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EDITORIAL

Focus on stochastic thermodynamics

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Abstract

We introduce the thirty papers collected in this 'focus on' issue. The contributions explore conceptual issues within and around stochastic thermodynamics, use this framework for the theoretical modeling and experimental investigation of specific systems, and provide further perspectives on and for this active field.

Over the last ten years, stochastic thermodynamics has evolved into a comprehensive framework for describing small driven systems using the notions of classical thermodynamics like work, heat and entropy production on the level of individual fluctuating trajectories as reviewed in [1–4]. The present 'focus on' selection reports on the latest developments and presents new perspectives in the field, both theoretical and experimental. The thirty articles featured in this collection can roughly be ordered into six, partially overlapping, groups.

One original motivation for developing classical thermodynamics was to understand the laws governing heat engines and to optimize their performance. Within stochastic thermodynamics, these issues are explored for micro- and nano-sized engines which has led to new insight valid even for macroscopic engines. Calvo Hernandez *et al* discuss the role of a finite cycle-time and the inevitable dissipation coming with it in an approach that unifies heat engines and refrigerators for which they derive and discuss optimization criteria [5]. For such cyclic engines, Izumida and Okuda present a phenomenological theory along the lines of linear irreversible thermodynamics based on a local equilibrium assumption [6]. Sheng and Tu discuss a hidden symmetry and higher order constitutive relations for tightly coupled heat engines [7]. If a steady-state engine runs only for a finite time, output and input will be fluctuating quantities leading to the concept of stochastic efficiency that can be analyzed using a large deviation approach. Gingrich *et al* investigate the subtleties arising in time-asymmetric steady-state heat engines [8]. Proesmans and Van den Broeck investigate and illustrate stochastic efficiency with five case studies including examples of isothermal engines [9].

Molecular motors and, more generally, all cellular and biochemical processes typically run under isothermal conditions. A paradigmatic motor is the F1-ATPase for which Toyabe and Muneyuki present experimental results studying the response of single molecules to an external torque [10]. Two theoretical papers deal with the efficiency of molecular motors. Schmitt *et al* discuss the interplay between a power-stroke mechanism and rectification of thermal fluctuations through ATP consumption [11]. Zuckermann *et al* explore the role of persistence for creating linear motion without spatial or temporal asymmetry [12]. Copolymerization against an external force shares some similarities with molecular motors. Gaspard investigates how the force-velocity relation, entropy production and other quantities depends on the type of polymerization and the presence of disorder [13]. Lahiri *et al* study kinetics and thermodynamics of reversible polymerization in closed systems for two variants, with and without a total conservation law [14]. Hartich *et al* discuss the analogy between bacterial sensing and kinetic proofreading that emerges within a stochastic thermodynamics modelling of both processes [15].

Fluctuation relations provide constraints on the distribution of thermodynamic quantities like work, heat and entropy production. These results have the status of theorems under well-specified assumptions on initial states, dynamics and type of driving. It is crucial to explore in experiments how well the theoretical assumptions are matched in specific realizations as done here in three papers. Gieseler *et al* study fluctuation relations for a levitated nano-scale silica sphere in a low density gas parametrically driven by a periodically modulated laser trap [16]. The fluctuation theorem for entropy production involved in a transition from one steady-state to another is explored by Granger *et al* for an RC-circuit [17]. Alemany *et al* present data and theory on the modification of fluctuation theorems for partially equilibrated initial states of DNA-hairpins, closing with a perspective on thermodynamic inference based on partial experimental data [18].

Measurement and subsequent feedback control of a system coupled to a heat bath allows for processes that, at first sight, seem to violate the second law. If, however, the information gained in the measurement is integrated into the analysis, the second law is restored. Exploring this interface between thermodynamics and information theory is a lively topic in stochastic thermodynamics as several contributions in this collection show. Horowitz and Sandberg discuss the role of various information theoretic measures and how they correspond to the thermodynamic cost of acquiring information through measurement procedures [19]. Um *et al* study a similar issue for a two-level system and explore the efficiency of such an information machine [20]. Shiraishi *et al* deal with an autonomous information engine for which measurement and feedback are separated [21]. Bechhoefer discusses the role of measurement errors and feedback using the formalism of hidden Markov models that leads him to explore a phase transition in an information engine [22].

Many-body systems lead to emergent behaviour which is studied in several papers of this collection. Imparato investigates driven coupled oscillators that show a dynamical phase transition from a desynchronized to a synchronized state for which he determines power and efficiency at maximum power for different types of driving [23]. Sasa shows how the emerging collective dynamics in such systems at the transition can be determined and interpreted using concepts from stochastic and steady-state thermodynamics [24]. Experimental results for the work distribution of interacting colloidal particles forming a colloidal crystal that is driven across a commensurate periodic light field are presented by Gomez-Solano *et al* [25]. Transport in interacting systems is studied by Becker *et al* for a boundary driven set-up, for which they show simulations that support predictions from macroscopic fluctuation theory and the additivity principle [26]. For a driven many-particle system with zero-range interactions, Asban and Rahav derive an effective non-linear diffusion equation and discuss the applicability of the no-pumping theorem to such systems [27]. Transport through a double quantum dot coupled to a quantum point contact is analyzed by Cuetera and Esposito who derive the statistics of energy and particle currents [28].

Various conceptual and fundamental aspects are discussed in the last group of theoretical papers. Usually, the bath providing the embedding of the driven system is assumed to be equilibrated. Basu *et al* study the force on a probe particle when the whole medium is slighly driven and discuss how such a probe could be used operationally to measure excess quantities in steady state thermodynamics [29]. For a bath made up of quantum harmonic oscillators that are coupled to a driven quantum system, Aurell and Eichhorn identify three contributions to the change of the von Neumann entropy of the bath, two of which seem not to have a classical correspondence [30]. Typically, fluctuation relations are derived assuming a Hamiltonian or Markovian dynamics. Dieterich *et al* discuss such relations for anomalous dynamics based on fractional Fokker-Planck equations [31]. Ford discusses various measures of thermodynamic irreversibility with a focus on the role of initially non-symmetric velocity distributions [32]. Ma and Qian revisit the well-known multi-dimensional Ornstein-Uhlenbeck process as a paradigm of how to derive an emergent macroscopic description of a complex stochastic dynamics from its mesoscopic law of motion [33]. Last, but certainly not least, Knoch and Speck present a general new method of how to coarse-grain, or renormalize, Markov networks for systems driven into a steady state such that the entropy production of the original network remains preserved [34].

In conclusion, this collection shows on the one hand that stochastic thermodynamics has by now been well established as a useful framework for analyzing a large variety of non-equilibrium systems. On the other hand, there is still progress on exploring its conceptual foundations and extending its range of applicability towards neighboring fields. We hope that by browsing through this collection and by reading selected contributions, researchers from different communities get motivated to contribute to these activities with their expertise of concepts or of specific systems.

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