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ICT-ENERGY

L E T T E R S

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Welcome to this special edition of ICT-Energy LETTERS, entirely devoted to the presentation of the short abstracts of the International Conference **Micro Energy 2017**. The ambition of this conference, that is part of a large event called "Gubbio Scienza" (Gubbio Science), is to bring together international scientists from academia, research centres and industry to discuss recent development in the topic of micro energy and its use for powering sensing and communicating devices. Here you find the short abstracts of the oral presentations, organized according to the four different sessions. Session I - Micro energy harvesting (Energy transformation processes at micro and nano scales, mathematical models, harvesting efficiency, thermoelectric, photovoltaic, electrostatic, electrodynamic, piezoelectric, harvesting in biological systems, novel concepts in energy harvesting). Session II - Micro energy dissipation (Noise and friction phenomena, fundamental limits in energy dissipation, Landauer bound, heat dissipation, thermodynamics of non-equilibrium systems, stochastic resonance and noise induced phenomena). Session III - Micro energy storage (High performance batteries, super capacitors, micro-fuel cells, non-conventional storage systems). Session IV - Micro energy use (Autonomous wireless sensors, zero-power computing, zero-power sensing, IoT, approximate computing, energy aware software, transient computing). (LG)

MICRO ENERGY 2017

Gubbio (IT) – July 4 - 7, 2017

Conference program

3 Jul. Mon

18.00 Welcome cocktail

4 Jul. Tue *Session I – Micro Energy Harvesting*

09:00 – 09:30	E. Yeatman (Imperial College)
09:30 – 10:00	D. Galayko (UPMC)
10.00 – 10:30	F. Cottone (NiPS Lab)
10:30 – 11:00	C. Rusu (ACREO)
11:00 – 11:30	*Coffee break*
11:30 – 12:00	R. R. Deza (Univ. Mar del Plata)
12:00 – 12:30	D. Mallick (Tyndall)
12:30 – 13:00	Talk from EC representative (FET Unit)
13:00 – 14:30	*Lunch*
14.30 – 15:00	t.b.a.
15.00 – 15:30	V. Bottarel (STMicroelectronics)
15.30 – 16:00	P. Farber (IMH)
16.00 – 16:30	*Coffee break*
16.30 – 17:00	L. Catacuzzeno (UNIPG)
17.00 – 17:30	A. Pattanayak (Carleton College)
17.30 – 18:00	A. Pasharavesh (Univ. Shariff)

5 Jul. Wed *Session II – Micro Energy Dissipation*

09:00 – 09:30	A. Bachtold (ICFO)
09:30 – 10:00	D. Lopez (UPMC)
10.00 – 10:30	I. Neri (NiPS Lab)
10:30 – 11:00	S. Ciliberto (Univ. Lyon)
11:00 – 11:30	*Coffee break*
11:30 – 12:00	N. Anderson (Univ. Massachusetts)
12:00 – 12:30	I. Ercan (Univ. Bogazici)
12:30 – 13:00	E. Lutz (Univ. Erlangen-Nurnberg)
13:00 – 14:30	*Lunch*

14.30 – 15:00	M. Esposito (Univ. Luxemburg)
15.00 – 15:30	A. Vulpiani (Univ. La Sapienza)
15.30 – 16:00	H. Wio (Univ. Cantabria)
16:00 – 16:30	*Coffee break*
16.30 – 17:00	M.C. Diamantini (NiPS Lab)
17.00 – 17:30	F. Marchesoni (Univ. Camerino)
17.30 – 18:00	M. Lopez-Suarez (NiPS Lab)

6 jul. Thu

09:00 – 09:30	M. Jack (Univ. Otago)
09:30 – 10:00	D. Chiuchiù (NiPS Lab)
10.00 – 10:30	N. Ganesh (Univ. Massachusetts)
10:30 – 11:00	t.b.a.
11:00 – 11:30	*Coffee break*

Session III – Micro Energy Storage

11:30 – 12:00	V. Zhirnov (SRC)
12:00 – 12:30	I. Rossetti (Univ. Milano)
12:30 – 13:00	t.b.a
13:00 – 14:30	*Lunch*
15.00 – 17.00	*Poster Session*
17:30 – 18:30	Piazza Grande: excursion with *sightseeing train*
18:30 – 19:30	Palazzo dei Consoli: visit and lecture on the *Iguvine Tablets*
19:30	Crescia con prosciutto (traditional meal)

7 Jul. Fri *Session IV – Micro Energy Use*

09:00 – 9:30	F. Gonzalez-Zalba (Hitachi Cambridge)
09:30 – 10:00	Gaël Pillonnet (CEA Leti)
10.00 – 10:30	R. Canegallo (STMicroelectronics)
10:30 – 11:00	M. Madami (UNIPG)
11:00 – 11:30	*Coffee break*
11:30 – 12:00	A. Ionescu (EPFL)
12:00 – 12:30	S. Houri (TU Delft)
12:30 – 13:00	F. Ambroglini (Wisepower)
13:00 – 14:30	*Lunch*
14.30 – 15:00	A. Bogliolo (Univ. Urbino)
15.00 – 15:30	K. Takeuchi (NTT)
15.30 – 16:00	P. Gentili (UNIPG)
16:00 – 16:30	*Coffee break*
16.30 – 17:00	L. Benini (ETHZ)
17.00 – 17:30	F. Orfei (NiPS Lab)
17.30 – 18:00	t.b.a.
20.00	*Banquet & Special event*

MICRO ENERGY 2017

Gubbio (IT) – July 4 - 7, 2017

Abstracts

Session I: Micro Energy Harvesting

Mechanical resonators based on graphene

Adrian Bachtold
ICFO

When a graphene layer is suspended over a circular hole, the graphene vibrates as a music drum. However, such a graphene drum has an extremely small mass. Another difference is the quality factor Q, which becomes extremely large in graphene resonators at cryogenic temperature (Q above 1 million). Because of this combination of low mass and high quality factor, the motion is enormously sensitive to external forces.

Here, we couple the graphene resonator to a superconducting cavity via the radiation pressure interaction. The superconducting cavity allows us to transduce the graphene motion with unprecedented sensitivity. We sideband cool the graphene motion to an average phonon occupation that approaches the quantum ground-state.

We show that the graphene resonator is a fantastic force sensor with a sensitivity approaching the fundamental limit imposed by thermo-mechanical noise. We find that energy decays in a way that has thus far never been observed nor predicted. As the energy of a vibrational mode freely decays, the rate of energy decay switches abruptly to lower values, in stark contrast to what happens in the paradigm of a system directly coupled to an environmental bath. Our finding is related to the hybridization of the measured mode with other modes of the resonator. Our work opens up new possibilities to manipulate vibrational states, engineer hybrid states with mechanical modes at completely different frequencies, and to study the collective motion of this highly tunable system.

Analog Front End for Efficient Energy Harvesting from Piezoelectric Transducer

Valeria Bottarel
STMicroelectronics

This work describes an Analog Front End for Efficient Harvesting. In addition to the description of the energy harvesting frontend circuitry for piezoelectric transducer, some autonomous systems peculiar functionalities are presented. The system includes: low quiescent current voltage regulator, transducer energy detector that keeps the front end from dissipating when no energy is available to be harvested, and lithium battery charger functionality, in addition to the storage capacitance charging circuit for battery-less systems.

For what concerns harvesting circuit, the base idea is that if the electronics applies a low frequency â€“ dc condition to the piezoelectric material, it interferes on the deformation of the piezoelectric material, actuating it. The presented frontend circuit allows piezoelectric deformation in open circuit condition and detects the maximum deflection point. It operates during the piezoelectric voltage peak, by short-circuiting the piezoelectric material output capacitance C with an external inductance L. The energy transfer occurs as a resonant LC transfer at sufficiently high electronic frequency, such that the electronic behavior cannot actuate the piezoelectric material due to mechanical inertia. After the energy transfer, the piezoelectric cantilever is left with the maximum mechanical deformation, but without any charge on it.

This condition is a sort of pre-charge that allows for doubled voltage peak in the subsequent deformation. Alternatively, it is possible to harvest both negative and positive peaks through a full bridge. When the energy transfer is completed, the front-end circuit opens the LC ring and the inductor current flows through a diode to a storage element. Thus, the current on the inductance is transformed again, and stored as charge on a capacitance.

The current-output of this step-up converter front-end also allows the harvested voltage to be higher than the peak on the transducer.

Energy harvesting from electrically polarized biological cells: a theoretical study

Luigi Catacuzzeno
University of Perugia

Microenergy harvesting has lately been attracting special attention in the field of human implantable biomedical microdevices. Currently, these devices are powered by batteries, with the concern of limited lifetime, side effects, large size. Investigation is therefore presently strong in developing methods to harvest energy for implantable devices directly from the ambient environment. Energies that are today more commonly considered include thermal energy (human heat), kinetic energy (body motion), chemical reaction energy. Here we propose scavenging energy from the electric field (potential difference) existing across excitable cell membranes, and present a theoretical study to predict the amount of energy that can be scavenged from this source.

By modeling a biological cell membrane as an RC electrical circuit, we simulated the power that can be generated by a model cell incorporating the ion channels and transporters typical of a hippocampal neuron.

The model cell included Na+, K+ and Cl--selective ion channels as the pathways for passive ion fluxes, and the Na+/K+ pump that actively (using high-energy ATP) moves Na+ and K+ ions in opposite directions across the membrane against their electrochemical potential, to maintain the transmembrane ionic gradients. In order to assess the feasibility of using a biological cell to provide electrical power, we connected the intracellular side of the cell to a variable resistance, and calculated the power produced as the product of the current flowing through the resistance, and the potential difference maintained by the cell at steady-state. Our model indicates that the cell absorbs a chemical power of about 50 pW to fuel all the Na+/K+ ATPases, while only 1 pW is made available as current passing through the implanted resistance, resulting in a chemical to electrical energy conversion efficiency of about 2%. Notably, we found that the power produced by the model cell can be sensibly increased using human skeletal muscle cells which have a much higher number of ion channels and transporters and larger cell dimensions than most neurons, and are optimized to store and use chemical energy needed for movement.

Our simulations indicate that the Na+/K+ ATPases contained in a single skeletal muscle cell absorb a power of about 70 nW for their activity, and can give back to a connected device a power of about 5 nW, with a conversion efficiency of about 7%.

In conclusion, our simulations suggest that skeletal muscle cells can generate an amount of power sufficient to fuel currently available integrated microcircuits, and may thus represent a possible source of energy for future human implantable microsystems.

Micro-scale energy harvesting systems and materials

Francesco Cottone
NiPS Laboratory, University of Perugia

The development and proliferation of wireless sensors networks and smart electronics is being slowed down by the problem of energy autonomy.

In order to address this issue, both academic and industry efforts are recently growing in the quest for more efficient low-power electronics from one side and energy harvesting systems from the other.

In particular, the possibility of capturing energy directly from the ambient will enable a scenario of perpetual maintenance-free devices for future wireless technologies, such as Internet-of-Things. In this regard, mechanical energy is one of the most abundant and otherwise wasted energy source. However, one of the main technological challenge is the miniaturization of vibrational generators. In this talk, some recent developments with examples of innovative piezoelectric and electrostatic micro-systems and materials will be illustrated.

Enhancing energy harvesting by coupling monostable oscillators

Roberto Raul Deza
IFIMAR (Mar del Plata U. and CONICET, Argentina)
H.S. Wio[1], J.I. Peña Rosselló[2], R.R. Deza[2] and P. Hänggi[3]

The performance of a ring of linearly coupled, monostable nonlinear oscillators is optimized towards its goal of acting as energy harvester---through piezoelectric transduction---of mesoscopic fluctuations, which are modeled as Ornstein--Uhlenbeck noises. For a single oscillator, the maximum output voltage and overall efficiency are attained for a soft piecewise-linear potential (providing a weak attractive constant force) but they are still fairly large for a harmonic potential. When several harmonic springs are linearly and bidirectionally coupled to form a ring, it is found that counter-phase coupling can largely improve the performance while in-phase coupling worsens it. Moreover, it turns out that few (two or three) coupled units perform better than more. Finally, we discuss some possible alternative schemes.

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Progress in Computational Fluid Dynamics Simulation of a Microbial Fuel Cell

Peter Farber
University of Otago
P. Farber, J. Grabel, N. Kroppen, L. Potschke, M. Rosenbaum, D. Roos, J. Steffens, P. Ueberholz

Commercial Computational Fluid Dynamics (CFD) codes offer a great flexibility to model complex 3D geometries. They have many physical models on board, nevertheless bioelectrochemical reactions in a Microbial Fuel Cell (MFC) are not included.

In this talk, we discuss the extension of Ansys Fluent commercial CFD code to simulate a bioelectrochemical model of an anode in a microliter sized MFC. The biofilm on the anode is a mixed culture enriched with the electroactive model organism Geobacter sulfurreducens and is treated as a conductive material. Besides the stationary 3D Navier-Stokes equation for fluid flow and the species balance equation for acetate in the water and in the biofilm, the model consists of a model for the species mass fraction of acetate at the boundary between water and biofilm. Furthermore, we added a sink for acetate as a source for electrons and a stationary electric charge density balance equation in the biofilm.

Using this extended commercial CFD code allowed the model to analyse the bioelectrochemical conversion of acetate and current production in a microliter sized MFC.

Near-limits electrostatic kinetic energy harvesting from arbitrary input vibrations

Armine Karami, Dimitri Galayko
UPMC, Paris

Kinetic energy harvesting (KEH) is viewed as a potential candidate to complement or replace batteries as power supplies for autonomous microsystems. In some applications, the system is submitted to external vibrations from its environment, which at its scale constitute a large reserve of energy. KEH is interested in the conception of microsystems allowing to convert part of this energy in electrical energy.

For about fifteen years, the research community on KEH has explored different techniques so as to implement such systems. Among these techniques, the electrostatic transduction mechanism has major advantages, such as compatibility with batch fabrication processes. However, electrostatic KEHs present some challenges with regard to their optimization and to the systematization of their conception. These challenges are linked with the complexity of the electrical interfaces required to optimize the conversion, combined with the nonlinear dynamics inherent to electrostatic KEH.

In this talk, we formally pose the problem kinetic energy harvesting from arbitrary types of external vibration inputs, with performances approaching the physical limits. On this subject, we present the control problems arising from the design of such near-limits kinetic energy harvesters. We then show some early results on the conception of such kinetic energy harvesters, using the electrostatic transduction mechanism.

In particular, the electrical interfaces needed to implement the needed controls, and their impact on the system's performances, are discussed. We finish by discussing, as directions for future research, how more sophisticated controls as well as techniques coming from data science can possibly enhance the system's performances.

Irreversibility and Dissipation in General Finite State Automata

Natesh Ganesh
University of Massachusetts, Amherst

Irreversibility and dissipation for a broad range of finite-state automata (FSA) are considered from a physical-information-theoretic perspective.

A quantitative measure for the computational irreversibility of finite state automata is introduced, and a fundamental lower bound on the average energy dissipated per state transition is obtained.

The irreversibility measure and energy bound are applicable to any realization of an automaton that registers abstract FSA states in states of a physical system coupled to a thermal environment, and that evolves via a sequence of interactions with an external system holding a physical instantiation of a random input string. The energy bounds, which follow from quantum dynamics and entropic inequalities alone, can be regarded as generalizations of LandauerÊ¼s Principle applicable to FSAs and tailorable to specified automata. Results for various cases are summarized and illustrated with simple examples.

This work fully generalizes our earlier results (Phys. Lett. A 377, 3266 (2013)), which applied specifically to deterministic, irreducible automata.

Analytical and numerical simulations of energy harvesting using MEMS devices operating in nonlinear regime

Abdolreza Pasharavesh
Department of Mechanical Engineering, Sharif University of Technology

While macro-scale piezoelectric generators require base excitations with moderately large amplitudes to transit from the linear regime of vibration to the nonlinear one, for a MEMS harvester due to its small dimensions, this transition can occur at oscillatory base motions even smaller than a few microns, which necessitates the nonlinear analysis of MEMS harvesting devices in most environments.

In this paper the coupled electromechanical behavior of a typical MEMS-based piezoelectric harvester in the nonlinear regime is investigated. Lagrangeâ€™s equations are used in accordance to the assumed mode method to extract the coupled nonlinear equations of motion governing the lateral deflection and output voltage. An analytical solution to the derived equations is performed employing the perturbation method of multiple scales providing the nonlinear frequency responses of the output power.

Results indicate that although the effect of nonlinear inertia increases due to utilizing large tip masses in these harvesters, nonlinear curvature is still the dominant effect leading to hardening behavior of the response.

The comparison of the responses of the nonlinear and linear devices shows a considerable enhancement of the frequency bandwidth in the nonlinear regime. Also a nonlinear coupled electromechanical FE simulation of the harvester is conducted using the ABAQUS software where a very good agreement is observed between the results of this simulation with both analytical and numerical solutions of the governing equations.

Quantum effects in nonlinear vibrational energy harvesting

Arjendu Pattanayak
Carleton College (USA)

We have explored a model bistable vibrational energy harvester in detail to elucidate the dynamical mechanisms which lead to the best performance, especially as it relates to higher energy orbits and chaos. Further, recent advances in nanoelectromechanical systems engineering indicate that such systems could operate at a scale where quantum mechanical effects are non-trivial.

Using a semiclassical approximation to a quantum state diffusion model, we explore the effects of these quantum effects and find that these can lead to a substantial increase in the efficiency with which the harvester is able to convert energy.

Energy harvester design inspired from fractal geometries

Cristina Rusu
RISE Acreo

Fractal-based geometry concept is exploited in a wide range of applications such as planar antenna for RFID tags or for RF energy harvesting by maximizing the length of the radiating material being compact in size and giving multi-band or broadband operation capabilities, and also as photodiode harvester by increasing the perimeter-to-area ratio which translates into more collected charges.

Energy harvester inspired by fractal design has not been widely investigated yet.

The discussion is done on different types of vibration energy harvester having a numbers of transducers elements positioned in different parts of the cantilever elements in order to exploit different frequencies modes and also to increase the number of piezoelements that could add their voltages allowing to acquire more energy. Different configurations with their performances deduced from simulations will be described.

Work is in progress for exploring the advantages of fractal-inspired geometrical configuration.

Kinetic Energy Harvesting: Rotating Systems

Eric Yeatman
Imperial College London

Driven by advances in microelectronics, sensors, and radio technology, highly miniature, low cost wireless devices are proliferating rapidly in a wide range of applications. This is enabling the distribution of sensing capability throughout household, urban and other environments (pervasive sensing), as well as the enhancement of previously passive artefacts with intelligence and connectivity (the Internet of Things).
These technologies offer major benefits, including enhanced energy efficiency, system resilience and adaptability, and the provision of new functions and services for users. However, adoption is significantly impeded by the maintenance burden of replacing or recharging huge numbers of batteries.
Energy harvesting - the collection of otherwise unexploited energy in the local environment - is attracting increasing attention as a solution to this problem.
Kinetic energy harvesting - the extraction of power from ambient motion and vibration - has been explored by a large number of researchers, and many devices have been demonstrated. Most, particularly in the micro-scale, use oscillating internal motion; this avoids the need for bearings, but restricts the internal motion range. This talk will focus on micro-engineered devices for kinetic energy harvesting using rotating mechanisms, powered by random vibrations such as human body motion, or by fluid flow. It will be shown that piezoelectric transduction can be employed in such devices, and that this can give significant advantages over electromagnetic devices in terms of device cost and complexity, operating frequency range, and scaling. New scaling laws for these systems will be presented, as well as a number of practical devices for different applications.

Session II: Micro Energy Dissipation

Landauer's Limit and the Physicality of Information

Neal Anderson
University of Massachusetts Amherst

A resurgence of interest in Landauer's Principle has been stimulated by recent experimental probes, theoretical progress in nanoscale thermodynamics, and the continued push for computation at extreme energy efficiencies. However, the nature of the underlying connection between information loss and dissipation in computation - and even its necessity - remains stubbornly controversial. One persistent source of this controversy, I argue, is lack of a clear and consistent definition of information that is thoroughly physical on the one hand and compatible with notions of information used in digital computation on the other. Abstract mathematical measures - absent an explicit physical grounding - fail on the first count, while widely used physical self-entropy and observer-independent mutual information measures fall short on the second.
In this talk I advocate for an alternative conception of physical information that closes this gap, introduce an associated quantitative information measure, and show how this measure enables generalization of Landauer's Principle and clarification of the dissipative origins of irreversible information loss in computational contexts. I focus specifically on the controversial distinction between irreversible (unconditional) erasure of unknown data and reversible (conditional) erasure of known data, and show how our conception of information clarifies this distinction and enables straightforward physical accounting of differences in the respective erasure costs. Finally, I discuss advantages for determination of irreversibility induced energy efficiency limits in computing scenarios far more complex than the idealized one-bit memories routinely employed in investigations of Landauer's Principle.

A protocol for reaching equilibrium arbitrary fast

Sergio Ciliberto
ENSL-CNRS

When a control parameter of a system is suddenly changed, the accessible phase space changes too and the system needs its characteristic relaxation time to reach the final equilibrium distribution. An important and relevant question is whether it is possible to travel from an equilibrium state to another in an arbitrary time, much shorter than the natural relaxation time.
Such strategies are reminiscent of those worked out in the recent field of Shortcut to Adiabaticity, that aim at developing protocols, both in quantum and in classical regimes, allowing the system to move as fast as possible from one equilibrium position to a new one, provided that there exist an adiabatic transformation relating the two. Proof of principle experiments have been carried out for isolated systems.
Instead in open system the reduction of the relaxation time, which is frequently desired and necessary, is often obtained by complex feedback processes. In this talk, we present a protocol, named Engineered Swift Equilibration (ESE), that shortcuts time-consuming relaxations, We tested experimentally this protocol on a Brownian particle trapped in an optical potential first and then on an AFM cantilever. We show that applying a specific driving, one can reach equilibrium in an arbitrary short time. We also estimate the energetic cost to get such a time reduction.
The ESE method paves the way for applications in micro and nano devices, in high speed AFM, or in monitoring mesoscopic chemical or biological process.

References:
(1) Engineered Swift Equilibration, I. A. Martinez; A. Petrosyan; D. Gury-Odelin; E. Trizac; S. Ciliberto, Nature Physics, Vol 12, 843 (2016).
(2) Arbitrary fast modulation of an atomic force microscope, A. Le Cunuder; I. A. Martinez; A. Petrosyan; D. Gury-Odelin; E. Trizac; S. Ciliberto, . Applied Physics Letters, 109, 113502 (2016)

Thermodynamics of the slow solutions to the gas-piston equations

Davide Chiuchiu'
NiPS Laboratory, University of Perugia

A gas in a canister and compressed by a piston is a very simple systems which has been extensively studied since the birth of thermodynamics.
Despite that, gases and pistons still plays an important role in physics: they are one of the few system available in nonequilibrium thermodynamics where it's possible to derive analytical results. This is a key feature in this field as analytic formulas are fundamental to give insight on the open problems of dissipation and relaxation to equilibrium.
In this talk we pursue this line of research and introduce a new series-expansion to define the heat exchanged by the gas during a nonequilibrium transformation. The main advantages of our new expansion are the following: (1) it can be derived with few general assumptions, (2) all its terms are defined through an analytic recurrence relation and, (3) it can be computed to any desired order of precision.

The super insulator: a new topological state of matter

Maria Cristina Diamantini
NiPS Laboratory, University of Perugia

In a loop of superconducting wire, electric current can flow indefinitely without a power supply.
Can we have batteries that do not loose energy when not in use?
Superinsulators, materials that have infinite resistance, have been theoretically predicted in 1996 and experimentally observed in 2008. They correspond to the confining phase of a topological field theory containing a mixed Chern-Simons term and they represent thus an experimentally accessible toy model to understand confinement in QCD.

Energy Efficiency Limits in Brownian Circuits

Ilke Ercan
Bogazici University

The saturation in the efficiency and performance scaling of conventional electronic technologies instigates the development of novel computational paradigms. Brownian computing is among the promising alternatives that can exploit fluctuations in circuits to increase the efficiency of information processing in electronics. A Brownian cellular automaton, where signals propagate randomly and are driven by local transition rules, can be made computationally universal by embedding arbitrary asynchronous circuits on it.

In this work, we perform a physical-information-theoretic analysis on the efficiency limitations of a Brownian NAND gate and half-adder circuits developed based on the methods proposed by Peper et al. The theoretical approach we propose here goes beyond the earlier methodology we developed by capturing the stochasticity as well as the asynchronicity in Brownian circuits and yields fundamental lower bounds on energy efficiency of information processing in Brownian computing. Single Electron Tunnelling (SET) devices enable the simulation of noise and fluctuations in a fashion similar to Brownian search and are therefore employed as an illustrative example in realizing the circuit we design. The method we develop establishes a solid ground that enables studying computational and physical features of this emerging technology on an equal footing, and yield fundamental lower bounds that provide valuable insights into how far the efficiency of this computing strategy can be improved in principle. In determining the fundamental bounds on energy efficiency in Brownian circuits we also provide a physical-information-theoretic comparison of the proposed performance improvement of this technology proposal against its alternatives.

Loss processes and efficiency limitations of Brownian motors

Michael Jack
University of Otago
M. W. Jack[1],J. Devine[1], C. Tumlin[2] and K. J.Challis[3]

Molecular scale devices that transform energy at room temperature can be mathematically modelled as Brownian motion. Brownian motors have complex interactions with their environments that may or may not lead to dissipation and reductions in efficiency. We consider the loss processes and efficiency of a number of different types of Brownian motors within a consistent thermodynamic framework.
First, we consider the case of an isothermal motor with two degrees of freedom. We illustrate and interpret the loss processes and show that this motor is able to reach the dissipation-less limit and perfect efficiency despite constant exchange of energy with its environment.
Second, we consider a motor with two degrees of freedoms but in this case each degree of freedom is in contact with a reservoir of different constant temperature. We show that this motor displays non-vanishing probability current vortices that mean it is never able to reach perfect efficiency. Finally, we consider a Brownian motor strongly interacting with its local environment such that it creates self-induced temperature gradients. We show how these self-induced gradients lead to losses and efficiency limitations.

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Embracing nonlinear dynamics in micro and nano-mechanical systems

Daniel Lopez
Argonne National Laboratory

The field of MEMS (Micro Electro Mechanical Systems) is now a well-established engineering domain with demonstrated impact in science and product development. Unfortunately, as the dimensions of the devices are reduced from the micro- to the nano-scale, the direct scaling of the MEMS fundamentals principles and fabrication processes cease to work. In nano-mechanical devices, thermal fluctuations and fluctuation-induced forces become relatively stronger causing significant changes in the mechanical properties of the structural materials, on their static and dynamic behavior, and on the manner in which they interact with the surrounding environment. Furthermore, when going from micro- to nano-electromechanical systems, the devices linear dynamic range can be reduced to the point where the amplitudes needed for lineal response are below the noise level and, as a consequence, operation in the nonlinear regime is unavoidable. This combination of nonlinear dynamics and high sensitivity to fluctuations has been seen as a deleterious combination for the advance of nano mechanical devices. Rather than continuing to struggle to avoid these phenomena, it is of interest to consider how micro/nanosystem might effectively capitalize on this nonlinear response.
In this talk, I will demonstrate that nonlinearity offers unique possibilities for the controlled response of MEMS devices and, thereby, a host of novel application opportunities. Examples of these opportunities include the development of compact frequency sources with low phase noise, the engineering of dissipation reservoirs to control energy decay processes, and the enhancement of synchronization range between microscopic and macroscopic oscillators.

Nonequilibrium information erasure

Eric Lutz
University of Erlangen-Nurnberg

We investigate the erasure of information stored in a nonequilibrium state of a symmetric underdamped memory. We introduce nonequilibrium erasure protocols that exploit the initial preparation energy and show that they allow to reach nonequilibrium Landauer bounds on heat and work. We further establish that writing and erasing operations need to be treated on an equal footing away from equilibrium and that their combined energetic cost is larger than kT ln 2 per bit. We finally provide numerical simulations with realistic parameters of an optically levitated nanosphere memory.

Brownian Transport in Narrow Channels

Fabio Marchesoni
Universita' di Camerino

Directed Brownian transport (ratcheting) in narrow channels of various geometries [1] has been demonstrated in the presence of different external biases, including periodic drives and other time correlated energy sources.
We discuss how hydrodynamic effects can be incorporated in the standard reduced formalism (aka Fick-Jacobs-Zwanzig model) to reproduce recent experimental observations [2].
We further propose the design of high-efficiency autonomous ratchets [3] by employing active (or self-propelling) Brownian particles both in dilute solutions and binary mixtures.

References
[1] P. Hänggi and F. Marchesoni, Rev. Mod. Phys. 81, 387 (2009)
[2] H.P. Zhang et al, submitted (2017)
[3] P.K. Pulak, V.R. Misko, F. Marchesoni, F. Nori, Phys. Rev. Lett. 110, 268301 (2013)

Fundamental energy costs for memory preservation

Igor Neri
NiPS Laboratory, University of Perugia

In 1961 Landauer pointed out that resetting a binary memory requires a minimum energy of k_BTln(2) where kB is the Boltzmann constant and T the absolute temperature of the memory device.
Any memory however, is doomed to loose its content as time proceeds if no action is taken. In order to avoid memory loss, a refresh procedure is periodically performed with time interval t_R.
In this paper we show that it does exist a fundamental bound to the minimum energy required to preserve one bit of information for a time t, with probability of error less than P_E, and that this energy is a monotonically decreasing function of t_R. Two main conclusions are drawn: the good news is that, in principle, the cost of remembering can be arbitrarily reduced if the refresh procedure is performed often enough. The bad news is that no memory can be preserved forever, no matter how much energy is invested.

Dynamics and thermodynamics of driven open quantum systems using Landau-Zener theory

Juzar Thingna
University of Luxembourg

Common wisdom from the theory of open systems suggests that a system connected to an infinite reservoir can be described by approximate kinetic schemes known as master equations.
In case of autonomous systems, the kinetic description holds as long as the system mixes with several levels of the reservoir. In this work, we investigate the effect of driving on the validity of a kinetic scheme by comparing with exact quantum simulations.
We study the dynamics of a driven spinless quantum dot that moves through a finite sea of autonomous dots (reservoir) and find two distinct regimes wherein kinetic descriptions hold:
1) The dense reservoir regime is like the autonomous Redfield quantum master equation adapted for time-dependent driving;
2) A sparse reservoir regime wherein a kinetic scheme based on the Landau-Zener physics holds. In both cases the master equations describing the dynamics of the system share the same form in the Markovian limit and are fully consistent with stochastic thermodynamics. Our study demonstrates the importance of properly accounting for the system-reservoir interaction energy in the thermodynamic quantities for the agreement between the full and the kinetic descriptions.

Linear and non-linear thermodynamics of a kinetic heat engine with fast transformations

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We investigate a kinetic heat engine model constituted by particles enclosed in a box where one side acts as a thermostat and the opposite side is a piston exerting a given pressure. Pressure and temperature are varied in a cyclical protocol of period τ and their relative excursions δ and ϵ respectively, constitute the thermodynamic forces dragging the system out-of-equilibrium.
The analysis of the entropy production of the system allows to define the conjugated fluxes, which are proportional to the extracted work and the consumed heat.
The dynamics of the piston can be approximated, through a coarse-graining procedure, by a Klein-Kramers equation which - in the linear regime - yields analytic expressions for the Onsager coefficients and the entropy production. A study of the efficiency at maximum power shows that the Curzon- Ahlborn formula is always an upper limit which is approached at increasing values of the thermodynamic forces, i.e. outside of the linear regime.

Noise Induced Phase Transitions and Coupled Brownian Motors: Non Standard Hysteretic Cycles

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Recent work [1,2,3] have shown the possibility, through a noise induced symmetry breaking leading to a nonequilibrium phase transition, of obtaining a set of coupled Brownian motors. It was also shown [4] that in some parameter region such a system could show negative mobility (that is motion opposed to the applied force) and anomalous hysteretic behavior (clockwise in opposition to the usual counter-clockwise). Using an explicit mean-field approximation and colored multiplicative noises, it was found a contraction of the ordered phase (and re-entrance as a function of the coupling) on one hand, and a shift from anomalous to normal hysteretic behavior on the other [5].
This behavior was obtained in systems presenting a noise induced phase transition that originates from a short time instability. Here we discuss a similar system, but where the noise induced phase transition is originated in an entropic mechanism [6].
Some preliminary studies that exploits such a mechanism indicate the possibility of obtaining no standard hysteretic cycles: anti-clockwise but showing a staircase-like structure. Depending on the parameter region, the hysteresis diagram could have one or more blocks, that can be explored as a whole or step by step, opening the possibility of exploiting it as a noise-controlled multipurpose logic gate[7].

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Micro-electromechanical logic devices operated at thermodynamic limits

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The erasure of one classical bit of information is a dissipative process.
The minimum heat produced during this operation has been theorized by Rolf Landauer in 1961 to be equal to kB T ln2 (approximately 2.75 zJ at room temperature) and takes the name of Landauer limit. The same reasoning used to obtain the Landauer limit has been used in the past to theorize a fundamental bound in operating irreversible logic operations.
In this work, we will show how micro-electromechanical systems (MEMS) can be used as memory devices and logic gates. We will then evaluate the energetic expenditure to operate such devices showing that the memorization process, starting from an unknown state, is bounded by the Landauer limit. Irreversible logic gates (e.g. an OR gate), on the contrary, can be operated with arbitrarily low energy provided the operation is slow enough and frictional phenomena are properly addressed.

Session III: Micro Energy Storage

Solar energy storage: catalytic and photocatalytic processes for the production of H2

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H_2 is considered a promising energy vector to be used either as fuel in internal combustion engines, or in fuel cells, with overall higher efficiency. More generally, it can be seen as a way to store solar energy, to be used as support for intermittent renewable sources (e.g. photovoltaics or wind). At the moment it is predominantly produced through thermochemical processes based on fossil sources (i.e. exploiting the solar energy stored in such raw materials in the ancient past. Increasing efforts are put in place to adapt such thermocatalytic processes to the conversion of biomass, leading to a virtuous cycle, which exploits the energy sored in biomass during its growth in a shorter time cycle. Examples will be given on the steam reforming of bioethanol, which is a process in very advanced engineering stage.
On the other hand, the direct use of solar energy is intriguing for H_2 production. The direct photocatalytic water splitting is thermodynamically limited by the high Gibbs free energy (237 kJ/mol) and very low efficiency is reported for direct WS also for kinetic reasons. Sacrificial reagents, such as methanol or EDTA, can improve hydrogen productivity, but they are non renewable. Compared to thermochemical processes, photocatalytic reforming (PR) is a valid approach to produce H_2 under ambient conditions and using sunlight, the cheapest energy source available on earth. PR is also thermodynamically more feasible than WS. Thus, the attention is here focused on the use of waste organic compounds to be used as sacrificial agents, such as organic compounds obtained through the photoreduction of CO_2 or the photoreforming of waste organic solutions.

Energy in the Small: Scaling limits for micron-size energy sources

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SRC

For micron-scale Information and Communication Technology (ICT) systems, such as Internet-of Things, implantable diagnostics/therapy etc., the available volume for on-board energy supplies is very limited.
Thus, the capacity of an energy source, in terms of both energy stored and the rate at which it can deliver energy, can place severe constraints on system operation. In this talk, fundamental scaling limits for a variety of micron-size energy sources are investigated; including capacitors, galvanic and fuel cells, the supercapacitor, and radioisotope sources.
An overview of the energy available for harvesting from a variety of sources is also provided. The architectural implications including system operation will also be discussed. Each of the essential units in an ICT system (such as, e.g. storage, communication, processing, energy etc.) occupies certain volume in space, and taken together, they determine the scaling limits of an electronic system. Therefore, theoretically optimal partitioning within a fixed space envelope needs to be explored.

Session IV: Micro Energy Use

Development of an energetically autonomous system for indoor tracking

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This work describes the development of a product energetically autonomous, originally conceived for the indoor tracking of people.
The device is made by a power management unit that use an indoor photovoltaic (PV) and an electromagnetic (EMH) transducer for energy harvesting and a radio transmitter. Both BLE and RFID solutions has been studied and developed. The device communicates with a set of specifics receivers to perform indoor tracking of people or objects or goods.
The device has been developed pursuing the main task of tracking people on indoor, then in this perspective the R&D has been focused on the transducer to convert the kinetic energy that come from human body movement on electrical power.
Experimental results show that once wears by people in an environment with an illuminance level of 150 lx the device is self-sustaining allowing a BLE communication every 20s. The device can operate reducing the communication frequency also with an illuminance level of 75 lx and no motion. A system to manage possible excess of energy have been also implemented in order to allow transmission also in case of temporary absence of environmental energy. The device demonstrates how a tracking device for indoor use is implemented using energy available in the environment.

Plenty of Room at the Bottom? Micropower Deep Learning for IoT end-nodes

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ETHZ/UNIBO

Deep convolutional neural networks are being regarded today as an extremely effective and flexible approach for extracting actionable, high-level information from the wealth of raw data produced by a wide variety of sensory data sources. CNNs are however computationally demanding: today they typically run on GPU-accelerated compute servers or high-end embedded platforms. Industry and academia are racing to bring CNN inference (first) and training (next) within ever tighter power envelopes, targeting mobile and wearable applications. Recent results, including our PULP and ORIGAMI chips, demonstrate there is plenty of room at the bottom: pj/OP (GOPS/mW) computational efficiency, needed for deploying CNNs in the mobile/wearable scenario, is within reach.
However, this is not enough: 1000x energy efficiency improvement, within a mW power envelope and with low-cost CMOS processes, is required for deploying CNNs on IoT end-nodes. The fj/OP milestone will require heterogeneous (3D) integration with ultra-efficient die-to-die communication, mixed-signal pre-processing, event-based approximate computing.

Embedded energy emulation and monitoring in WSNs

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In spite of the availability of accurate models to estimate and simulate the power consumption of all the components of a WSN in all possible operating modes, it is very hard to capture the effect on power consumption of runtime phenomena like overhearing and packet losses possibly caused by interference among nodes and environmental conditions. At the same time, it is very hard to make in-field measurements of the actual consumption of each node of a large WSN, while also monitoring its workload.
These issues become even more challenging when dealing with energy harvesting WSNs that are powered by time varying energy sources. We present embedded energy monitoring and emulation as a viable solution to instrument large scale testbeds.
We outline the HW-SW architecture of the proposed solution and we present preliminary experimental results.

Experiences of an autonomous wireless sensor and actuator network (WSAN) in IoT domotic application

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This work describes the project of a WSAN made up of autonomous sensor and actuator nodes for a domotic application.
The Internet of Things (IoT) nodes are composed of a low-power microcontroller, a sub-GHz radio for data communication, a power management unit with indoor photovoltaic (PV) or thermoelectric (TEG) transducer for energy harvesting, rechargeable battery, sensor devices and/or actuators. Connectivity between nodes and the network gateway is provided by DASH7, a low-power open source protocol that supports two communication models: the pull model for query-response method (e.g. smart heating) and the push model for data transfer initiated from the nodes (e.g. sensor alarms).
The WSAN experiences two different tasks: smart heating control and water flood sensing. The first consists of temperature sensing node supplied by indoor PV harvester and actuating node, supplied by TEG harvester connected to hot pipe of the radiator, that drive a brushed DC motor connected to the radiator valve. The second consists of water flood sensing node and an actuating node driving a brushed DC motor connected to the water supply system to cut off water flux, both supplied by indoor PV harvesters. To ensure the self-sustainability of the nodes, the average energy harvested has to be greater than the average energy consumed. Experimental results show that, with an illuminance level of 300 lx and a temperature gap of about 10 Â°C between hot water pipe and environment, the first application is self-sustaining if the temperature is sampled every 7 minutes and the radiator valve is controlled every 19 (8) minutes if valve setting change is kept below 25 % (10 %) of its full range. The second application is self-sustaining, i.e. is able to detect and react to water flood, with 150 lx of illuminance level. Both applications demonstrate how an autonomous WSAN for domestic use is implemented using energy available in the environment.

A Clever Strategy for Computing by Micro-Energy: Exploiting the Emergent Properties of Out-of-Equilibrium Systems

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Nowadays, scientists are striving to win the Computational Complexity challenges. A first challenge is solving, accurately and in reasonable time, exponential problems having large dimensions. Another challenge concerns about the formulation of universally valid and effective algorithms for recognizing variable patterns.
To try to win these challenges, scientists are following two strategies. On one hand, they are improving current electronic computers, but on the other, they are developing the research line of Natural Computing. The latter consists in drawing inspiration from nature to propose new algorithms and new materials to compute. We are contributing to the development of Natural Computing by devising chemical systems that, working out-of-equilibrium and in non-linear regime, mimic natural phenomena and exhibit emergent properties. Emergent properties result powerful tools for transforming micro-energy in computing power. This idea is substantiated by a few examples. A first example is from chaos-computing and demonstrates how the dynamic of a chaotic hydrodynamic photochemical oscillator works as a Turing machine [1]. Two other examples come from neuromorphic engineering, whose purpose is to implement brain-like computer, imitating the performances of human intelligence [2]. One example shows that a system of properly chosen photochromic compounds can extend human vision to the UV by mimicking the way humans distinguish colors [3]. Another example reports how oscillatory reactions and photo-excitable systems, communicating through light, can emulate neural dynamics and exhibit the emergent property of synchronization [4].

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Energy dissipation in single-electron devices

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When a single electron is non-adiabatically cycled through a charge degeneracy point additional components appear on the ac-response of single-electron devices. The resistive part, known as the Sisyphus resistance, as well as the reactive component, known as the quantum capacitance, have been studied for single-electron devices dominated by 3 dimensional density of states [1,2].
Here we present measurements on the Sisyphus effect and the quantum capacitance on a quantum object with a zero dimensional density of states, i.e. a quantum dot. The dissipative and dispersive components of a few-electron quantum dot system in silicon at frequencies comparable to the electron tunnel rates (Î“) are studied in detail. Differently from traditional radio frequency single electron transistor, the ac-excitation (f) is applied on the top gate of a silicon nanotransistor [3, 4].
The zero dimensional nature of the quantum dot modifies the electron tunnel rates which become independent of bias voltage at milikelvin temperatures. Consequently the high-frequency dissipative and dispersive response is preserved at large bias.
Additionally, we explore the dependence of the Sisyphus response with the electron tunnel rates. We demonstrate that a maximum of the resistive signal is achieved when Î“~2Ï€f. In this case, energy dissipation is maximal.
Finally, we study the dependence of the high-frequency response with temperature and find that we can that single-electron devices at high frequencies can be used for as primary thermometers.

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Computing with nanomechanical resonators

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In this work we will explore the potential of micro/nanomechanical systems (MEMS/NEMS) resonators to act as logic elements for digital computation.
In particular we look into three possible implementation of such a solution: the driven linear resonator, the nonlinear duffing bistable resonator, and the parametrically driven oscillator.
In addition to exploring the working principle of such systems, the analysis also includes an estimation of the performance-dissipation envelope of logic operation performed on these devices, and how these are affected by scaling.

Spin-wave logic: a new paradigm for low energy computing

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It is widely acknowledged that Moore's law the exponential scaling of semiconductor performance in the past few decades is about to come to an end. The research field for future beyond CMOS computing technology is wide open for complete new ideas and paradigms. A promising direction is based on the idea to use the spin degree of freedom of electrons (instead of their sole electric charge) to encode, process and transmit information. An entire research field spintronics has raised and flourished from this idea. There are different possible approaches to use electron spins for information processing: one straightforward way is to use the magnetic states of interacting magnetic particles to build magnetic bits and magnetic logic gates. A less straightforward way is to use collective excitations of a spin-lattice - spin-waves - for information transport and processing. Both approaches share a clear advantage from the point of view of energy dissipation with respect to the CMOS technology because they are not directly affected by Ohmic losses. The usage of spin-waves [1,2] provides an additional degree of freedom in data processing, it opens the way to non-Boolean computing algorithm, and allows for a further downscale of the computing elements. Wave-based computing provides relatively simple and elegant ways for e.g. doing linear filtering, or calculating Fourier transforms. These are important computing tasks which may be responsible for the bulk of the power consumption especially in specialized tasks like image processing algorithms and in neural networks. This presentation will be focused on giving a wide picture of the state-of-the-art in the research field of spin-wave logic by reviewing recent experimental and simulation results from different research groups working in the field.

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Capacitive Adiabatic Logic: a new paradigm for low-power computation

Gael Pillonnet
CEA-Leti

Existing hardware implementation such as field effect, single-electron transistors, MEMS relays, offer energy consumption for logic operation orders of magnitude higher than Landauer limit.
This paper introduces a new paradigm based on the combination of adiabatic operation and contact less mechanical elements. The principle relies on a variable capacitances which form modulated capacitor divider. By smoothing the transition to switch between logic states, the proposed logic scheme achieves a quasi zero-power logic dissipation without any non-adiabatic part. This method break the inherent trade-off between leakage and switching losses by using metal-metal junctions instead of semiconductor counterpart.
This proposal relies on contact-less mechanical operation to avoid any reliability problem well-known in MEMS relays.

Development of an ultra low power wireless communication technology

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Increased obsolete social infrastructure will increase the cost of maintenance and renewal, and if tough financial conditions continue, it will be necessary not only to develop necessary social infrastructure but also to maintain and update existing facilities There is a danger of hindering. Furthermore, concerning the aged social infrastructure, unless timely and appropriate maintenance is carried out, there is concern that the risk of serious accidents will increase.
For this reason, the Ministry of Internal Affairs and Communications of Japan conducted a project to develop a wireless communication technology that enables sensors to be installed in infrastructure and remote monitoring at all times.
In order to reduce the power consumption of the sensor node as a whole and to extend the operation period and to make the power supply autonomous by the energy harvesting technology, we developed a wireless communication technology whose power consumption is less than 1/1000th of the conventional technology.
In addition, in order to realize efficient data collection and propagation, we have developed a wireless communication control technology that transmits data by interlocking many sensors that greatly simplify communication control information.

Energy management for autonomous wireless sensors

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This work presents the way the energy consumption of a custom wireless sensor node for the IOT - Internet of Things - has been optimized. The optimization is required each time a device has to be powered with batteries or by an energy harvester, even if energy consumption reduction should be always pursuit.
In the first part of the talk the node will be described. Then the energy requirements of each electronic components will be analysed and, last but not least, the firmware optimization will be described.

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