DY 2: Stochastic thermodynamics and information processing

Time: Monday 9:30–12:30 Location: HÜL 186

Invited Talk DY 2.1 Mon 9:30 HÜL 186

Stochastic thermodynamics and the thermodynamic uncertainty relation — •Udo Seifert — Universität Stuttgart

Stochastic thermodynamics is a universal framework to describe driven systems in a thermodynamically consistent way. It has lead to universal relations like the Jarzynski relation and the fluctuation theorem. More recently, a new inequality, the thermodynamic uncertainty relation, has been found. It provides a constraint on the dispersion of any current in terms of the overall entropy production and can also be framed as bounding the inevitable cost of precision in any nonequilibrium process. I will discuss the origin of this relation, the generalization to a bound on extreme fluctuations, and show a few of its applications.

DY 2.2 Mon 10:00 HÜL 186

Stochastic thermodynamics based on incomplete information: Generalized Jarzynski equality with measurement errors with or without feedback — •Christopher Wächtler, Philipp Strasberg, and Tobias Brandes — Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstr. 36, 10623 Berlin, Germany

In the derivation of fluctuation relations, and in stochastic thermodynamics in general, it is tacitly assumed that we can measure the system perfectly, i.e., without measurement errors. We here demonstrate for a driven system immersed in a single heat bath, for which the classic Jarzynski equality [1] holds, how to relax this assumption. Based on a general measurement model akin to Bayesian inference we derive a general expression for the fluctuation relation of the *measured* work and we study the case of an overdamped Brownian particle in particular. We then generalize our results further and incorporate feedback in our description. We argue that, if measurement errors are fully taken into account by the agent who controls *and* observes the system, the standard Jarzynski-Sagawa-Ueda relation [2] should be formulated differently. We again explicitly demonstrate this for an overdamped Brownian particle where the fluctuation relation of the measured work differs significantly from the efficacy parameter [2]. Instead, the generalized fluctuation relation under feedback control, $\langle e^{-\beta(W-\Delta F)-I}\rangle = 1$, holds only for a superobserver having perfect access to *both* the system and detector degrees of freedom.

[1] C. Jarzynski, PRL 78, 2690 (1997).
[2] T. Sagawa and M. Ueda, PRL 104, 090602 (2010).

DY 2.3 Mon 10:15 HÜL 186

Quantum and Information Thermodynamics: A Unifying Framework based on Repeated Interactions — •Philipp Strasberg[1,2], Gernot Schaller[1], Tobias Brandes[1], and Massimiliano Esposito[2] — [1]Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstr. 36, D-10623 Berlin, Germany — [2]Complex Systems and Statistical Mechanics, Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg, Luxembourg

We expand the standard thermodynamic framework of a system coupled to a thermal reservoir by considering a stream of independently prepared units repeatedly put into contact with the system. These units can be in any nonequilibrium state and interact with the system with an arbitrary strength and duration. We show that this stream constitutes an effective resource of nonequilibrium free energy and unifies many previously separately studied phenomena. This includes, e.g., work and information reservoirs, Landauer's principle, Maxwell's demon, the micromaser, extraction of work from quantum coherence and much more. Some of these (but not all) applications are presented in the talk.

Reference: arXiv 1610.01829

DY 2.4 Mon 10:30 HÜL 186

Stochastic Thermodynamics of Learning — •Sebastian Goldt and Udo Seifert — II. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart

Virtually every organism gathers information about its noisy environment and builds models from that data, mostly using neural networks. Here, we use stochastic thermodynamics to analyse the efficiency of neural networks in two learning scenarios. We show that the total entropy production of the network bounds the information that the network can infer from data or learn from a teacher [1]. We introduce a learning efficiency $\eta \leq 1$ and discuss the conditions for optimal learning. Finally, we analyse the efficiency of the Hebbian, Perceptron and AdaTron learning algorithms, well-known from machine learning and statistical physics.

[1] S. Goldt and U. Seifert, Stochastic Thermodynamics of Learning. PRL, in press; arxiv:1611.09428

DY 2.5 Mon 10:45 HÜL 186

Cost and Precision of Brownian Clocks — •Andre C Barato — Max Planck Institute for the Physics of Complex Systems

Brownian clocks are biomolecular networks that can count time. A paradigmatic example are proteins that go through a cycle thus regulating some oscillatory behaviour in a living system. Typically, such a cycle requires free energy often provided by ATP hydrolysis. We investigate the relation between the precision of such a clock and its thermodynamic costs. For clocks driven by a constant thermodynamic force, a given precision requires a minimal cost that diverges as the uncertainty of the clock vanishes. In marked contrast, we show that a clock driven by a periodic variation of an external protocol can achieve arbitrary precision at arbitrarily low cost. This result constitutes a fundamental difference between processes driven by a fixed thermodynamic force and those driven periodically. As a main technical tool, we map a periodically driven system with a deterministic protocol to one subject to an external protocol that changes in stochastic time intervals, which simplifies calculations significantly.

Reference: [1] A. C. Barato and U. Seifert; Cost and precision of Brownian clocks; accepted in Phys. Rev. X, arXiv:1610.07960 (2016).

DY 2.6 Mon 11:00 HÜL 186

Extreme values of mesoscopic currents in physics and biology — •Edgar Roldan[1], Izaak Neri[1,2], Simone Pigolotti[1], and Frank Jülicher[1] — [1]Max Planck Institut fur Physik Komplexer Systeme — [2]Max Planck Institute for Molecular Cell Biology and Genetics

The dynamics of mesoscopic systems driven out of equilibrium often exhibits currents against the external driving, as shown in a plethora of experiments inter alia, colloidal systems trapped with optical tweezers and single molecule experiments with molecular motors. What is the maximal mesoscopic current against the external driving that can be observed in a given time? We show that the extreme-value statistics of active molecular processes are governed by the statistics of entropy production. For example, the infimum the entropy production during the stepping a molecular motor can be related to the maximal excursion of the motor against the direction of an external force. We recently derived the infimum law for entropy production: The negative record of entropy production in a given time cannot be below minus the Boltzmann constant. Using the Infimum Law, we make predictions for the distribution of the maximum backtrack depth of RNA polymerases and for the maximum distance traveled by a colloidal particle in a periodic potential against an external force. Our results are extensively validated with numerical simulations and are in agreement with experimental data.

References [1] I Neri, É Roldán, F Jülicher, arXiv:1604.04159 (2016).

15 min. break

DY 2.7 Mon 11:30 HÜL 186

Universality of Infima and Stopping Time Statistics of Entropy Production in Steady States — •Izaak Neri[1,2], Édgar Roldán[1], Simone Pigolotti[1], and Frank Jülicher[1] — [1]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [2]Max Planck Institute of Molecular Cell Biology and Genetics, Dresden, Germany

We show that the statistics of infima, stopping times and passage probabilities of entropy production in nonequilibrium steady states are universal. Our main results are: (i) the distribution of the global infimum of entropy production is exponential with mean equal to minus Boltzmann's constant; (ii) we find the exact expressions for the passage probabilities of entropy production to reach a given value; (iii) we derive a fluctuation theorem for stopping-time distributions of entropy production. Our work reveals the importance of martingales to nonequilibrium thermodynamics, since all our results follow from the martingality of entropy production.

DY 2.8 Mon 11:45 HÜL 186

Thermodynamics of error correction — •Simone Pigolotti[1] and Pablo Sartori[2] — [1]Max-Planck Institute for the Physics of Complex Systems, Dresden, Germany — [2]Rockefeller University, New York

Biological systems are able to replicate information with outstanding accuracy. In biochemical reactions, such as DNA duplication, different monomers can be distinguished because of their binding energies or via non-equilibrium kinetic mechanisms. I will show how, in simple copying reactions, these two discrimination modes are mutually exclusive and lead to opposite tradeoffs between error, dissipation and reaction velocity. In multi-step reactions, such as in kinetic proofreading, these different modes can be combined to improve overall accuracy. I will conclude by discussing how the second law of thermodynamics can be used to directly relate copying accuracy with thermodynamic observables.

DY 2.9 Mon 12:00 HÜL 186

Nonequilibrium Thermodynamics of Chemical Networks — •Riccardo Rao and Massimiliano Esposito — University of Luxembourg, Luxembourg, Luxembourg

Chemical Networks (CN) are large sets of coupled chemical reactions where some of the species are externally controlled. Cell metabolism and biochemical signal transduction networks are notable examples of CN. We present a rigorous nonequilibrium thermodynamic description of CN in terms of deterministic rate equations. Our description is inspired by Stochastic Thermodynamics and is based on Chemical Reaction Network Theory. The energy and entropy balances of CN are derived and a nonequilibrium Gibbs free energy is introduced. This latter is related to the chemical work necessary to create nonequilibrium states and to the driving work necessary to control the network far from equilibrium. We finally discuss these different forms of work in the stochastic framework.

R. Rao and M. Esposito, "Nonequilibrium Thermodynamics of Chemical Reaction Networks: Wisdom from Stochastic Thermodynamics", Accepted for publication in Phys. Rev. X, arXiv: 1602.07257.

DY 2.10 Mon 12:15 HÜL 186

Hidden and Emergent Cycles in Biochemical Reaction Networks — •Artur Wachtel, Matteo Polettini, and Massimiliano Esposito — Complex Systems and Statistical Mechanics, University of Luxembourg, Luxembourg

We study biochemical reaction networks which naturally arise in the molecular description of biological systems. On the macroscopic level, one describes the dynamics of these systems by differential rate equations, while on a microscopical level the dynamics is inherently stochastic, giving rise to a Markov jump process.

In this talk we give a classification of different topological cycles in these reaction networks: hidden and emergent cycles. The hidden cycles give rise to interesting dynamics and their absence implies agreement of the stochastic and deterministic descriptions. The emergent cycles on the other hand dictate the thermodynamic properties of the network. We exemplify our classification on real biochemical networks and on a small but illuminating toy model.

[1] Polettini, Esposito. J. Chem. Phys. 141, 024117 (2014)
[2] Polettini, Wachtel, Esposito. J. Chem. Phys. 143, 184103 (2015)