

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

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(Dated: November 5, 2025)

The Boltzmann distribution for an equilibrium system constrain 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 generalisation 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 [6, 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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Fitness Landscapes and the Origin of Species Sergey Gavrilets,2018-06-05 The origin of species has fascinated both biologists and the general public since the publication of Darwin s Origin of Species in 1859 Significant progress in understanding the process was achieved in the modern synthesis when Theodosius Dobzhansky Ernst Mayr and others reconciled Mendelian genetics with Darwin s natural selection Although evolutionary biologists have developed significant new theory and data about speciation in the years since the modern synthesis this book represents the first systematic attempt to summarize and generalize what mathematical models tell us about the dynamics of speciation Fitness Landscapes and the Origin of Species presents both an overview of the forty years of previous theoretical research and the author s new results Sergey Gavrilets uses a unified framework based on the notion of fitness landscapes introduced by Sewall Wright in 1932 generalizing this notion to explore the consequences of the huge dimensionality of fitness landscapes that correspond to biological systems In contrast to previous theoretical work which was based largely on numerical simulations Gavrilets develops simple mathematical models that allow for analytical investigation and clear interpretation in biological terms Covering controversial topics including sympatric speciation and the effects of sexual conflict on speciation this book builds for the first time a general quantitative theory for the origin of species

Frontiers in Computational and Systems Biology Jianfeng Feng,Wenjiang Fu,Fengzhu Sun,2010-06-14 Biological and biomedical studies have entered a new era over the past two decades thanks to the wide use of mathematical models and computational approaches A booming of computational biology which sheerly was a theoretician s fantasy twenty years ago has become a reality Obsession with computational biology and theoretical approaches is evidenced in articles hailing the arrival of what are va ously called quantitative biology bioinformatics theoretical biology and systems biology New technologies and data

resources in genetics such as the International HapMap project enable large scale studies such as genome wide association studies which could potentially identify most common genetic variants as well as rare variants of the human DNA that may alter individual's susceptibility to disease and the response to medical treatment. Meanwhile the multi electrode recording from behaving animals makes it feasible to control the animal's mental activity which could potentially lead to the development of useful brain machine interfaces bracing the sheer volume of genetic genomic and other type of data an essential approach is first of all to avoid drowning the true signal in the data. It has been witnessed that theoretical approach to biology has emerged as a powerful and stimulating research paradigm in biological studies which in turn leads to a new search paradigm in mathematics physics and computer science and moves forward with the interplays among experimental studies and outcomes simulation studies and theoretical investigations

Facets of Systems Science George J. Klir, 2012-12-06 This book has a rather strange history. It began in spring 1989 thirteen years after our Systems Science Department at SUNY Binghamton was established when I was asked by a group of students in our doctoral program to have a meeting with them. The spokesman of the group Cliff Joslyn opened our meeting by stating its purpose I can closely paraphrase what he said. We called this meeting to discuss with you as Chairman of the Department a fundamental problem with our systems science curriculum. In general we consider it a good curriculum we learn a lot of concepts principles and methodological tools mathematical computational heuristic which are fundamental to understanding and dealing with systems. And yet we learn virtually nothing about systems science itself. What is systems science? What are its historical roots? What are its aims? Where does it stand and where is it likely to go? These are pressing questions to us. After all aren't we supposed to carry the systems science flag after we graduate from this program? We feel that a broad introductory course to systems science is urgently needed in the curriculum. Do you agree with this assessment? The answer was obvious and yet not easy to give. I agree of course but I do not see how the situation could be alleviated in the foreseeable future

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