STOCHASTIC THERMODYNAMICS OF COMPLEX SYSTEMS

ONLINE CSH WORKSHOP

AGENDA

May 27 – May 29, 2020

COMPLEXITY SCIENCE HUB VIENNA
PALAIS STROZZI
JOSEFSTAEDTER STRASSE 39
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Workshop description

Stochastic thermodynamics is a powerful extension of conventional equilibrium statistical physics designed for analyzing non-equilibrium thermodynamics of small systems, down to the level of individual trajectories. In stochastic thermodynamics, we typically consider a system undergoing a continuous-time Markov process while coupled to (one or more) infinite heat, particle, or work reservoirs. If there is a single infinite heat reservoir and local detailed balance holds, then the equilibrium distribution is the ordinary Boltzmann distribution.

On the other hand, in many complex systems, the equilibrium distribution is different from the Boltzmann distribution. These kinds of equilibria arise because the reservoirs are finite, the dynamics are non-Markovian, or some other assumption of conventional stochastic thermodynamics is violated.

In addition, in conventional stochastic thermodynamics we are typically allowed to vary the trajectory of the Hamiltonian and rate matrices through time in arbitrary ways (perhaps subject to restrictions like local detailed balance, or irreducibility). But real-world systems are almost always extremely constrained in the kinds of trajectories of Hamiltonians and rate matrices they can follow. A simple example is if we decompose a closed system into two subsystems, one of which we identify as the "finite heat bath", and then only allow ourselves to vary the Hamiltonian over the other subsystem. Another example is a system that is open, being connected to an infinite external heat bath, but which decomposes into a set of multiple subsystems, where there are locality-based constraints on which subsystem can directly affect which other subsystem.

These issues raise a host of intertwined questions, which this workshop aims to investigate:

1) What are the necessary and sufficient conditions for a thermodynamic system to have a non-Boltzmann equilibrium distribution, e.g., by having finite heat baths or an infinite number of baths? What equilibria arise if we extend conventional stochastic thermodynamics, e.g., to involve non-linear master equations (or in some other way violate the assumption of Markovian evolution)? How can we experimentally test such extensions of conventional stochastic thermodynamics? In particular, how can we identify experimentally accessible macroscopic quantities like thermodynamic work and heat with the quantities arising in such extensions of stochastic thermodynamic? Do we need to generalize the concept of entropy to analyze these scenarios? What is the role of Maximum entropy principle in these scenarios?

2) What are the thermodynamic consequences of constraints on the trajectories of the Hamiltonian and / or rate matrices? What if the system is non-Markovian? How does the answer change if there is no external (infinite) heat reservoir coupled to the system? Are there high-level taxonomies of the form of the constraints, which are useful for analyzing their thermodynamics behavior?

Workshop Organizers

David Wolpert	Santa Fe Institute, External Faculty Complexity Science Hub Vienna, Arizona State University
Jan Korbel	Medical University of Vienna, Complexity Science Hub Vienna

Speakers

Nihat Ay	Max Planck Institute for Mathematics in the Natural Sciences
Alex Boyd	Nanyang Technological University
Kay Bradner	University of Nottingham
Michele Campisi	University of Florence
Gavin Crooks	University of California, Berkeley
Massimiliano Esposito	University of Luxembourg
Rudolf Hanel	Complexity Science Hub Vienna, Medical University of Vienna
Yoshihiko Hasegawa	University of Tokyo
Sosuke Ito	University of Tokyo
Christopher Jarzynski	University of Maryland
Artemy Kolchinsky	Santa Fe Institute
Jan Korbel	Complexity Science Hub Vienna, Medical University of Vienna
Krzysztof Ptaszynski	Polish Academy of Sciences
Paul Riechers	Nanyang Technological University
Takahiro Sagawa	University of Tokyo
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Udo Seifert	University of Stuttgart
Naoto Shiraishi	Gakushuin University
Philipp Strasberg	Autonomous University of Barcelona
Stefan Thurner	Complexity Science Hub Vienna, Medical University of Vienna
Henrik Wilming	ETH Zurich
David Wolpert	Santa Fe Institute, Complexity Science Hub Vienna

Non-presenting participants (tentative)

Miguel Aguilera	University of the Basque Country
Andrew Alexander	Princeton University
Franciszek Bartnik	Technical University of Vienna
Arnab Barua	Braunschweig Integrated Centre of Systems Biology
Aviv Bergman	Albert Einstein College of Medicine
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Hyun-Myung Chun	University of Michigan

Shamil Chandaria	Google DeepMind
Alexander Cheplev	Weizmann Institute of Science
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Jonas Dalege	Santa Fe Institute
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Timothy Ekeh	University of Cambridge
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Carlos Floyd	University of Maryland
Matthias Frenzl	Technical University of Vienna
Miguel Fuentes	Santa Fe Institute
Mirta Galesic	Santa Fe Institute
Qi Gao	University of Michigan
Rosalba Garcia Millan	Imperial College London
Galor Geva	Tel Aviv University
Daniel Ghamari	Sharif University of Technology
Todd Gingrich	Northwestern University
Herbert Gintis	Central European University
Sebastian Goldt	Ecole Normale Supérieure Paris
Mile Gu	Nanyang Technological University
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Michael Hochberg	CNRS University of Montpellier
Jordan Horowitz	University of Michigan
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Srividya Iyer-Biswas	Purdue University
Velimir Ilic	Serbian Academy of Sciences and Arts
Sara Imari	Arizona State University
Henrik Jensen	Imperial College London
Julian Kappler	University of Cambridge
Gülce Kardeş	University of Leipzig
Vladislav Kashansky	Alpen-Adria University of Klagenfurth
Emre Kaya	Kadir Has University
Janos Kertesz	Central European University
Swanand Khanapurkar	Arizona State University
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Hildegard Meyer-Ortmanns	Jacobs University Bremen
Azade Mohamadi	Federal University of Pernambuco
Dimitris Nakos	Foundation for Research and Technology Hellas
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Thomas Ouldridge	Imperial College London
Milan Paluš	Academy of Sciences of the Czech Republic
Jugal Patel	McGill University
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Tuan Pham Minh	Complexity Science Hub Vienna, Medical University of Vienna
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Michael Rizzo	independent scholar
Fernando Rosas	Imperial College London
John Rundle	University of California
Arunabha Saha	University of Calcutta
Matteo Saponati	International Max-Planck School for Neural Circuits
William Schueller	Complexity Science Hub Vienna
Varun Sharma	Georgia Tech
Rana Shajari	Alzahra University
Sadasivan Shankar	Harvard University
Mohammad Sherafati	Shahid Beheshti University
Hideaki Shimazaki	Hokkaido University
Guilherme De Sousa	University of Maryland
Clemens von-Stengel	University of Cambridge
Dominik Šafránek	University of California, Santa Cruz
Zlata Tabachová	Czech Technical University in Prague
Bosiljka Tadic	Jozef Stefan Institute
Constantino Tsallis	The Brazilian Center for Research in Physics
Masahito Ueda	University of Tokyo
Raam Uzdin	The Hebrew University of Jerusalem

Demyan Vakhrameev	University of Bristol
Juan Pablo Vigneaux	Max Planck Institute for Mathematics in the Natural Sciences
Maximilian Vossel	Max Planck Institute for Biophysical Chemistry
Hadrien Vroylandt	Northwestern University
Sara Imari Walker	Arizona State University
Benjamin Walter	Imperial College London
Michael Wassermair	Technical University of Vienna
Hila Weissman	Israel Institute of Technology
Valeria Widler	University of Vienna
Chris Wood	Santa Fe Institute
Meng Xu	Pace University in New York
Cigdem Yalcin	Istanbul University

ABOUT THE COMPLEXITY SCIENCE HUB VIENNA

The objective of CSH is to host, educate, and inspire complex systems scientists who are dedicated to collect, handle, aggregate, and make sense of big data in ways that are directly valuable for science and society. Focus areas include smart cities, innovation dynamics, medical, social, ecological, and economic systems. CSH is a joint initiative of AIT Austrian Institute of Technology, IIASA International Institute for Applied Systems Analysis, Medical University of Vienna, Vienna University of Technology, Graz University of Technology, and Vienna University of Economics and Business.

IMPORTANT INFORMATION

Registration

The videoconference is open to all scholars interested in the topic of the workshop. For registration to the conference, please send a short email to office@csh.ac.at.

Zoom

The whole conference will be available through videoconferencing software Zoom. The login details will be sent to registered participants a few days before the workshop.

Sessions

The workshop is divided into six sessions. The title of each session describes the session's main focus. Note through that due to the time zone restrictions, not all talks in a session fully correspond to the title of the session.

Each session starts with a short introduction by the session chair. That is followed by three to four talks. Each talk is 20 minutes long, followed by a 10-minute Q&A. Each session ends with a discussion on the topic of the session.

Talks

No questions will be allowed during the talk. Everyone except the speaker will be muted.

Q&A

Participants may ask questions during the Q&A session after each talk using the Zoom chat feature. The session chair will unmute the questioner and they can ask the speaker their question.

Recording

All talks will be recorded, and the videos will be published on the CSH YouTube channel. *Please tell us immediately if you do not wish to be recorded.*

Discussion

After each session, there will be a time for general discussion. Each such discussion will be moderated by the Session Chair. If you want to contribute to the discussion, please raise your virtual hand to get the attention of the chair. Discussions will not be recorded.

Presentations

We would like all presentations to be uploaded to the workshop page **before** the presentation. We therefore ask the presenters to email their presentations to jan.korbel@meduniwien.ac.at

Streaming

The entire workshop will be streamed on the Facebook page of the Complexity Science Hub (@CSHVienna).

Website

The workshop website is: https://www.csh.ac.at/event/csh-workshop-stochastic-thermodynamics-complex-systems/. We will upload all the relevant information there.

Contact information

You can contact the workshop organizers at the following addresses:

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AGENDA

Note: all times are listed in Central European Summer Time (CEST)

Note: All talks are 20 minutes followed by ten minutes for Q&A

Note: Each session starts with some brief opening remarks by the session chair, describing the topic of that session.

Note: Discussion sessions are moderated by the associated session chair. Please use either public chat or raise your virtual hand to get their attention; otherwise you will be muted.

Wednesday, May 27, 2020

12:30 - 13:00 *Testing the connection*
13:00 - 13:10 *Welcome and Introduction*

Session 1
The role of entropy and maximum entropy principle in non-equilibrium thermodynamics
Chair: M. Esposito

13:10 - 13:15 *Opening remarks*
13:15 - 13:35 Stefan Thurner
Q&A
13:45 - 14:05 Takahiro Sagawa
Q&A
14:15 - 14:35 Naoto Shiraishi
Q&A

14:45 - 15:30 *Discussion session 1*

15:30 – 16:00 *Break*

Session 2
Stochastic thermodynamics for complex systems with very strong coupling among subsystems
Chair: A. Kolchinsky

16:00 - 16:05 *Opening remarks*
16:05 - 16:25 David Wolpert
Q&A
16:35 - 16:55 Philipp Strasberg
Q&A
17:05 - 17:25 Massimiliano Esposito
Q&A
17:35 - 17:55 Krzysztof Ptaszyński
Q&A

18:05 - 18:45 *Discussion session 2*

Thursday, May 28, 2020

Session 3
Thermodynamic uncertainty relations for complex systems
Chair: T. Sagawa

13:00 - 13:05 *Opening remarks*
13:05 - 13:25 Yoshihiko Hasegawa
Q&A
13:35 - 13:55 Sosuke Ito
Q&A
14:05 - 14:25 Paul Riechers
Q&A
14:35 - 14:55 Udo Seifert
Q&A

15:05 - 15:45 *Discussion session 3*

15:45 – 16:15 *Break*

Session 4
Stochastic thermodynamics for non-Boltzmann equilibrium distributions
Chair: D. Wolpert

16:15 - 16:20 *Opening remarks*
16:20 - 16:40 Artemy Kolchinsky
Q&A
16:50 - 17:10 Michele Campisi
Q&A
17:20 - 17:40 Jan Korbel
Q&A
17:50 - 18:10 Christopher Jarzynski
Q&A

18:20 - 19:00 *Discussion session 4*

Friday, May 29, 2020

Session 5
Information-theoretic measures for thermodynamics of complex systems
Chair: J. Korbel

13:00 - 13:05 *Opening remarks*
13:05 - 13:25 Keiji Saito
Q&A
13:35 - 13:55 Alec Boyd
Q&A
14:05 - 14:25 Kay Brandner
Q&A

14:35 - 15:10 *Discussion on possibility of an annual virtual workshop*
15:10 - 15:30 *Discussion session 5*
15:30 - 16:00 *break*

Session 6
General features of non-equilibrium thermodynamics for complex systems
Chair: C. Jarzynski

16:00 - 16:05 *Opening remarks*
16:05 - 16:25 Rudolf Hanel
Q&A
16:35 - 16:55 Nihat Ay
Q&A
17:05 - 17:25 Henrik Wilming
Q&A
17:35 - 17:55 Gavin Crooks
Q&A

18:05 - 18:45 *Discussion session 6*
18:45 - 19:00 *Closing remarks*

ABSTRACTS

Wednesday, 27th May

Session 1
Chair: M. Esposito

Stefan Thurner

Title: tba

Abstract: tba

Takahiro Sagawa

Title: *On the existence of a complete thermodynamic potential for quantum many-body systems*

Abstract: In equilibrium thermodynamics, the Boltzmann entropy serves as a complete thermodynamic potential that characterizes state convertibility in a necessary and sufficient manner. In this talk, I will present our recent result [1] that a complete thermodynamic potential emerges for many-body systems under physically reasonable assumptions, even in out-of-equilibrium and fully quantum situations. Our proof is based on resource-theory formalism of thermodynamics and a quantum ergodic theorem. The complete thermodynamic potential is in general given by a quantity called the spectral divergence rate, while under the above-mentioned assumptions it reduces to the Kullback-Leibler (KL) divergence rate.

References:
[1] P. Faist, T. Sagawa, et al., PRL123, 250601 (2019).

Naoto Shiraishi

Title: *Some bounds on entropy production stronger than the second law of thermodynamics*

Abstract: Entropy production is the pivotal quantity in thermodynamics, which characterizes the degree of irreversibility of thermodynamic processes. The second law of thermodynamics provides a universal and fundamental bound on entropy production. The second law applies any processes and claims nonnegativity of entropy production. The equality of this bound is achieved when the process is quasistatic.

On the other hand, various thermodynamic processes are obviously not quasistatic. Finite-speed processes and relaxation processes are two important classes of such processes. By restricting processes to such classes, stronger bounds than the second law are expected to exist. However, in spite of this natural anticipation, no stronger bound than the second law has been obtained.

In this talk, we provide stronger bounds than the second law for the above-mentioned two classes of processes. On finite speed processes, we prove that quick state transformation inevitably accompanies much entropy production [1]. This inequality serves as a speed limit for classical

systems. On relaxation processes, we derive a nontrivial lower bound on entropy production [2]. This bound is obtained as a corollary of a novel variational representation of entropy production rate. These results elucidate the nature of thermodynamic irreversibility in depth.

References:
[1] N. Shiraishi, K Funo, and K. Saito, PRL 121, 070601 (2018).
[2] N. Shiraishi and K. Saito, PRL 123, 110603 (2019).

Discussion session 1

Title: *The role of entropy and maximum entropy principle in non-equlibrium thermodynamics*

Session 2
Chair: A. Kolchinsky

David Wolpert

Title: *The thermodynamic effects of constraints on rate matrix dependencies in multipartite processes*

Abstract: I consider multipartite processes in which there are constraints on each subsystem's rate matrix, restricting which other subsystems can directly affect its dynamics. First, I derive a strictly nonzero lower bound on the minimal achievable entropy production rate of the process in terms of these constraints on the rate matrices of its subsystems. This bound is related to the “learning rate” of stationary bipartite systems, and more generally to the “information flow” in bipartite systems. Then I derive novel “joint” fluctuation theorems governing the joint distribution of the entropy production values of all the subsystems.

Philipp Strasberg

Title: *Nonequilibrium entropy and the second law of thermodynamics*

Abstract: The second law of thermodynamics asserts that the thermodynamic entropy in the universe increases. To derive this statement microscopically, it is therefore necessary to start first of all with a definition of thermodynamic entropy valid in and out of equilibrium. Surprisingly, not much can be found about this basic question in the literature. In this talk I will propose one definition, which is known in the literature as observational entropy. Based on this I will derive the second law of thermodynamics. In contrast to previous approaches, the present approach is not only conceptually more satisfying, but also very flexible, allowing to apply the same formalism to a wide range of problems.

Massimiliano Esposito

Title: *Dissipation bounds precision and speed*

Abstract: I will briefly present a method unifying and generalizing many thermodynamic uncertainty relations [Falasco, Esposito & Delvenne, arXiv:1906.11360] and I will then discuss a dissipation-time uncertainty relation which is a novel form of speed limit: the smaller the dissipation, the larger the time to perform a process [Falasco & Esposito, arXiv:2002.03234].

References:

Falasco, Esposito & Delvenne, arXiv:1906.11360
Falasco & Esposito, arXiv:2002.03234

Krzysztof Ptaszyński

Title: *Entropy production in open systems: the predominant role of intra-environment correlations*

Abstract: The emergence of thermodynamic irreversibility from microscopically reversible unitary dynamics is one of the major problems of statistical physics. As previously demonstrated, the microscopic origin of the entropy production can be explained as a result of generation of correlations between the initially uncorrelated degrees of freedom. Here we show that for small systems coupled to extended environments, in the broad range of physically relevant conditions, the entropy production is predominantly caused by the generation of the mutual information between the degrees of freedom within the environment rather than, as often assumed, between the system and the environment. It is because the latter contribution is strongly bounded from above by the Araki-Lieb inequality, and therefore is not time-extensive, in contrast to the entropy production itself. We also demonstrate that the system-environment mutual information may undergo conversion into the intra-environment correlations at timescales even longer than the relaxation time of the system.

Discussion session 2

Title: *Stochastic thermodynamics for strongly correlated complex systems*

Thursday, 28th May

Session 3
Chair: T. Sagawa

Yoshihiko Hasegawa

Title: *Thermodynamic uncertainty relation for open quantum systems*

Abstract: We use quantum estimation theory to derive a thermodynamic uncertainty relation in Markovian open quantum systems, which bounds the fluctuation of continuous measurements. The derived quantum thermodynamic uncertainty relation holds for arbitrary continuous measurements satisfying a scaling relation. We derive two relations; the first relation bounds the fluctuation by the dynamical activity and the second one by the entropy production. We apply our bounds to a two-level atom driven by a laser field and a three-level quantum thermal machine with jump and diffusion measurements. No matter how we measure quantum systems, observables satisfying the scaling relation should obey the quantum thermodynamic uncertainty relation, which cannot be deduced from the classical relations.

Sosuke Ito

Title: *Information geometry and thermodynamic uncertainty relationships*

Abstract: In this talk, I would like to review a relationship between thermodynamic uncertainty relationships and a differential geometric theory of information, i.e., information geometry.
In information geometry, the Fisher information of time is a measure of speed in a space of the probability simplex, and it is useful to understand stochastic dynamics of relaxation to a stationary state. I mainly discuss a duality between the Fisher information of time and the entropy production, which leads to several variants of thermodynamic uncertainty relationships.

Paul Riechers

Title: *The Error-Dissipation Tradeoff when Computing with Time-Symmetric Protocols*

Abstract: For both engineered computation in our digital devices and natural computation in nonequilibrium steady states, time-symmetric control appears to be a practical constraint. I will show that this constraint has profound thermodynamic implications. In particular, for non-reciprocated computations, dissipation must diverge as reliability increases. Reciprocity is stricter than logical reversibility; and it depends on the time-reversal symmetries of the memory elements involved. Hence, the time-reversal symmetries of the memory elements play a crucial role in determining whether a computation can be performed with thermodynamic efficiency.

Udo Seifert

Title: *The thermodynamic uncertainty relation*

Abstract: The thermodynamic uncertainty relation discovered in 2015 is arguably one of the most promising insights arising from stochastic thermodynamics. It relates the mean and fluctuations of any current to the overall entropy production in a non-equilibrium steady state. It provides a lower bound on the Inevitable cost of temporal precision of processes, leading, e.g. to the minimal cost for measuring time in a finite temperature environment. As a tool for thermodynamic inference, it gives, e.g., a model-free universal upper bound on the efficiency of molecular motors in terms of experimentally accessible observables.

Discussion session 3

Title: *Thermodynamic uncertainty relations for complex systems*

Session 4
Chair: D. Wolpert

Artemy Kolchinsky

Title: *Bounds on thermodynamic efficiency of physical processes with driving constraints*

(Artemy Kolchinsky, David H. Wolpert)

Abstract: We investigate the maximal extractable work and minimal entropy production (EP) involved in transforming a system from some initial distribution p some final distribution p′, given constraints on the available driving protocols. We derive several bounds on the EP which from constraints on symmetries, modularity, and coarse graining of the driving. We use our results to decompose information acquired in a measurement of a system into "useful information" (which can be used to extract work from the system) and "useless information" (which cannot be used to extract work from the system).

Michele Campisi

Title: *Thermodynamics of a Quantum Annealer*

(Lorenzo Buffoni, Michele Campisi)

Abstract: The D-wave processor is a partially controllable open quantum system which exchanges energy with its surrounding environment (in the form of heat) and with the external time dependent control fields (in the form of work). Despite being rarely thought as such, it is a thermodynamic machine. Here we investigate the properties of the D-Wave quantum annealers from a thermodynamical perspective. We performed a number of reverse-annealing experiments on the D-

Wave 2000Q via the open access cloud server Leap, with the aim of understanding what type of thermal operation the machine performs, and quantifying the degree of dissipation that accompanies it, as well as the amount of heat and work that it exchanges. The latter is a challenging task in view of the fact that one can experimentally access only the overall energy change occurring in the processor, (which is the sum of heat and work it receives). However, recent results of non-equilibrium thermodynamics (namely, the fluctuation theorem and the thermodynamic uncertainty relations), allow to calculate lower bounds on the average entropy production (which quantifies the degree of dissipation) as well as the average heat and work exchanges. The analysis of the collected experimental data shows that 1) in a reverse annealing process the D-Wave processor works as a thermal accelerator and 2) its evolution involves an increasing amount of dissipation with increasing transverse field.

References:
L. Buffoni, M. Campisi, arXiv:2003.02055

Jan Korbel

Title: *Second law, detailed balance and linear Markovian dynamics determine Shannon entropy*

(Jan Korbel, David H. Wolpert)

Abstract: In this talk, we consider a thermal system that satisfies three requirements: 1) The dynamics is Markovian 2) The local equilibrium distribution that maximizes the entropic functional fulfills local detailed balance and 3) the second law of thermodynamics is fulfilled. We show that these three requirements constrain the relation between the form of the master equation and the entropic functional. For the case of a linear master equation, we show that the entropic functional must be the Shannon entropy. On the other hand, for systems with a non-Boltzmann equilibrium distribution, the entropic functional is not Shannon entropy, and the dynamics cannot be Markovian and linear. As an example, we show this for the case of a system coupled to a finite heat bath.

Christopher Jarzynski

Title: *Thermalization via low-dimensional chaos*

Abstract: When a heavy, slow system interacts with a fast, low-dimensional chaotic system, the latter acts as a kind of miniature heat bath. The evolution of the slow system is described by a Fokker-Planck equation, with dissipation and diffusion coefficients that capture the effects of the fast, chaotic motion. Under these dynamics, the slow system evolves to a state of statistical equilibrium with the fast system, but this state is described by a non-Boltzmann probability distribution. This problem has been analyzed as a model in dynamical systems. Its description within the framework of stochastic thermodynamics remains to be established

Discussion session 4

Title: *Stochastic thermodynamics for non-Boltzmann equilibrium distributions*

Friday, 29th May

<u>*Session 5*</u>
Chair: J. Korbel

Keiji Saito

Title: *Fluctuating hydrodynamics in lattice systems: microscopic view and thermodynamics*

Abstract: The fluctuating hydrodynamics theory (FHT) has been an important tool for analyzing the nonequilibrium phenomena of lattice systems. However, despite its practical success, its microscopic derivation is still lacking. In this talk, we discuss the microscopic derivation of the FHT, using the coarse-graining and projection procedure; the ensemble equivalence turns out to be critical. The Green-Kubo like formula for the bare transports are presented and the numerical simulation shows that the bare transport coefficients exist for a large coarse-graining length. We also discuss the thermodynamic structure.

Alec Boyd

Title: *Time Symmetries of Memory Determines Thermodynamic Efficiency*

Abstract: Practical physical computers, such as modern digital electronics and biochemical systems, are subject to constraints that result in divergent dissipation for low-error computations. This *dissipation divergence* is explicitly dependent on both the computation at hand and the time symmetries of the memory device (the substrate of the computation). We find that a given computation may not dissipate at all when implemented in time-asymmetric magnetic memory, while the dissipation diverges maximally when implemented in time-symmetric positional memory, and vice versa. We derive a device-independent lower bound for the dissipation of a computation and show how to construct a memory with time symmetries that achieve that bound.

Kay Brandner

Title: *Quantum Jump Approach to Microscopic Heat Engines*

Abstract: Modern solid-state technologies could soon make it possible to scrutinize the operation cycles of quantum heat engines by counting the photons that are emitted and absorbed by their working systems. Using the quantum-jump approach to open-system dynamics, we show that such experiments would give access to a set of observables that determine the trade-off between power and efficiency in finite-time engine cycles. To this end, we investigate the single-jump statistics of thermodynamic fluxes such as heat currents and entropy production. Within this framework, we derive a general bound on the power of microscopic heat engines, which includes several earlier results as special cases and admits a transparent physical interpretation in terms of single-photon measurements. We illustrate our theory with a numerical simulation of a single-qubit engine, which is in reach of current technology.

Discussion on possibility of an annual virtual workshop
In this session, we will discuss the possibility of an annual virtual workshop on the topic of non-equilibrium thermodynamics. We will discuss the possible format of the workshop, how many days will be optimal, if the host institution should be rotating, etc. We will also call the participants for joining the organization committee of the discussed virtual annual workshop.

Discussion session 5

Title: *Information-theoretic measures for thermodynamics of complex systems*

<u>Session 6</u>
Chair: C. Jarzynski

Rudolf Hanel

Title: *Equilibrium and non-equilibrium thermodynamics of small systems with emergent structures*

(Jan Korbel, Simon D. Lindner, Rudolf Hanel, Stefan Thurner)

Abstract: We derive the entropy for a closed system of particles that can form structures, molecules in the simplest case. The entropy differs from the Boltzmann-Gibbs entropy by a term that captures the molecule states. For large systems the approach is equivalent to the grand canonical ensemble. For small systems, large molecules start to play a dominant role. The number of molecules becomes the key quantity and appears explicitly in the second law of thermodynamics and in fluctuation theorems.

References:
J. Korbel, S. D. Lindner, R. Hanel and S. Thurner, arXiv:2004.06491

Nihat Ay

Title: *On the Information-Geometric Perspective of Stochastic Thermodynamics*

Abstract: In the first part of my presentation, I will outline the core structures of Information Geometry. In particular, I will focus on dynamical systems given by a gradient vector field. In this context, the role of the Fisher-Rao metric in connection with the Kullback-Leibler divergence will be highlighted. In the second part, I will then outline corresponding structures relevant for an information-geometric theory of Stochastic Thermodynamics. This will lead us to a modification of the classical theory and connects to recent works on the so-called Wasserstein or optimal transport geometry**.**

Henrik Wilming

Title: *The effect of control restrictions in quantum thermodynamics*

Abstract: In the formulation of general thermodynamic bounds, we usually assume that an experimenter has unlimited control over the Hamiltonian of a working system. I revisit some older results and discuss, mostly in terms of simple toy-models, how restricted control leads to dissipation in thermodynamic cycles, even if the set of available Hamiltonians in principle allows one to implement arbitrary unitary time-evolution on the working-system. We also see that in such situations there exist "passive" out-of-equilibrium initial conditions from which no positive work can be extracted unless significant control is also available over the degrees of freedom of the heat bath.

Gavin Crooks

Title: tba

Abstract: tba

Discussion session 6

Title: *General features of non-equilibrium thermodynamics for complex systems*