

Thermodynamic Length in Stochastic Thermodynamics of Far-From-Equilibrium Systems: Unification of Fluctuation Relation and Thermodynamic Uncertainty Relation

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The Boltzmann distribution for an equilibrium system constrains the statistics of the system by the energetics. Despite the non-equilibrium generalization of the Boltzmann distribution being studied extensively, a unified framework valid for far-from-equilibrium discrete state systems is lacking. Here, we derive an exact path-integral representation for discrete state processes and represent it using the exponential of the action for stochastic transition dynamics. Solving the variational problem, the effective action is shown to be equal to the inferred entropy production rate (a thermodynamic quantity) and a non-quadratic dissipation function of the thermodynamic length (TL) defined for microscopic stochastic currents (a dynamic quantity). This formulates a far-from-equilibrium analog of the Boltzmann distribution, namely, the minimum action principle. The non-quadratic dissipation function is physically attributed to incorporating non-Gaussian fluctuations or far-from-equilibrium non-conservative driving. Further, an exact large deviation dynamical rate functional is derived. The equivalence of the variational formulation with the information geometric formulation is proved. The non-quadratic TL recovers the non-quadratic thermodynamic-kinetic uncertainty relation (TKUR) and the speed limits, which are tighter than the close-to-equilibrium quadratic formulations. Moreover, if the transition affinities are known, the non-quadratic TL recovers the fluctuation relation (FR). The minimum action principle manifests the non-quadratic TKUR and FR as two faces corresponding to the thermodynamic inference and partial control descriptions, respectively. In addition, the validity of these results is extended to coarse-grained observable currents, strengthening the experimental/numerical applicability of them.

1. INTRODUCTION

The Boltzmann distribution is the most fundamental principle in Statistical Physics. It formulates an equivalence between thermodynamics and statistics for equilibrium systems, valid in the thermodynamic limit [1]. Finite-size/particle systems prone to non-equilibrium fluctuations are ubiquitous and violate the assumption of the thermodynamic limit. By relaxing the assumption of the thermodynamic limit, the framework of stochastic thermodynamics (ST) enables to define thermodynamic quantities for the stochastic transition of a microscopic system [2–4]. In ST, the thermodynamic dissipation cost to sustain non-equilibrium fluctuations and/or driving is quantified by the entropy production rate (EPR). Recently, ST has been extended to ‘non-reciprocal’ systems that violate ‘actio-reactio’ symmetry, and to coarse-grained macroscopic systems [5, 6] due to an exact coarse-graining of microscopic systems [6]. This has cemented the applicability of ST to experimentally/practically relevant real-world systems.

The fluctuation relation (FR) is a fundamental seminal law in ST, which connects the time-reversal asymmetry of dynamics to the stochastic thermodynamic cost [2–5, 7–26]. The first-order mean-field approximation of FR recovers the second law of thermodynamics (an approximate law). Recently, the Thermodynamic-Kinetic Uncertainty Relation (TKUR) has revealed a lower bound on thermodynamic dissipation (a thermodynamic quantity) using the current precision (a dynamic quantity) [27–34]. TKUR obtains a tighter lower bound on the thermodynamic dissipation required to

sustain a non-equilibrium process than the second law of thermodynamics. TKUR’s relation to Speed Limits (SL) has been explored [35–39]. FR and TKUR have been understood as different fundamental laws in ST, and the connection between them is missing. TKUR has been derived using FR [40–43], but the lower bound obtained on dissipation was loose [40–43]. Although TKUR has a practical advantage for thermodynamic inference, in contrast to FR, the fundamental/seminal origin of TKUR is debatable.

Non-equilibrium generalizations of the Boltzmann distribution have been explored extensively [26, 44–68], and its applications to biological systems are studied [69–72]. However, the non-equilibrium generalization of the Boltzmann distribution has two major drawbacks. First, a Gaussian approximation for fluctuations/driving, which is identified by a quadratic relation between EPR and driving forces/fluctuations [73–79]. The Gaussian approximation for fluctuations was originally derived to study close-to-equilibrium (cEQ) systems [80, 81] and extended to path-integral formalism around the mean-field description [82–85]: a top-down approach towards transition fluctuations. However, non-Gaussian fluctuations are important for far-from-equilibrium (fEQ) or finitely small size systems. Second, a coherent and unified description of fEQ systems grounded in a single underlying principle is missing, due to the contradictions between different formulations.

In this work, we derive the minimum action principle for the EPR of discrete state processes [86]. To this end, we use the second quantization method, namely, the Doi-Peliti field theory (DPFT), which preserves non-Gaussian transition fluctuations due to its bottom-up construction [8, 87–91]. We derive an exact transition probability measure for discrete state processes, which is equal to the exponential of the action. Hence, a variational formulation for discrete state pro-

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