DY 21: Stochastic Thermodynamics

Time: Tuesday 9:30–12:45 Location: ZEU/0114

DY 21.1 Tue 9:30 ZEU/0114

Thermodynamic bounds and error correction for faulty coarse graining — •Jann van der Meer and Keiji Saito — Department of Physics No. 1, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

At the nanoscale, random effects govern not only the dynamics of a physical system but may also affect its observation. This work introduces a novel paradigm for coarse graining that eschews the assignment of a unique coarse-grained trajectory to a microscopic one. Instead, observations are not only coarse-grained but are also accompanied by a small chance of error. Formulating the problem in terms of path weights, we identify a condition on the structure of errors that ensures that the observed entropy production does not increase. As a result, the framework of stochastic thermodynamics for estimating entropy production can be extended to this broader class of systems. As an application, we consider Markov networks in which individual transitions can be observed but may be mistaken for each other. We motivate, derive, and illustrate thermodynamic bounds that relate the error sensitivity of the observed entropy production to the strength of the driving and are valid for arbitrary network topologies. If sufficiently many transitions in the network can be observed, redundancies in the coarse-grained trajectories can be used to detect and correct errors, which potentially improves naive estimates of entropy production. We conclude with an outlook on subsequent research on thermodynamic bounds for erroneous coarse graining.

DY 21.2 Tue 9:45 ZEU/0114

Between heat engine and information engine, characteristics of the entropy production rate in a Brownian ratchet. — Adrien Meynard, Marc Lagoin, Caroline Crauste-Thibierge, and •Antoine Naert — Univ Lyon, Ens de Lyon, Univ Claude Bernard, CNRS, Laboratoire de Physique, F-69342 Lyon, France

A two-state device such as a Brownian ratchet can be regarded as a *heat engine* or an *information engine*. Our experiment, at the centimeter scale, gives access to long time series of all observables of interest, resolved in time. These are the heat flux $\dot{q}_1(t)$ supplied by the hot (athermal) bath, at an (effective) temperature kT_1, and the work produced per unit time $\dot{w}(t)$.

Taking advantage of the discreet operation of such 1-bit elementary information device, an example of a Maxwell's demon, we can measure the rate of entropy production. We infer a comprehensive characterization of the rate of entropy produced by this device, in the Boltzmann sense. Our findings are compatible with a Poisson point process.

In steady state operation, this entropy is to be released as heat into the surrounding, at ambient temperature $k_B T_2$. (Note that $\dot{q}_2(t)$ is distinct from the various losses.) The heat over temperature ratios of the exchanges with the hot and cold baths are of the same order of magnitude:

$$\frac{\langle \dot{q}_1 \rangle}{kT_1} \simeq \frac{\langle \dot{q}_2 \rangle}{k_B T_2}. \tag{1}$$

We confirm that, within the limit of experimental uncertainties, entropy is conserved in a lossless heat engine, just like energy is.

DY 21.3 Tue 10:00 ZEU/0114

Minimum Action Principle for Entropy Production Rate of Far-From-Equilibrium Systems — •Atul Tanaji Mohite and Heiko Rieger — Department of Theoretical Physics and Center for Biophysics, Saarland University, Saarbrücken, Germany

The Boltzmann distribution connects the energetics of an equilibrium system with its statistical properties, and it is desirable to have a similar principle for non-equilibrium systems. Here, we derive a variational principle for the entropy production rate (EPR) of far-from-equilibrium discrete state systems, relating it to the action for the transition probability measure of discrete state processes [1,2]. This principle leads to a tighter, non-quadratic formulation of the dissipation function, speed limits, the thermodynamic-kinetic uncertainty relation, the large deviation rate functional, and the fluctuation relation, all within a unified framework of the thermodynamic length [2]. Additionally, the optimal control of non-conservative transition affinities using the underlying geodesic structure is explored, and the corresponding slow-driving and finite-time optimal driving exact protocols are analytically computed [1,3]. We demonstrate that discontinuous endpoint jumps in optimal protocols are a generic, model-independent physical mechanism that reduces entropy production during finite-time driving of far-from-equilibrium systems [3].

[1]A.T. Mohite and H. Riger, arXiv:2511.00967. [2]A.T. Mohite and H. Riger, arXiv:2511.00970. [3]A.T. Mohite and H. Riger, arXiv:2511.00974.

DY 21.4 Tue 10:15 ZEU/0114

Asymptotic limit laws of projected empirical currents — •Felix Tippner and Aljaz Godec — Mathematical Physics and Stochastic Dynamics, Institute of Physics, University of Freiburg (GER)

Most experimental measurements capture only a restricted subset of a system's degrees of freedom at any given time. As a result, the higher-dimensional stochastic process that describes the full physical system, such as the high-dimensional conformational dynamics of proteins, can typically be observed only in terms of low-dimensional projections, which are also subject to experimental and sampling constraints. These projections inevitably give rise to non-Markovian behaviour and typically obscure key features of the underlying dynamics, including irreversible probability currents that distinguish driven from reversible systems. The main result of the present work is an asymptotic limit law, i.e., a sharpening of the central limit theorem, for empirical currents of projected observables.

DY 21.5 Tue 10:30 ZEU/0114

Nonlinear Response Theory for Nonequilibrium Biochemical Networks — Ruicheng Bao[1] and •Shiling Liang[2,3,4] — [1]University of Tokyo, Tokyo, Japan — [2]MPI-PKS, Dresden, Germany — [3]MPI-CBG, Dresden, Germnay — [4]CSBD, Dresden, Germany

Living cells process information through biochemical networks operating far from equilibrium. Understanding how these systems respond to finite perturbations, such as changes in enzyme concentrations or metabolic fluxes, is essential, yet the fluctuation-dissipation theorem applies only near equilibrium.

This talk introduces a framework that fills this gap. We derive an exact identity that links nonlinear responses to linear ones through a physically meaningful scaling factor, based on a connection between steady-state responses and mean first-passage times. This provides bidirectional inference: predicting global responses from local biochemical changes, and inferring metabolic costs from measurable observables. We also establish a universal response-resolution limit, a strong-perturbation analogue of the fluctuation-dissipation theorem, which sets fundamental bounds on signal detectability.

Using transcriptional regulation as an example, we show how these parameter-independent bounds constrain the computational expressibility of gene networks. Reliable detection of transcription factor changes requires fold-changes above a universal threshold. Overall, this framework defines general physical limits on cellular information processing, with implications for metabolic control and signal transduction.

DY 21.6 Tue 10:45 ZEU/0114

Compensating random transition-detection blackouts in Markov networks — •Alexander Maier, Benjamin Häsler, and Udo Seifert — II. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart, Germany

In Markov networks, measurement blackouts with unknown frequency compromise observations such that thermodynamic quantities can no longer be inferred reliably. In particular, the observed currents neither discern equilibrium from non-equilibrium nor can they be used in extant estimators of entropy production. Our strategy to eliminate these effects is based on formally attributing the blackouts to a second channel connecting states. The unknown frequency of blackouts and the true underlying transition rates can be determined from the short-time limit of observed waiting-time distributions. A post-modification of observed trajectory data yields a virtual effective dynamics from which the lower bound on entropy production based on thermodynamic uncertainty relations can be recovered fully. Moreover, the post-processed data can be used in waiting-time based estimators. Crucially, our strategy does neither require the blackouts to occur homogeneously nor symmetrically under time-reversal. Reference: Alexander M. Maier, Benjamin Häsler and Udo Seifert, arXiv:2511.14679 (2025)

15 min. break

Invited Talk DY 21.7 Tue 11:15 ZEU/0114

Why Life Is Hot — •Tanja Schilling[1], Patrick Warren[2], and Wilson Poon[3] — [1]Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]The Hartree Centre, STFC Daresbury Laboratory, Warrington, WA4 4AD, United Kingdom — [3]School of Physics and Astronomy, The University of Edinburgh, Peter Guthrie Tait Road, Edinburgh EH9 3FD, United Kingdom

Biological organisms use strongly driven cycles to optimize the output of chemical reactions. This mechanism is versatile, it is employed to meet a large variety of cost functions such as robustness, precision, or sensitivity to external stimuli. However, the improvements over the equilibrium behaviour come at the cost of increased production of heat. We show that the heat generated by this mechanism constitutes a large part of the total heat produced by living organisms. Further we demonstrate that the effect saturates and that nature operates near saturation. Hence we conclude that the heat production of living organisms is consequence of their need to function accurately and to adapt flexibly to varying demands.

DY 21.8 Tue 11:45 ZEU/0114

Optimal Localisation against a Flow — •Till Welker and Patrick Pietzonka — School of Physics and Astronomy, University of Edinburgh, United Kingdom

How much work does it cost for a propelled particle to stay localised near a stationary target, defying thermal noise and a constant flow that would carry it away? We study the control of such a particle in finite time and find optimal protocols for time-dependent propulsion speed and diffusivity, without feedback. Accuracy, quantified via the mean squared deviation from the target, and energetic cost turn out to be connected by a trade-off relation, which complements the one between precision and cost known in stochastic thermodynamics. We show that accuracy better than a certain threshold requires active driving , which comes at a cost that increases with accuracy. The optimal protocols have discontinuous propulsion speed and diffusivity, switching between a passive drift state with vanishing diffusivity and an active propulsion state. If the initial position is fixed, an initial jump of the particle, enabled by a sudden burst of propulsion, can be optimal. This study highlights how a time-dependent diffusivity enhances optimal control and sets benchmarks for artificial self-propelled particles navigating noisy environments.

DY 21.9 Tue 12:00 ZEU/0114

Thermodynamic optimal control out of equilibrium: insights from active and driven systems — •Kristian Olsen[1], Rémi Goerlich[2,1], Yael Roichman[2,3], and Hartmut Löwen[1] — [1]Institut für Theoretische Physik II - Weiche Materie, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany — [2]Raymond & Beverly Sackler School of Chemistry, Tel Aviv University, Tel Aviv 6997801, Israel — [3]Raymond & Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Tel Aviv 6997801, Israel

Optimal control far from equilibrium raises intriguing questions in stochastic thermodynamics and offers a route to design microscopic engines that operate out of equilibrium. We study thermodynamically optimal protocols for a harmonically trapped particle driven by arbitrary time-dependent forces, including those from active matter or external fields [1]. The resulting protocols are able to harness non-equilibrium forces to extract a net work. We provide exact solutions for the optimal protocol and associated work for arbitrary forces and protocol duration. We also derive a quasistatic work bound that splits into three parts: an information-geometric term capturing energy stored in an initial non-equilibrium state, the work extracted from time-averaged forces, and extra work from fast dynamical modes. Finally, we analyze the energetic cost of adding boundary constraints, giving insights into the cost of precision in these protocols.

1. Harnessing non-equilibrium forces to optimize work extraction, Kristian Stølevik Olsen, Rémi Goerlich, Yael Roichman and Hartmut Löwen, In press Nature Communications, arXiv: 2504.07049, 2025.

DY 21.10 Tue 12:15 ZEU/0114

Searching with Memory: Experiments on Stochastic Resetting in Complex Fluids — •Felix Ginot and Clemens Bechinger — University of Konstanz, 78457 Konstanz, Germany

Many natural and technological search processes, from molecular reactions to robotic exploration, benefit from occasionally resetting and trying again. This mechanism, known as stochastic resetting (SR), is well understood in simple memoryless environments, but real systems often exhibit complex relaxation dynamics that retain information about recent motion.

We experimentally investigate SR in a viscoelastic fluid by tracking a colloidal particle undergoing controlled resets. The fluid's delayed elastic response creates restoring forces that oppose each reset and reduce search efficiency. We show that these memory effects can be tuned: holding the particle at the trap center allows the fluid to relax and erase residual memory. With a target present, this control significantly lowers the mean passage time, with optimal performance at intermediate resetting rates. In this regime, memory induces temporal correlations that bunch target encounters and speed up repeated hits.

These results demonstrate that environmental memory can both hinder and enhance search, and they point to new strategies for optimizing transport in non-Markovian media.

DY 21.11 Tue 12:30 ZEU/0114

Information as a Thermodynamic Resource in Non-Markovian Stochastic Systems — •Lokesh Chinnakanna Muruga, Felix Ginot, and Clemens Bechinger — Fachbereich Physik, Universität Konstanz, Konstanz, Germany

The interplay between information and thermodynamics lies at the core of modern stochastic physics. Classical thermodynamics links quantities such as entropy, temperature, and free energy solely to the physical state of a system. Contemporary developments from Maxwell demon and Szilard engine led to fluctuation theorems which revealed that information itself acts as a thermodynamic resource. The acquisition, storage, and use of information can reshape energy landscapes, enable work extraction, and modulate entropy production without violating the second law. In this work, we explore how information stored in unobserved degrees of freedom affects work extraction and equilibrium dynamics in stochastic systems. Using time-resolved position measurements of an optically trapped Brownian particle in a non-Markovian fluid, we show that correlations in the measurement encode memory effects that reveal multiple hidden configurational states. We introduce a new protocol to distinguish these information-bearing states experimentally and quantify their influence on relaxation and work extraction efficiency. Our results highlight how information, whether explicit or hidden can be leveraged as a functional resource for energy extraction and control at the microscale.