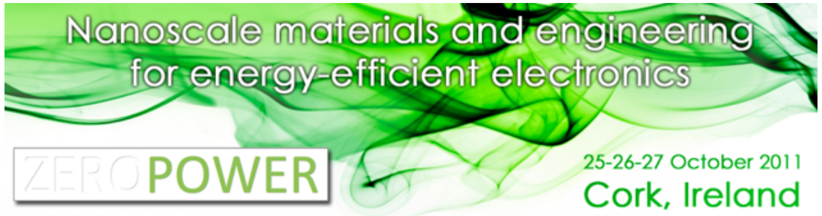
Download the IV issue (July 2012) at: www.nanoenergyletters.eu

Meeting is important !

We are bringing togheter a newly born community (2ZeroP) with a wider scientific and industrial (both pre-existing and novel) community.

ZEROPOWER workshop
The Community building is one of the important goals of the ZEROPOWER activity. In order to reach such a goal a number of action are planned and particularly there are 3 annual ZEROPOWER workshops planned during the project life time.

The first one was organized by Tyndall-UCC in Cork, Ireland from Tuesday 25th October to Thursday 27th October 2011.



ZEROPOWER Workshop - Glasgow, 3-4 July 2012

ZEROPOWER workshop

October 16-18 2012, Barcelona

Campus UAB, Bellaterra

Info on http://www.zero-power.eu

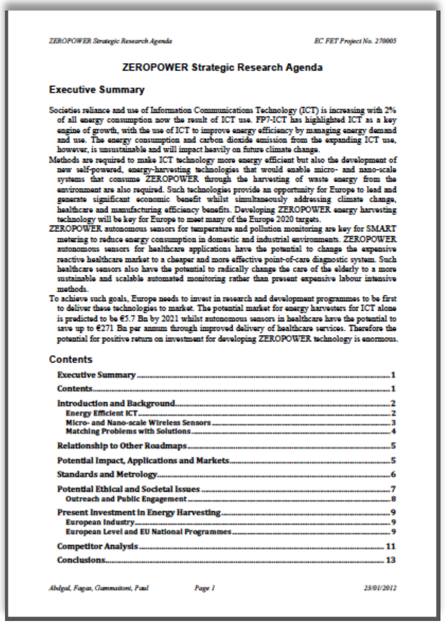
Looking ahed is important !

We are bringing togheter a newly born community (2ZeroP) with a wider scientific and industrial (both pre-existing and novel) community.

ZEROPOWER Research Agenda
A research agenda for “ICT-Energy” roadmapping, including strategic objectives, identification of research drivers and measures for assessment.

A first draft of the ZEROPOWER Research Agenda has been made publicly available via deliverable D3.1

on www.zero-power.eu


ZEROPOWER Strategic Research Agenda *EC FET Project No. 270005*

ZEROPOWER Strategic Research Agenda

Executive Summary

Societies reliance and use of Information Communications Technology (ICT) is increasing with 2% of all energy consumption now the result of ICT use. FP7-ICT has highlighted ICT as a key engine of growth, with the use of ICT to improve energy efficiency by managing energy demand and use. The energy consumption and carbon dioxide emission from the expanding ICT use, however, is unsustainable and will impact heavily on future climate change.

Methods are required to make ICT technology more energy efficient but also the development of new self-powered, energy-harvesting technologies that would enable micro- and nano-scale systems that consume ZEROPOWER through the harvesting of waste energy from the environment are also required. Such technologies provide an opportunity for Europe to lead and generate significant economic benefit whilst simultaneously addressing climate change, healthcare and manufacturing efficiency benefits. Developing ZEROPOWER energy harvesting technology will be key for Europe to meet many of the Europe 2020 targets.

ZEROPOWER autonomous sensors for temperature and pollution monitoring are key for SMART metering to reduce energy consumption in domestic and industrial environments. ZEROPOWER autonomous sensors for healthcare applications have the potential to change the expensive reactive healthcare market to a cheaper and more effective point-of-care diagnostic system. Such healthcare sensors also have the potential to radically change the care of the elderly to a more sustainable and scalable automated monitoring rather than present expensive labour intensive methods.

To achieve such goals, Europe needs to invest in research and development programmes to be first to deliver these technologies to market. The potential market for energy harvesters for ICT alone is predicted to be €5.7 Bn by 2021 whilst autonomous sensors in healthcare have the potential to save up to €271 Bn per annum through improved delivery of healthcare services. Therefore the potential for positive return on investment for developing ZEROPOWER technology is enormous.

Contents

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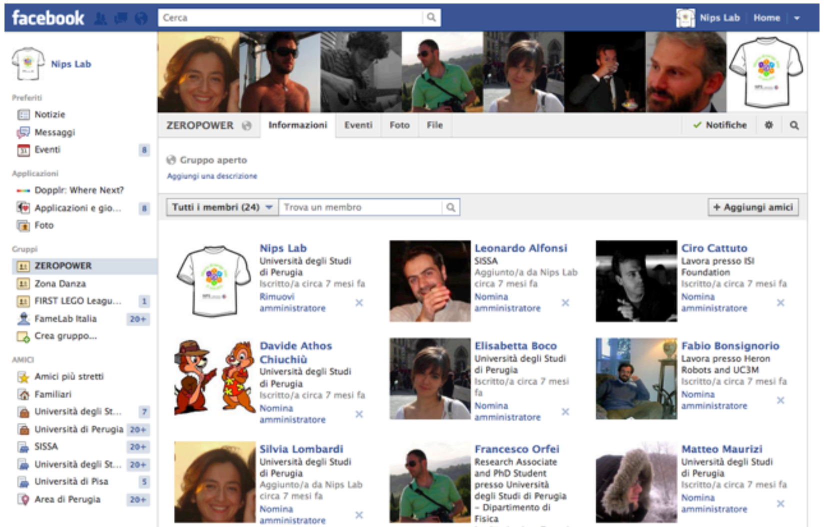
Outreach is important !

zero-power

@zeropower0

http://www.zero-power.eu



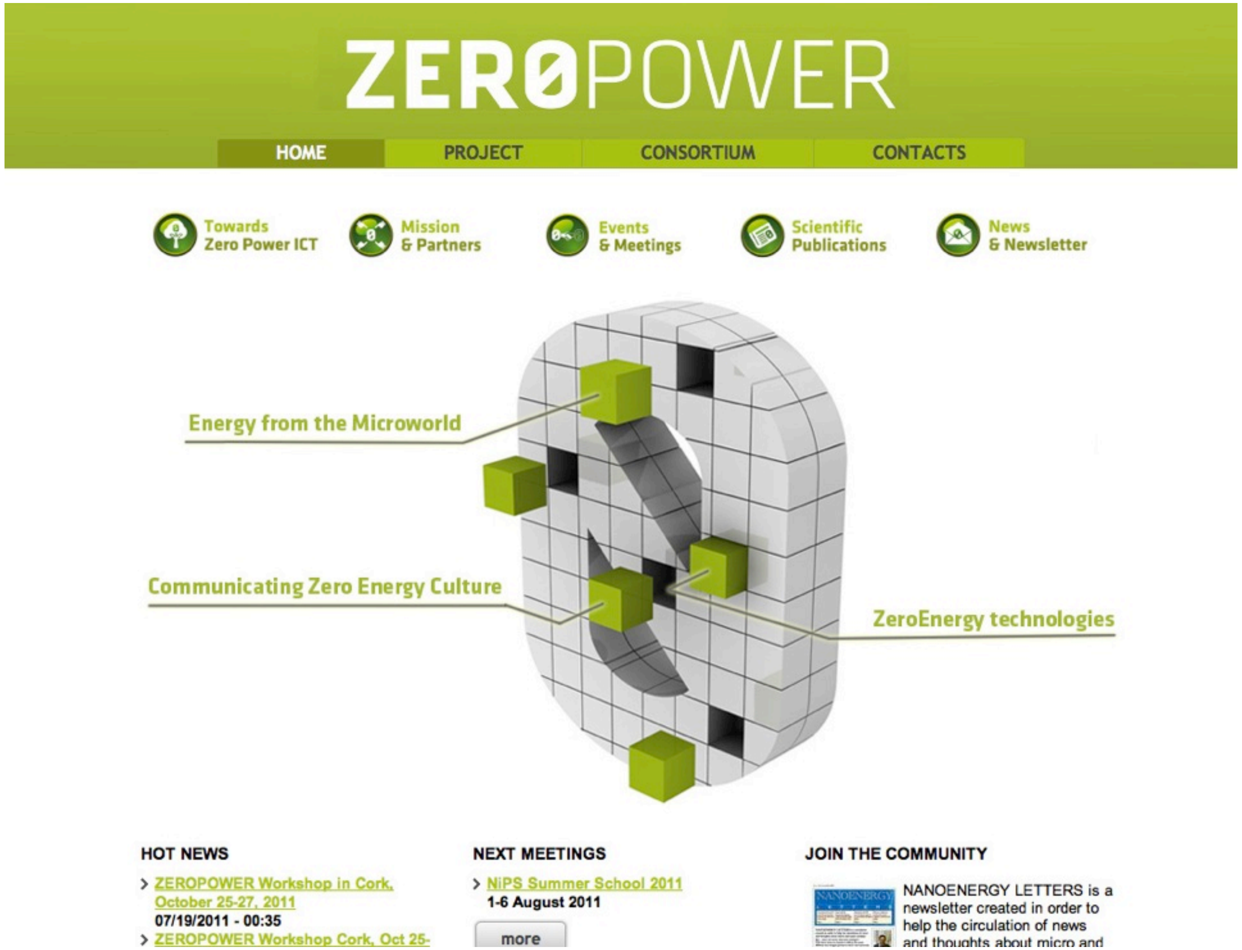
ZEROPOWER group

Outreach is important !

Micro-Energy Day

Info on: www.microenergyday.eu

Coomunication through web site: www.zero-power.eu



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- Gammaitoni L, Vocca H, Neri I, Travasso F, Orfei F. 2011. Vibration Energy Harvesting: Linear and Non Linear Oscillator Approaches. Sustainable Energy Harvesting Technologies - Past, Present and Future.
- Vocca H, Neri I, Travasso F, Gammaitoni L. 2012. Kinetic energy harvesting with bistable oscillators. Applied Energy.
- Gammaitoni L. 2012 There's plenty of energy at the bottom (micro and nano scale nonlinear noise harvesting). Contemporary Physics. :1-17.
- Gammaitoni L. 2012. Energy dissipation in small-scale shape-change dynamics. Physical Review E. 85

Assignement

The concept of 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.
How does this definition apply to micro and nanoscale devices?
What is the main limitation in its application at nanoscales?