kT Log 2 ’12 Cuenca: Quantum Fluctuations and Information

Scientific Report

Summary

The workshop sought to address the role of quantum fluctuations in nonequilibrium statistical mechanics and information theory. To this end, we brought together experts in non-equilibrium statistical mechanics and in quantum information. The result was an exchange of ideas and methods highlighting the intimate connection between information theory and quantum thermodynamics.

The format of the conference fostered an atmosphere of discussion and collaboration. The invited speakers had ample time to present detailed talks that stimulated fruitful scientific interactions.

Besides the invited speakers, a number of PhD students and Postdoctoral fellows were able to participate, both by giving short talks and by engaging in discussions.

Scientific Content

The presentations in the first session (Thursday morning) focused on the exploitation of information through feedback in thermodynamics, both classical and quantum. **Massimiliano Esposito** presented a concise thermodynamic framework for feedback in a class of classical systems. The discussion continued with **Takahiro Sagawa** with a discussion of how feedback can be utilized to extract work from quantum systems. **Udo Seifert** expanded the considerations with a presentation on the efficiency with which energy can be converted to work, with and without feedback. The final presentations of the morning introduced three experimental proposals on how the conversion of heat and information to work can be tested in both classical and quantum scenarios using a trapped quantum ion by **Eric Lutz**, in nanoelectronic systems by **Jukka Pekola**, and with a trapped colloidal particle by **Yuta Hirayama**.

That afternoon in the second session, the focus shifted to thermodynamic fluctuations in quantum systems. **Takaaki Monnai** began the afternoon by demonstrating the broad implications of time-reversal symmetry in thermodynamics. These ideas were echoed by **Michele Campisi** with his discussion of the various definitions of work in quantum systems and there relationships. After these remarks, **Jordan Horowitz** and **Bei-lok Hu** provided two alternative frameworks for the study of fluctuations of work and other thermodynamic variables in far from equilibrium quantum systems.

Day two brought the discussion from fluctuations to the foundations of thermodynamics and its connection with information theory. The third session

(Friday morning) began with **Vlatko Vedral** applying information theory to the foundational understanding of the second law of the thermodynamics. Then **Sandu Popescu** introduced a simple framework for analyzing how very small thermal machines turn heat into work. The role of measurements was then addressed by **Peter Talkner** by presenting a model study demonstrating how repeated quantum measurements can act as a very hot environment. The connection between information processing, namely Landauer's principle, and thermodynamics was the key issue in the following talk by **Janet Anders**. Finallu,t he morning concluded with **Susana Huelga**, who introduced to the audience the possible role of quantum coherence in photosynthesis.

In the fourth session (Friday afternoon), the speakers examined the effects of observation within the framework of information theory and thermodynamics. In particular, **Ramon Munoz-Tapia** discussed the role of information for quantum discrimination, and **Atonio Acin** presented results describing under what conditions an observed system appears thermodynamic.

The final session (Saturday morning) explored aspects of work fluctuations in quantum and classical systems. **Hal Tasaki** began the morning with a review of recent results on a possible thermodynamic framework for nonequilibrium steady states, including the role of work. Then **Hai Tao Quan**, **Aki Kutvonen**, and **John Goold**, discussed various scenarios that highlight the importance of the definition of work in quantum systems, and how knowledge of its fluctuations can be used to extract useful information about a system under investigation.

Impact and Results

The meeting has been outstanding success. It fostered an environment of discussion, interaction, and collaboration. Furthermore, many of the participants reported to us that they found the experience both enjoyable and fruitful.

The main goal the workshop was to explore the role of quantum fluctuations in information theory and thermodynamics. To this end, we united experts from diverse fields – statistical mechanics and quantum information theory -- many of whom have demonstrated interest in the intersection of these fields. As a result, many of the topics contained aspects and ideas bowered from both fields. In particular, there were many discussions about how information enters into thermodynamics, how it is used, and it is processed. Alternatively, many talks focused on the correction definition of thermodynamic quantities in quantum systems, such as entropy, which is a key component in discussions of information theoretic ideas like Landauer's principle. It is clear that these two communities have much to learn from each other with a variety of overlapping questions. This workshops provides an early attempt to unite these fields, and it will hopefully foster an exchange, allowing information theory and quantum thermodynamics to inform the others future development.

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Conference Program

	Thursday	Friday	Saturday
9:00-9:20	Esposito	Vedral	Tasaki
9:20-9:40			
9:40-10:00	Sagawa	Popescu	Quan
10:00-10:20			
10:20-10:40	Seifert	Talkner	Kutvonen
10:40-11:00			Goold
11:00-11:30	Coffee Break	Coffee Break	Coffee Break
11:30-11:50	Lutz	Anders	
11:50-12:10			
12:10-12:30	Pekola	Huelga	
12:30-12-50			
12:50-13:10	Hiryama	Mazzola	
13:10-15:30	Lunch	Free afternoon: discussions, visit to Cuenca, etc.	
15:30-15:50	Monnai		
15:50-16:10			
16:10-16:30	Campisi		
16:30-16:50			
16:50-17:20	Coffee Break		
17:20-17:40	Horowitz		
17:40-18:00			
18:00-18:20	Hu		
18:20-18:40			
18:40-19:00			
19:00-19:20		Muñoz-Tapia	
19:20-19:40			
19:40-20:00		Acín	
20:00-20:20			
20:30-22:00		Dinner	

Thursday May 24, 2012:

8:50 am – 9:00 am	Welcome Address Juan M. R. Parrondo, Jordan M. Horowitz, and Christian Van den Broeck
9:00 am – 9:40 am	"Stochastic thermodynamics and information" Massimiliano Esposito, University of Luxembourg
9:40 am – 10:20 am	"Nonequilibrium thermodynamics of quantum feedback control" Takahiro Sagawa, Hakubi Center, Kyoto University
10:20 am – 11:00 am	"From a rotary motor to an information engine: Efficiency and feedback at the micron scale" Udo Seifert, University of Stuttgart
11:00 am – 11:30 am	Coffee Break
11:30 am – 12:10 pm	"Single ion heat engine at maximum efficiency and maximum power" Eric Lutz, FU Berlin
12:10 pm – 12:50 pm	"Dissipated work, fluctuation relations and Maxwell's demon in electron tunneling" Jukka Pekola, Aalto University
12:50 pm – 1:10 pm	"Experimental realization of Szilard's engine" Yuta Hirayama, University of Tokyo
1:10 pm – 3:30 pm	Lunch Break
3:30 pm – 4:10 pm	"Microscopic reversibility of open systems" Takaaki Monnai, Osaka City University
4:10 pm – 4:50 pm	"Quantum fluctuation relations" Michele Campisi, Universisaet Augsburg
4:50 pm – 5:20 pm	Coffee Break
5:20 pm – 6:00 pm	"Thermodynamics for quantum trajectories" Jordan M. Horowitz, Universidad Completense de Madrid
6:00 pm – 6:40 pm	"Quantum and classical fluctuation theorems from a decoherent-histories open-system analysis" Bei-Lok Hu, University of Maryland

Friday May 25, 2012:

9:00 am – 9:40 am	"The quantum arrow of time and correlations" Vlatko Vedral, University of Oxford/National University of Singapore
9:40 am – 10:20 am	"Virtual qubits, virtual temperatures, and the foundations of thermodynamics" Sandu Popescu, University of Bristol
10:20 am – 11:00 am	"Approaching infinite temperature upon repeated measurements of a quantum system" Peter Talkner, Universisaet Augsburg
11:00 am – 11:30 am	Coffee Break
11:30 am – 12:10 pm	"Landauer's erasure principle in the strongly coupled quantum regime" Janet Anders, University College London
12:10 pm – 12:50 pm	"Electronic coherence and recoherence in pigment protein complexes: The fundamental role of non-equilibrium vibrational structures" Susana Huelga, Universitaet Ulm
12:50 pm – 1:10 pm	"Activating optomechanical entanglement" Laura Mazzola, Queen's University Belfast
1:10 pm – 7:00 pm	Lunch Break
7:00 pm – 7:40 pm	"Quantum state discrimination" Ramón Muñoz-Tapia, Universitat Autonoma Barcelona
7:40 pm – 8:20 pm	"Local Temperature and correlations" Atonio Acín, Institut de Ciències Fotòniques
8:30 pm	Conference Dinner

Saturday May 26, 2012:

9:00 am – 9:40 am	“Entropy and exact ‘thermodynamic’ relations for nonequilibrium steady states” Hal Tasaki, Gekushuin University
9:40 am – 10:20 am	“Validity of nonequilibrium work relations for the rapidly expanding quantum piston” Haitao Quan, University of Maryland
10:20 am – 10:40 am	“Dissipated work and fluctuation relations in non-equilibrium single-electron transitions” Aki Kutvonen, Aalto University
10:40 am – 11:00 pm	“Quantum work fluctuations in a class of quenched Fermi systems” John Goold, University of Oxford
11:00 am – 11:50 pm	Coffee Break
11:50 am	Bus departs for train station

ABSTRACTS

Stochastic thermodynamics and information
Massimiliano Esposito, University of Luxembourg

I will emphasize the deep connection established by stochastic thermodynamics between information and nonequilibrum thermodynamics. More specifically, I will discuss the meaning, in terms of information, of recovering equilibrium thermodynamics [1]. I will also present the nonequilibrium Laundauer principle [2], and an elegant way to incorporate "Maxwell demon" feedbacks into the theory [3].

[1] M. Esposito, "Stochastic thermodynamics under coarse-graining", Phys. Rev. E 85, 041125 (2012).
[2] M. Esposito and C. Van den Broeck, "Second law and Landauer principle far from equilibrium", EPL 95, 40004 (2011).
[3] M. Esposito and G. Schaller, "Stochastic thermodynamics for 'Maxwell demon' feedbacks", arxiv:1204.5671.

Nonequilibrium thermodynamics of quantum feedback control
Takahiro Sagawa, The Hakubi Center, Kyoto University

In this talk, I'd like to discuss generalizations of the second law of thermodynamics [1] and the Hatano-Sasa-type inequality [2] in the presence of quantum feedback control. A special kind of the quantum mutual information is shown to play a crucial role in these generalizations. As a special example, I'd like to talk about the quantum Szilard engine with multi-particles [3].

[1] T. Sagawa and M. Ueda, Phys. Rev. Lett. 100, 080403 (2008).
[2] T. Sagawa, arXiv:1202.0983 (2012).
[3] S. W. Kim, T. Sagawa, S. De Liberato, and M. Ueda, Phys. Rev. Lett. 106, 070401 (2011).

From a rotary motor to an information engine: Efficiency and feedback at the micron scale
Udo Seifert, University of Stuttgart

I will discuss crucial concepts in stochastic thermodynamics with and without feedback control using simple model systems: For the rotary motor enzyme F1-ATPase, we have explored three different notions of efficiency and compared to experimental data [1]. For a feedback-controlled version of such a rotor as a simple model for a system with genuine non-equilibrium states, we can illustrate our generalization of the Sagawa-Ueda fluctuation theorem [2]. For a colloidal particle in a harmonic trap under feedback control, we can determine power, efficiency and efficiency at maximum power of such a cyclic information engine [3].

[1] E. Zimmermann and U. Seifert, in prep.
[2] D. Abreu and U. Seifert, PRL 108, 030601, 2012.
[3] M. Bauer, D. Abreu, and U. Seifert, arXiv: 1203.0184, 2012.

Single ion heat engine at maximum efficiency at maximum power
Eric Lutz, FU Berlin

We propose a concrete experimental scheme to realize a quantum heat engine with a single ion as a working gas. We confine the ion in a modified linear Paul trap and implement an Otto cycle by coupling it to engineered laser baths. We analytically determine the efficiency at maximum power in various regimes. We perform extensive Monte Carlo simulations of the engine to demonstrate its feasibility. We further show that it can run at maximum efficiency.

Dissipated work, fluctuation relations and Maxwell's demon in electron tunneling
Jukka Pekola, Aalto University

I discuss the distribution of dissipated work in gate-driven single-electron and Cooper pair transitions. In our recent experiments this distribution was measured in a metallic single-electron box using a readout based on the detection of the timing of individual tunneling events with respect to the external drive. This set-up can be extended and adapted to devise a Maxwell's demon for electrons. As a basic system to investigate quantum fluctuation relations, I discuss the gate-driven Cooper pair box, where dissipation is determined by Landau-Zener transitions.

Experimental realization of Szilard's engine
Yuta Hirayama, University of Tokyo

We develop a method to realize Szilard's engine experimentally in classical system. In this study, an optically trapped micro-particle in water plays the role of a single molecule confined in a box. Depending on the positional information of the particle, we control the effective potential of the optical tweezers, by modulating laser beam with electro-optic deflector. Thus we mimic the compression and expansion of the box in Szilard's engine. We will verify the relation between the extracted work from the particle and the information content of the position measurement. Also, we will discuss the relation between the speed of the feedback control and the time efficiency of the information-heat engine.

Microscopic reversibility of open systems
Takaaki Monnai, Osaka City University

The time reversal symmetry of the equations of motion equally allows time forward and reversed processes. In this talk, we show an expression of the microscopic reversibility for open systems, which states that the ratio of the probabilities of the time forward and reversed trajectories is directly connected to a degree of time reversal asymmetry of the final state for an externally forced Liouvillian reversible dynamics. This expression of the microscopic reversibility is a model-independent thermodynamic relation valid out of equilibrium. We will discuss on the physical implications of this relation. For example, it gives a microscopic expression of the heat provided that the system interacts with a large reservoir, and the subdynamics is well-described by the Markovian stochastic dynamics. It also provides a condition for thermalization processes. When the system is submitted to a thermalization after a quench, the probabilities of the forward and reversed trajectories are almost equal, which is also the case for the quantum open systems.

[1] T. Monnai, arxiv:1202.5648 .
[2] T. Monnai, J. Phys. A: Math. Theor. 45, 125001 (2012).

Quantum fluctuation relations
Michele Campisi, Universisaet Augsburg

The second law of thermodynamics poses a stringent constraint on the direction that physical processes may take in macroscopic systems. As their size shrinks, processes taking the opposite direction, apparently defying the second law, become possible and the fluctuation theorems quantify the likelihood of their occurrence. We will address the following issues concerning quantum fluctuation theorems: i) the problem of gauge freedom affecting the definitions of work and free energy, ii) the notions of inclusive, exclusive and dissipated work [1], iii) the absence of a work operator in quantum mechanics and the notion of two-point quantum observable, iv) the difficulties related to the experimental verification of quantum fluctuation theorems and the possibility to overcome them; v) the robustness of fluctuation relations to quantum mechanical measurements.

[1] M. Campisi, P. Hänggi, and P. Talkner. Reviews of Modern Physics 83, 771 (2011).
[2] M. Campisi, P. Talkner, and P. Hänggi. Physical Review Letters 105, 104601 (2010).
[3] M. Campisi, P. Talkner, and P. Hänggi. Physical Review E 83, 041114 (2011).

Thermodynamics for quantum trajectories
Jordan M. Horowitz, Universidad Complutense de Madrid

Stochastic thermodynamics is a theoretical framework that assigns thermodynamic quantities – such as work and entropy – to individual fluctuating trajectories of small systems. As a theoretical tool, it has been useful in refining our understanding of irreversibility at the micron scale. In this talk, I develop an analogous framework for a forced quantum harmonic oscillator utilizing the quantum trajectories formalism. Consistent trajectory-dependent definitions of thermodynamic quantities are introduced, by engineering the thermal reservoir from a sequence of two-level systems. Furthermore, the connection between irreversibility and entropy production is confirmed by way of a detailed fluctuation theorem.

Quantum and classical fluctuation theorems from a decoherent-histories dpen-system analysis
Bei-Lok Hu, University of Maryland

We present a first-principles analysis of the nonequilibrium work distribution and the free energy difference of a quantum system interacting with a general environment (with arbitrary spectral density and for all temperatures) based on a well-understood micro-physics (quantum Brownian motion) model under the conditions stipulated by the Jarzynski equality and Crooks' fluctuation theorem (in short FTs). We use the decoherent history conceptual framework to explain how the notion of trajectories in a quantum system can be made viable and use the environment-induced decoherence scheme to assess the strength of noise which could provide sufficient decoherence to warrant the use of trajectories to define work in open quantum systems. From the solutions to the Langevin equation governing the stochastic dynamics of such systems we were able to produce formal expressions for these quantities entering in the FTs, and from them prove explicitly the validity of the FTs at the high temperature limit. At low temperatures our general results would enable one to identify the range of parameters where FTs may not hold or need be expressed differently. We explain the relation between classical and quantum FTs and the advantage of this micro-physics open-system approach over the phenomenological modeling and energy-level calculations for substitute closed quantum systems. This is based on our recent paper with Yigit Subasi [3].

[1] C. Jarzynski, Phys. Rev. Lett. 78, 2690 (1997).
[2] G. E. Crooks, Phys. Rev. E 60, 2721 (1999).
[3] Yigit Subasi and B. L. Hu, Phys. Rev. E 85, 011112 (2012).

The quantum arrow of time and correlations
Vlatko Vedral, University of Oxford/National University of Singapore

One way of arguing for entropy increase in a universe evolving unitarily is to neglect correlations between subsystems. I will argue that the existence of this kind of arrow of time requires a strict absence of the initial correlations between the subsystems. In other words, any initil correlations, no matter how small, could lead to a reversal of the arrow of time. I discuss relations to other approaches to irreversibility.

Virtual qubits, virtual temperatures, and the foundations of thermodynamics
Sandu Popescu, University of Bristol

We argue that thermal machines can be understood from the perspective of 'virtual qubits' at 'virtual temperatures': The relevant way to view the two heat baths which drive a thermal machine is as a composite system. Virtual qubits are two-level subsystems of this composite, and their virtual temperatures can take on any value, positive or negative. Thermal machines act upon an external system by placing it in thermal contact with a well-selected range of virtual qubits and temperatures. We demonstrate these claims by studying the smallest thermal machines. We show further that this perspective provides a powerful way to view thermodynamics, by analysing a number of phenomena. This includes approaching Carnot efficiency (where we find that all machines do so essentially by becoming equivalent to the smallest thermal machines), entropy production in irreversible machines, and a way to view work in terms of negative temperature and population inversion. Moreover we introduce the idea of "genuine" thermal machines and are led to considering the concept of "strength" of work.

Approaching infinite temperature upon repeated measurements of a quantum system
Peter Talkner, Universisaet Augsburg

The influence of repeated projective measurements on the dynamics of the state of a quantum system is studied as a function of the time lag τ between successive measurements. In the limit of infinitely many measurements of the occupancy of a single state the total system approaches a uniform state. The asymptotic approach to this state is exponential in the case of finite Hilbert space dimension. The rate characterizing this approach undergoes a sharp transition from a monotonically increasing to an erratically varying function of the time between subsequent measurements.

Landauer's erasure principle in the strongly coupled quantum regime
Janet Anders, University College London

Landauer's principle is one of the prime examples of the connection of information theory and thermodynamics. In recent years several publications have discussed the possible violation of the second law of thermodynamics and Landauer's principle in the strongly coupled quantum regime. If true, these results would have powerful consequences for both thermodynamics and information theory. I will review the original discussion and argue why previous treatments were erroneous. It turns out that the established correlations in quantum systems at low temperatures require a rethink of how entropy, heat and work are calculated. I will show that a consistent treatment resolves the paradoxical situation.

Electronic coherence and recoherence in pigment protein complexes: The fundamental role of non-equilibrium vibrational structures
Susana Huelga, Universitaet Ulm

The possibility that coherence may be exploited in biological processes has opened up new avenues of exploration at the interface of physics and biology. Recent observations of oscillatory features in the optical response of photosynthetic complexes have been interpreted as evidence for surprisingly long-lasting electronic coherences which coexist with energy transport. Under these conditions, an interplay of quantum dynamics and dissipative processes has been suggested to drive efficient energy transport. The microscopic origin of these long-lived coherences, however, remains to be uncovered, and the presence and role of coherence under natural - as opposed to laboratory - conditions is hotly debated. Here we show that non-trivial spectral structures of environmental fluctuations, and particularly discrete vibrational modes, can lead to the spontaneous generation and sustenance of both oscillatory energy transport and electronic coherence on comparable timescales. These novel non-equilibrium processes, which in effect blur the traditional boundary between system and environment, show how complex environments may allow coherence to play a significant role in biological processes under a much wider range of conditions than previously believed.

Activating optomechanical entanglement
Laura Mazzola, Queen's University Belfast

We propose an experimentally feasible setup where the activation of optomechanical entanglement can be demonstrated from the pre-availability of non-classical mechanical correlations. Depending on the temperature of the bath surrounding the mechanical mirrors, we distinguish a high- and low-temperature activation scheme. We analyze the condition under which the protocol is successful and relate them to the current experimental state of the art.

Quantum state discrimination
Ramón Muñoz Tapia, Universitat Autonoma Barcelona

I review the essentials of quantum state discrimination. For pure states I show that adaptive local measurements provide identical performance as the optimal (collective) measurements. For mixed states I derive the Quantum Chernoff bound and the metric induced in the space of states. I show that, contrary to the pure state case, local measurements exhibit a gap in performance that persists in the asymptotic limit. Several extensions of the basic discrimination problem will also be briefly discussed

Local temperature and correlations
Antonio Acín, Institut de Ciències Fotòniques

We consider the concept of temperature in a setting beyond the standard thermodynamics prescriptions. Namely, rather than restricting to standard coarse-grained measurements, we consider observers able to master any possible quantum measurement--a scenario that might be relevant at nanoscopic scales. In this setting, we focus on quantum systems of coupled harmonic oscillators and study the question of whether the temperature is an intensive quantity, in the sense that a block of a thermal state can be approximated by an effective thermal state at the same temperature as the whole system. Using the quantum fidelity as figure of merit, we identify instances in which this approximation is not valid, as the block state and the reference thermal state are distinguishable for refined measurements. Actually, there are situation in which this distinguishability even increases with the block size. However, we also show that the two states do become less distinguishable with the block size for coarse-grained measurements--thus recovering the standard picture. We then go further and construct an effective thermal state which provides a good approximation of the block state for any observables and sizes. Finally, we point out the role entanglement plays in this scenario by showing that, in general, the thermodynamic paradigm of local intensive temperature applies whenever entanglement is not present in the system.

Entropy and exact "thermodynamic" relations for nonequilibrium steady states
Hal Tasaki, Gakushuin University

We outline our attempt to construct operationally meaningful thermodynamics for nonequilibrium steady states. We describe some rigorous results in the context of Markov jump processes.

Validity of nonequilibrium work relations for the rapidly expanding quantum piston
Haitao Quan, University of Maryland, College Park

We study the validity of quantum nonequilibrium work relations in the context of the rapidly expanding one-dimensional quantum piston. Utilizing exact solutions of the time-dependent Schrodinger equation, we find that the evolution of the wave function can be decomposed into static and dynamic components, which have simple semiclassical interpretations in terms of particle-piston collisions. We show that nonequilibrium work relations remain valid at any finite piston speed, provided both components are included, and we study explicitly the work distribution for this model system.

Haitao Quan, Chris Jarzynski. Phys. Rev. E. 85, 031102 (2012).
Physics Synopsis: http://physics.aps.org/synopsisfor/10.1103/PhysRevE.85.031102

Dissipated work and fluctuation relations in non-equilibrium single-electron transitions
Aki Kutvonen, Aalto University

We discuss a simple but experimentally realistic model system, a single-electron box (SEB), where common fluctuation relations can be tested for driven transitions. When the electronic system on the SEB island is driven out of equilibrium by the control parameter (gate voltage) non-isothermally, we observe deviations from the fluctuation relations.

Quantum work fluctuations in a class of quenched Fermi systems
John Goold, University of Oxford

The study of out-of-equillibrium dynamics of closed quantum systems has recently received renewed interest due to remarkable experimental progress in ultra-cold atomic physics. These experiments offer long coherence times and an unprecedented level of control, serving as an ideal testbed for basic out-of-equillibrium transformations. In a quantum quench, one of the parameters of the Hamiltonian is changed in a diadiabatic manner and non-trivial dynamics is observed. In this work we demonstrate how recently discovered quantum 'work' fluctuation relations can be used to explore the physics of strongly correlated manybody systems which are perturbed far from equillibrium.