Introduction

The conference is the 11th one of the biannual KIAS conferences on statistical physics since 2004. It aims to present new ideas in statistical physics and related fields and to facilitate scientific exchange and collaboration among leading scientists as well as students and postdocs. Information on the past conferences can be found in the tab named Links.

Topics include

nonequilibrium fluctuations and transport, stochastic thermodynamics, active matter, quantum information/thermodynamics, stochastic resetting, synchronization, bio-related problems, data science and machine learning, and more....

Organizers

Hyunggyu Park (KIAS)
Jae Sung Lee (KIAS)
Jae Dong Noh (UOS)
Yongjoo Baek (SNU)
David Mukamel (Weizmann)
Satya Majumdar (Orsay)

Program Schedule

The program consists of invited talks, contributed talks, and poster sessions.

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Day 1 – July 20 (Mon)

08:30-09:10	Registration/Coffee & Sandwiches	
09:10-09:20	Opening	
Morning Session Ⅰ		Chair : H. Park
09:20-10:00	H. Chaté	The Kuramoto–Vicsek model
10:00-10:40	J. Jeong	Motile Bacteria in 2D Complex Environments: A Statistical Physics Perspective
10:40-11:00	Break	
Morning Session Ⅱ		Chair : H. Rieger
11:00-11:40	H.-J. Zhou	Kinetic constraint-induced thermodynamic phase transitions in lattice spin models
11:40-12:00	S. Goh	Adaptive cohesion and pattern formation in pusher-type microswimmer suspensions
12:00-12:20	S. Awasthi	Hidden Dynamical Structure in Stochastic Intracellular Calcium Dynamics
12:20-15:00	Lunch	
Afternoon Session Ⅰ		Chair : S. N. Majumdar
15:00-15:40	H. J. Park	Can We Select Desired Microbial Collectives? Answers from Statistical Physics
15:40-16:20	D. Gupta	Cost of Non-instantaneous Stochastic Resetting
16:20-16:40	Break	
Afternoon Session Ⅱ		Chair : R. Golestanian
16:40-17:20	N. Shiraishi	Recent theoretical advances on integrability and non-integrability in quantum many-body systems
17:20-17:40	M. Ha	Dynamics of a local defect in one-dimensional driven flow: Interplay of jamming, condensation, and tracer diffusion
17:40-19:00	Poster Session	

Day 2 – July 21 (Tue)

08:30-09:20	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : H. Chaté
09:20-10:00	H. Reiger	Non-reciprocal flocking
10:00-10:40	J. S. Lee	Unified Hierarchy of Fluctuation-Response Identities and Inequalities in Nonequilibrium Markovian Dynamics
10:40-11:00	Break	
	Morning Session Ⅱ	Chair : J. Bechhoefer
11:00-11:40	R. Golestanian	Quantifying Dissipation in Active Matter
11:40-12:00	J.-M. Park	Distinguishing Chaos from Noise through Cross Prediction with Reservoir Computing
12:00-12:20	Y. Bae	Minibatch SGD without Replacement Drives Stable Convergence to Flat Minima
12:20-15:00	Photo / Lunch	
	Afternoon Session Ⅰ	Chair : J. Jeong
15:00-15:40	D.-S. Lee	Inflationary Metabolic Evolution and Heterogeneous Reaction Popularity
15:40-16:20	S. Jun	Towards Econophysiology
16:20-16:40	Break	
	Afternoon Session Ⅱ	Chair : L.-H. Tang
16:40-17:20	J. Jo	Functional oscillators interacting with environment
17:20-17:40	A. L. Chanu	Ordinal-Pattern-Based Analysis of Human Brain States from EEG Phase Dynamics
17:40-18:00	Break	
18:00-20:00	Banquet	

Day 3 – July 22 (Wed)

08:30-09:20	Coffee & Sandwiches	
Morning Session Ⅰ		Chair : H. J. Park
09:20-10:00	L.-H. Tang	From Bricks to Mansions: Zero-Energy Loops, Entropic Basins, and the Organization of Ground States in the 2D Spin Glass
10:00-10:40	S. Krishnamurthy	Finite-time Information Erasure (in Classical and Quantum Systems)
10:40-11:00	Break	
Morning Session Ⅱ		Chair : G. Oshanin
11:00-11:40	J. Bechhoefer	An information engine with high performance and efficiency
11:40-12:00	E. Kwon	Frequency-domain fluctuation–response relation as a diagnostic tool for nonequilibrium spectra
12:00-12:20	Y. Huang	Energy Conversion and Fluctuation Relations in Lévy Active Matter
12:20-13:30	Lunch	
13:30-20:00	**Excursion & Dinner**	

Day 4 – July 23 (Thu)

08:30-09:20	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : S. Krishnamurthy
09:20-10:00	G. Oshanin	Ornstein-Uhlenbeck Process Driven by Multiple Dichotomous Noises
10:00-10:40	Y. Baek	Inference of fluctuating information flow via machine learning
10:40-11:00	Break	
	Morning Session Ⅱ	Chair : H.-J.Zhou
11:00-11:20	E. Tjhung	Exact Results in Stochastic Processes with Division, Death, and Diffusion
11:20-11:40	H.-T. Han	Neural Estimation of Entropy Production in Coarse-Grained Systems via Trajectory Snippets: Application to Molecular Catenane Motors
11:40-12:20	S. N. Majumdar	Dynamically Emergent Correlations
12:20-15:00	**Closing & Lunch**	

[Talk 1]

The Kuramoto-Vicsek model

Hugues Chaté[1], Xia-qing Shi[2], Bruno Ventéjou[3], and Yujia Wang[2]
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[2]*Soochow University, Suzhou, China*
[3]*Université Grenoble-Alpes, France*

The Vicsek model is perhaps the most famous model in active matter studies. One can see it as an XY model where the spins move off-lattice at constant speed. This forces the model out-of-equilibrium, and allows for true long-range polar order in 2D. The Vicsek model is also well-known for exhibiting spontaneous segregation into dense and ordered structures traveling in a sparse gas.

There is one obvious way to introduce chirality in the Vicsek model: endow each constant-speed self-propelled particle with an intrinsic frequency/chirality. In continuous time, the equation governing the polarity of particles then becomes akin to that defining the famous Kuramoto model for synchronization, but for the fact that coupling is local in physical space.

This Kuramoto-Vicsek model is an ideal playground to study (dry) chiral aligning active matter. Over the last few years, we have uncovered quite a number of its remarkable properties. This talk will try to present them in a synthetic way.

[Talk 2]

Motile Bacteria in 2D Complex Environments: A Statistical Physics Perspective

Joonwoo Jeong[1]
[1]*Department of Physics, UNIST, Ulsan, Republic of Korea*

We present our experimental work, in which we employ motile bacteria as 'active colloids' in complex environments to explore nonequilibrium statistical physics.

First, we investigate how the active motility of these 'colloids' affects their partitioning behavior between two immiscible phases in an aqueous two-phase system, reminiscent of a two-level system in statistical mechanics. While 'dead' colloids follow the Boltzmann distribution, active motility facilitates barrier crossing. Our optical tweezer experiments, where we drag the bacteria across these interfaces, further elucidate the crossing events associated with interfacial tension. We conclude this section by introducing our Smoluchowski-style interpretation of the experimental data.

Second, we address the trap-and-escape dynamics of a 'colloid' within a soft confinement generated by another colloid. A bacterium swimming in a viscoelastic, slowly relaxing polymeric environment leaves behind a transient polymer-depleted trail that can 'trap' another swimming bacterium. Combining fluorescence optical microscopy, rheometry, and statistical analysis, we explain our experimental observations, showing that a higher polymer concentration and a shorter time lag between the leading and trapped bacteria result in longer mean escape times.

[1] J. Cheon, K. H. Choi, K. J. Modica, R. J. Mitchell, S. C. Takatori, J. Jeong, Phys. Rev. Lett. 135 (12), 128401 (2025)

[Talk 3]

Kinetic constraint-induced thermodynamic phase transitions in lattice spin models

Hai-Jun Zhou[1]
[1]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing*

The Fredrickson-Andersen (FA) model with hyperparameter K = 1 is a severely constrained kinetic lattice spin system, such that any site is temporarily blocked from changing its packing state (empty or occupied) if there is one or more occupied nearest neighbors. Starting from a completely random initial configuration with a fraction rho of sites being occupied, some of the sites may be permanently frozen to their initial state under this severe kinetic constraint. The remaining sites can switch states at least occasionally, and they form the unfrozen subsystem associated with the given initial configuration. The FA model is one of the basic models for understanding glassy dynamics [1].

In the present work we investigate thermodynamic phase transitions in such unfrozen subsystems of the two-dimensional square lattice and the three-dimensional cubic lattice by extensive numerical simulations [2]. We demonstrate that the giant connected component of the unfrozen subsystem will collapse at certain critical value rho_c of initial packing density, with rho_c = 0.2475 for the square lattice and rho_c = 0.2809 for the cubic lattice. This phase transition belongs to the same universality class of the conventional site percolation transition. We also observe that the ground states (densest packing configurations) experience a continuous crystal-to-glass phase transition at the critical value rho* = 0.1429 of initial packing density for the cubic lattice. For the two-dimensional square lattice we argue that long-range crystalline order is destroyed in the ground states as long as the initial packing density rho is positive.

We also extend this work to the case of K = 2, in which any site is temporarily blocked from changing its packing state if there are two or more occupied nearest neighbors. We also observe continuous phase transitions in three-dimensional cubic lattice.

[1] Hai-Jun Zhou, Chinese Physics B 33, 066402 (2024).

[2] Ruifeng Liu, Jianwen Zhou, Yejia Chen, Jiahang Chen, and Hai-Jun Zhou, Physical Review E (2026) under review.

[Talk 4]

Adaptive cohesion and pattern formation in pusher-type microswimmer suspensions

Segun Goh[1,2], Elmar Westphal[3], Roland G. Winkler[2], and Gerhard Gompper[2]
[1]*School of Liberal Studies, Sejong University, Korea*
[2]*Theoretical Physics of Living Matter, Institute for Advanced Simulation, Forschungszentrum Jülich, Germany*
[3]*Peter Grünberg Institute and Jülich Centre for Neutron Science, Forschungszentrum Jülich, Germany*

The emergence of dynamic structures and patterns is a hallmark of both biological and artificial active matter systems. Collective behavior in such systems is not solely determined by physical interactions between agents, but often relies on sensing of their environment, information processing, decision making and goal-oriented adaptation, implying the prevalence of non-reciprocal interactions. Here, we demonstrate that non-reciprocal cohesive adaptation, widely used to describe clustering tendencies in active systems, may give rise to long-lived filamentous patterns in pusher suspensions. This is surprising because extensile active stresses generated by self-propulsion are known to promote hydrodynamic instabilities, particularly for aligning particles, which results in chaotic dynamics [1]. Combining mesoscale hydrodynamic simulations with linear stability analysis of a generic model for active suspensions, we show that cohesion can indeed facilitate chain- and ring-like patterns in certain limiting cases. Our findings may provide guidance for controlling and stabilizing complex patterns in active microrobotic systems.

[1] S. Goh, E. Westphal, R. G. Winkler, and G. Gompper, Phys. Rev. Res. 7, 013142 (2025).

[Talk 5]

Hidden Dynamical Structure in Stochastic Intracellular Calcium Dynamics

Jaesung Choi[1], Athokpam Langlen Chanu[2,3], and Shakul Awasthi[4]
[1]*Center for Artificial Intelligence and Natural Sciences, Korea Institute for Advanced Study*
[2]*Asia Pacific Center for Theoretical Physics*
[3]*Department of Physics, Pohang University of Science and Technology*
[3]*School of Physics, Korea Institute for Advanced Study*

Intracellular calcium dynamics offer a biologically vital example of a noisy nonlinear system exhibiting diverse behaviors, including simple oscillations, bursting, and chaos. While deterministic models predict distinct dynamical regimes, intrinsic fluctuations from finite molecular populations in real cells often obscure these signatures. This raises the question of whether the underlying deterministic organization survives under realistic biological noise.

To address this, we use a stochastic model based on the feedback between calcium release and degradation, generating eight distinct dynamical states via a chemical Langevin description. Under realistic noise, these states become visually and statistically indistinguishable. We deploy a large-kernel convolutional neural network (CNN) designed to capture long-range temporal correlations over multiple oscillation cycles. Trained entirely on synthetic trajectories, the network distinguishes the eight noisy states with 90% accuracy.

Furthermore, the CNN generalizes remarkably well to real experimental calcium trajectories from pancreatic beta cells, achieving 96.8% classification accuracy. These results demonstrate that intrinsic cellular noise blurs but does not destroy the parameter-dependent deterministic structure of calcium oscillations. More broadly, this study proves that complex temporal patterns can be successfully recovered from highly fluctuating biological data using tailored deep learning methods.

Reference: J. Choi, A. L. Chanu, and S. Awasthi, PLOS Computational Biology 22, e1014240 (2026). DOI: 10.1371/journal.pcbi.1014240.

[Talk 6]

Can We Select Desired Microbial Collectives? Answers from Statistical Physics

Juhee Lee[1], Seong-Gyu Yang[1], Hye Jin Park[2], and Ludvig Lizana[1]
[1]*Integrated Science Lab, Department of Physics, Umeå University*
[2]*Department of Physics, Inha University*

Microbial collectives can perform complex functions — such as waste degradation, probiotic activity, and nutrient synthesis — that no single member species could achieve alone. Engineering such collectives through artificial selection holds great promise, yet the conditions under which selection succeeds or fails remain poorly understood.

The growth and death of microbial cells can be understood as a reaction scheme, a stochastic dynamics for which physics provides well-developed analytical tools. Thus, we use these tools to study collective selection. In our earlier work [1], we modeled collectives comprising slow- and fast-growing subpopulations undergoing repeated maturation-selection-reproduction cycles. Using Gaussian approximations and extreme value theory, we derived analytical conditions for selection success and showed that achievable target compositions depend critically on both the target and the initial collective composition.

Building on this foundation, we recently developed a more general and unified theoretical framework [2]. The selection protocol involves two dynamic timescales — bacterial doubling time and maturation duration — whose interplay maps naturally onto the mathematics of stochastic resetting. We treat the collective state as an effective particle evolving in a potential landscape, with resetting events governed by the group's extreme values. Via renewal theory and a Fokker-Planck formulation, this framework yields closed-form expressions for stationary distributions, capturing the long-time behavior of iterative selection dynamics in a transparent and analytically tractable way. Beyond microbial collectives, the framework applies broadly to group-resetting processes, as we demonstrate through an application to collective avoidance behavior. Together, these results offer a principled theoretical language for understanding and designing artificial selection protocols for microbial collectives.

[1] J. Lee, W. Shou, H. J. Park, eLife 13, RP97461 (2025).
[2] J. Lee, S.-G. Yang, H. J. Park, L. Lizana, Phys. Rev. Research 8, 013227 (2026).

[Talk 7]

Cost of Non-instantaneous Stochastic Resetting

Deepak Gupta

Technical University of Berlin, Germany

The physics of stochastic resetting has gained particular attention in recent years [1]. In general, stochastic resetting involves resetting a dynamical system to a prescribed state at random times, thereby interrupting its natural evolution. This mechanism is observed in various scientific disciplines, ranging from animal foraging strategies and computer algorithms to extreme events and target search processes in chemical and biological systems.

Recent experiments [2] have implemented resetting employing an external trap, whereby a system relaxes to the minimum of the trap and is reset in a finite time (in contrast to instantaneous resetting reported originally in Ref. [1]). In this talk, I will discuss the thermodynamic cost associated with such a stochastic resetting protocol. I will present a general framework, valid even for non-Poissonian resetting, that captures the thermodynamic work required to maintain a resetting process up to a given observation time. This framework enables us to calculate the moment-generating function of this work exactly. Moreover, I will discuss the regimes of optimization of the thermodynamic cost [3,4].

References:

1. M. R. Evans and S. N. Majumdar. Diffusion with stochastic resetting. Phys. Rev. Lett. 106, 160601 (2011).
1. R. Goerlich et al. Taming a Maxwell's demon for experimental stochastic resetting. Phys. Rev. E 112, 064116 (2025).
2. D. Gupta and C. A. Plata. Work fluctuations for diffusion dynamics submitted to stochastic return, New J. Phys. 24, 113034 (2022).
3. K. S. Olsen, D. Gupta, F. Mori, and S. Krishnamurthy. Thermodynamic cost of finite-time stochastic resetting, Phys. Rev. Res. 6, 033343 (2024).

[Talk 8]

Recent theoretical advances on integrability and non-integrability in quantum many-body systems

Naoto Shiraishi[1]

[1]*Graduate School of Arts and Sciences, the University of Tokyo*

We consider integrability and non-integrability of quantum spin chains. Here, the word integrable/non-integrable stands for the presence/absence of nontrivial local conserved quantities.

In the first part, we investigate a striking dichotomy. All quantum spin chains studied so far fall into two extremes: either the system possesses k-local conserved quantities for all k (complete integrability), or it possesses none at all (non-integrability). However, this dichotomy has remained entirely unexplained from a mathematical point of view. In this work, we rigorously prove the dichotomy for several classes of quantum spin chains. For nearest-neighbor, inversion-symmetric spin-1/2 chains, we prove this dichotomy by giving a complete classification into completely integrable and non-integrable models [1,2]. In particular, we show that all models other than the known integrable models are non-integrable. We also establish the dichotomy for SU(2)-symmetric spin-S chains with arbitrary S [3]. In this setting, we further show that the two cases are distinguished by an extremely simple computable quantity D^3: the model is completely integrable if (D^3=0), and non-integrable otherwise.

In the second part, we shed new light on quantum integrability. In the standard approach based on the Yang--Baxter equation, one starts from an R-matrix, and the Hamiltonian is obtained from logarithmic derivatives of the transfer matrix. Therefore, to solve a given Hamiltonian, one has to find a suitable R-matrix by a kind of craftsmanship, and thus it is far from obvious whether such an R-matrix exists. In contrast, we prove that Yang-Baxter solvability can be determined simply by examining a nested commutator of the local Hamiltonian [4]. This criterion, which is equivalent to the Reshetikhin condition, is also the lowest-order nontrivial consequence of the Yang-Baxter equation. Our result therefore reveals a surprising structure: the lowest-order relation already contains the full information of the Yang-Baxter equation.

[1] Mizuki Yamaguchi, Yuuya Chiba, Naoto Shiraishi, arXiv:2411.02162
[2] Mizuki Yamaguchi, Yuuya Chiba, Naoto Shiraishi, arXiv:2411.02163
[3] Naoto Shiraishi and Mizuki Yamaguchi, Phys. Rev. B 113, L241111 (2026)
[4] Naoto Shiraishi, Mizuki Yamaguchi, and Fuga Ishii, in preparation

[Talk 9]

Dynamics of a local defect in one-dimensional driven flow: Interplay of jamming, condensation, and tracer diffusion

Meesoon Ha
Department of Physics Education, Chosun University, Korea

We investigate the dynamics of a localized defect, known as the slow-bond (SB), in one-dimensional driven flows to uncover how particle interactions and defect-induced jamming shape the Kardar-Parisi-Zhang (KPZ) universality class. First, we introduce zero-range process (ZRP) hopping rates into the totally asymmetric simple exclusion process (TASEP) to explore the competition between SB-induced jamming and interaction-driven condensation. We construct a comprehensive phase diagram demonstrating that specific particle interactions actively suppress the jamming effect, thereby localizing the defect's impact in the thermodynamic limit. Furthermore, we deploy positive and negative passive tracer dynamics to probe the asymptotic KPZ properties of this modified system. By tracking the anomalous diffusion and displacement distributions of these tracers, we systematically reveal how the localized defect deforms KPZ universal dynamics.

[1] H. Soh and M. Ha, J. Stat. Mech. (2019) 094009.
[2] H. Soh, M. Ha, and H. Jeong, Phys. Rev. E **97**, 032120 (2018).
[3] H. Soh, Y. Baek, M. Ha, and H. Jeong, Phys. Rev. E **95**, 042123 (2017).

[Talk 10]

Non-reciprocal flocking

Heiko Rieger[1], Chul-Ung Woo[1], Jiwon Choi[1], Astik Haldar[1], and Jae Dong Noh[1,2]
[1]*Department of Physics, Saarland University, Germany*
[2]*Department of Physics, University of Seoul, Korea*

Non-reciprocal interactions in active matter gives rise to a multitude of fascinating phenomena among which are collective oscillatory states without intrinsic particle chirality and active turbulence. In a paradigmatic model for non-reciprocal flocking, the two species Vicsek model, we show that these two states coexist: chiral order for small flocks, and extensive spatiotemporal chaos for large flocks, both separated by a finite wavelength instability whose scale is set by the rotation radius of the chiral orbits. For system sizes larger than this length scale extensive spatiotemporal chaos unfolds, as manifested by a number of positive Lyapunov exponents that scales linearly with the system size. Moreover, it turns out that chiral quasi-long-range order can exist when density fluctuations are excluded. Finally, we discuss non-reciprocal flocking models with multiple species, one with symmetric phase shifts and one with random interactions.

[Talk 11]

Unified Hierarchy of Fluctuation-Response Identities and Inequalities in Nonequilibrium Markovian Dynamics

Hyun-Myung Chun[1], Euijoon Kwon[2], Hyunggyu Park[2], Jae Sung Lee[1,2]
[1]*School of Physics, Korea Institute for Advanced Study*
[2]*Quantum Universe Center, Korea Institute for Advanced Study*

Understanding the relationship between fluctuations and response is a central problem in nonequilibrium statistical physics. While the fluctuation-dissipation theorem provides this connection near equilibrium, a general framework valid far from equilibrium remains incomplete. In this talk, I present a unified fluctuation-response framework for nonequilibrium Markovian dynamics. For discrete-state systems described by Markov jump processes, we derive fluctuation-response identities and inequalities that relate fluctuations of general observables to their responses to perturbations of transition rates. Extending these ideas to continuous-state systems, we establish a fluctuation-response theory for Langevin dynamics that connects global fluctuations of observables to their responses to perturbations in force, mobility, and temperature. Together, these results reveal a unified hierarchical structure linking various identities and inequalities, in particular clarifying the relationship between the fluctuation-dissipation theorem and thermodynamic uncertainty relations.

References

[1] E. Kwon, H.-M. Chun, H. Park, and J. S. Lee, Phys. Rev. Lett 135, 097101 (2025).
[2] H.-M. Chun, E. Kwon, H. Park, and J. S. Lee, preprint arXiv:2601.16387.
[3] E. Kwon, H.-M. Chun, H. Park, and J. S. Lee, preprint arXiv:2605.05038.

[Talk 12]

Quantifying Dissipation in Active Matter

Ramin Golestanian[1,2]

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[2]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3PU, United Kingdom*

The intersection of stochastic thermodynamics and active matter is a very exciting and active field with great potential for opening new horizons for both disciplines. There are a number of important questions in the field: (1) How can we quantify dissipation? (2) How can we control active matter? (3) How can we build thermodynamically-consistent frameworks? (4) What is the role of momentum conservation? (5) Why should we care about dissipation? To answer these questions, we need to incorporate a minimal amount of the mechanistic aspects of active matter. In this talk, I will address these questions and present concrete examples in which one can obtain partial answers.

[1] R. Golestanian and A. Ajdari, Phys. Rev. E 77, 036308 (2008)
[2] B. Nasouri, A. Vilfan, and R. Golestanian, Phys. Rev. F 4, 073101 (2019)
[3] B. Nasouri, A. Vilfan, and R. Golestanian, Phys. Rev. Lett. 126, 034503 (2021)
[4] A. Daddi-Moussa-Ider, R. Golestanian, and A. Vilfan, Nat. Commun. 14, 6060 (2023)
[5] M. Chatzittofi, J. Agudo-Canalejo, and R. Golestanian, Phys. Rev. Res. 6, L022044 (2024)
[6] R. Bebon, J. F. Robinson, and T. Speck, Phys. Rev. X 15, 021050 (2025)
[7] R. Golestanian, Phys. Rev. Lett. 134, 207101 (2025)
[8] M.K. Johnsrud and R. Golestanian, Phys. Rev. Res. 7, L032053 (2025)
[9] M.K. Johnsrud and R. Golestanian, Phys. Rev. Res. 7, L032054 (2025)

[Talk 13]

Distinguishing Chaos from Noise through Cross Prediction with Reservoir Computing

Jaesung Choi[1], Athokpam Langlen Chanu[2,3], and Jong-Min Park[2,3]
[1]*Center for Artificial Intelligence and Natural Sciences, Korea Institute for Advanced Study*
[2]*Asia Pacific Center for Theoretical Physics*
[3]*Department of Physics, Pohang University of Science and Technology*

Many time series observed in nature exhibit irregular and seemingly unpredictable fluctuations. Determining whether such behavior originates from chaotic dynamics or from intrinsic stochastic fluctuations is a longstanding challenge in nonlinear science and time-series analysis. Although a variety of methods have been developed for this purpose, reliable discrimination remains difficult because stochastic processes can often mimic characteristic signatures of chaos. In this talk, I will present a learning-based framework for distinguishing chaotic dynamics from stochastic processes using time-series data. The proposed approach is motivated by the observation that conventional short-term prediction methods can be misled by stochastic processes with strong temporal correlations, which may exhibit apparent predictability despite the absence of an underlying deterministic rule. To overcome this limitation, we introduce a cross-prediction strategy in which the future change of a variable is predicted from its current value. This prediction task requires not only short-term predictability but also the ability to infer the deterministic structure governing the dynamics, providing a more stringent test for chaos. Implemented using reservoir computing, the framework yields a simple quantitative criterion for distinguishing chaos from noise based on the coefficient of determination between true and predicted future changes. Applications to a wide range of synthetic chaotic and stochastic systems reveal a clear separation between the two classes. We further apply the method to several empirical datasets previously analyzed in the literature and obtain classifications largely consistent with existing evidence. These results demonstrate that the proposed approach provides a simple, robust, and broadly applicable tool for distinguishing chaos from noise in time-series observations.

[Talk 14]

Minibatch SGD without Replacement Drives Stable Convergence to Flat Minima

Minseok M. Kim[1], Yongjae Oh[1], Euijoon Kwon[2], Yunsik Choe[1],
Yongjoo Baek[1], and ***Youngkyoung Bae***[1]
[1]*Department of Physics and Astronomy, Seoul National University*
[2]*School of Physics, Korea Institute for Advanced Study*

While the implicit regularization of Stochastic Gradient Descent (SGD) is often attributed to the spatial covariance of gradient noise, the impact of its temporal correlations remains underexplored. Notably, recent studies have revealed that standard minibatch sampling without replacement inherently induces temporal anti-correlations in the gradient noise. To isolate and examine the effects of this anti-correlation in SGD, we introduce a tunable temporal anti-correlation into the gradient updates. By analyzing the effective dynamics with a finite learning rate in the over-parameterized regime, we prove that anti-correlated noise induces a Hessian-dependent implicit regularizer that drives optimization toward flat minima. Importantly, we identify a stability-regularization trade-off governed by the correlation time: while strong anti-correlation suppresses parameter fluctuations, a moderate level is required to maximize the bias toward flatness. We empirically validate our theory on matrix sensing and image classification tasks, demonstrating that controlling the temporal structure of the noise outperforms standard SGD.

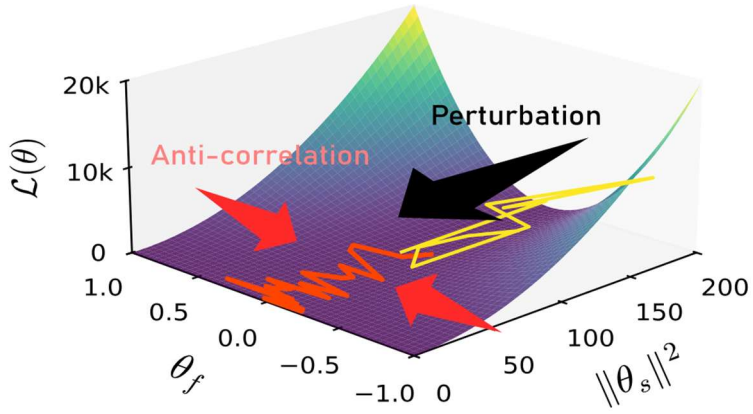

Figure 1. Schematics of the role of anti-correlated noise, in the SGD dynamics on the widening valley model (background loss surface). Red (yellow) line shows a path of parameters driven by anti-correlated (randomly perturbed) noise.

[Talk 15]

Inflationary Metabolic Evolution and Heterogeneous Reaction Popularity

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Bacterial metabolism exhibits both universality and diversity across species. Although most bacterial species contain similar numbers of metabolic reactions, the popularity of reactions across species is highly heterogeneous and follows a broad power-law distribution. We investigate how such statistical organization emerges from the evolutionary dynamics of metabolism by combining network evolution modeling with large-scale comparative analysis of bacterial metabolic repertoires [1].

Our framework describes metabolism as a growing evolutionary system in which reactions are recruited into metabolic networks and inherited along branching species lineages. We further reconstruct metabolism-based evolutionary histories directly from empirical reaction sets of thousands of bacterial species, allowing evolutionary trajectories to be inferred from present-day metabolic compositions. The analysis reveals an early inflationary phase of metabolic expansion, followed by increasingly heterogeneous reaction recruitment during diversification. These evolutionary patterns naturally explain the broad distribution of reaction popularity across species and indicate that extant metabolic repertoires retain measurable signatures of their evolutionary history.

[1] M.J. Lee and D.-S. Lee, Heterogeneous Popularity of Metabolic Reactions from Evolution, Phys. Rev. Lett. 132, 018401 (2024).

[Talk 16]

Towards Econophysiology

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Analogies between economics and cellular physiology have long been noted, but whether the mathematical structure of economic theory applies to cells has remained unclear. In this talk, I will first introduce the relevant biology for physicists, drawing on our recent work on cellular resource allocation [1]. I will then show that cellular resource allocation admits an exact mapping to general equilibrium theory: the proteome allocation that maximizes growth is a competitive equilibrium, and a decentralization theorem shows how this global optimum can be supported by local prices rather than imposed by central control. Because the correspondence is structural rather than merely analogical, concepts from economic theory can be translated into cellular physiology, while cellular systems provide a new physical setting in which to examine economic ideas.

[1] Thiermann et al., *Science* (2026); 10.1126/science.aeb6410
[2] S. Jun and A. Bisin, *in preparation*.

[Talk 17]

Functional oscillators interacting with environment

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Interacting oscillators, with or without external driving, have long been studied as a paradigm for emergent collective order. Much less understood, however, is the case in which the oscillators and their environment interact *mutually*—where the units not only sense the environment but also actively reshape it while performing a physiological function. In this talk, I introduce such a system realized in the pancreas. Pancreatic α, β, and δ cells behave as intrinsic oscillators that secrete hormones in response to glucose levels, and they interact with one another by modulating each other's secretion. These hormones, in turn, feed back on the glucose level, so that the coupled cellular oscillators close a loop of mutual regulation that maintains glucose homeostasis. I will discuss how this bidirectional coupling between oscillators and environment underlies robust regulation and controllable synchronization, and what it suggests for nonequilibrium collective dynamics.

[1] T. Song and J. Jo, *Phys. Biol.* **16**, 051001 (2019).
[2] D.-H. Park, T. Song, D.-T. Hoang, J. Xu, and J. Jo, *Sci. Rep.* **7**, 1602 (2017).
[3] D.-T. Hoang, M. Hara, and J. Jo, *PLoS ONE* **11**, e0152446 (2016).

[Talk 18]

Ordinal-Pattern-Based Analysis of Human Brain States from EEG Phase Dynamics

Athokpam Langlen Chanu[1,2], Youngjai Park[3,4], Jaesung Choi[5], Younghwa Cha[3,4,6], UnCheol Lee[7], Joon-Young Moon[3,4], and Jong-Min Park[1,2*]

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Human brain is a complex system. Understanding the relationship between brain states and the statistical properties of electroencephalography (EEG) signals is important. In this study, we investigate whether permutation entropy (PE) [1], an ordinal-pattern-based measure robust to noise, can serve as a robust biomarker of human brain states. We analyze EEG recordings obtained during a general anesthesia protocol comprising seven states, namely, eyes-closed (EC), propofol injection (P), loss of consciousness (LOC), burst (B), suppression (S), post-burst/suppression (PBS), and recovery (ROC). Following preprocessing, we compute relative phases and extract the dominant phase mode $\beta_1(t)$, which captures macroscopic anterior-posterior information flow [2,3]. We then compute the normalized PE, H, from its ordinal pattern distribution. To assess its discriminative capability, we employ decision-tree-based classifiers using H as a single feature. Our results [4] show a clear dependence of PE on brain state. Unconscious states (LOC, B and S) show significantly higher mean entropy and lower standard deviation than conscious states (EC, ROC) and boundary states (P and PBS). We also find a negative correlation between mean PE and the inverse participation ratio, supporting a link between entropy and consciousness depth. Using PE alone, the classifier distinguishes consciousness levels with an accuracy of 77-81%. We also examine the effects of embedding delay and data resolution on PE. Further, we investigate irreversibility across these brain states.

[1] Bandt, C., & Pompe, B. (2002). *Physical review letters*, **88**(17), 174102.
[2] Moon, J. Y., Lee, U., Blain-Moraes, S., & Mashour, G. A. (2015). *PLoS computational biology*, **11**(4), e1004225.
[3] Park, *et. al.* (2025) bioRxiv:10.1101/2025.03.12.642768
[4] Chanu, A. L., Park, Y., Choi, J., Cha, Y., Lee, U., Moon, J. Y., & Park, J. M. (2026).

Chaos, Solitons & Fractals, **209**, 118416.

[Talk 19]
From Bricks to Mansions: Zero-Energy Loops, Entropic Basins, and the Organization of Ground States in the 2D $\pm J$ Spin Glass

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How does the ground-state manifold of a disordered magnet organize itself—into a few broad valleys, or into many distinct basins separated by subtle, entropy-controlled bottlenecks? I will address this question in the 2D $\pm J$ Edwards–Anderson (random-bond Ising) model using entropic-sampling Monte Carlo [1], which gives direct access to the low-energy, magnetization-resolved density of states and lets us see how ground states cluster.

The central "building blocks" are zero-energy loops: closed spin-flip contours that cost no energy but reshape the accessible configuration space. A useful first description of loop–loop interactions is captured by an effective hard-core lattice-gas picture (geometric exclusion / "entropy locking"). Turning this into a truly formal theory, however, is where difficulties begin: the mapping must confront systematic under-counting and over-counting of configurations when loops are not independent (overlaps, compatibility constraints, and composite moves), and this is precisely where deeper mathematical structure is hiding. A visual tour will compare representative ground states from different entropic basins across phases—ferromagnetic, the transition region, and the spin-glass regime—highlighting how basin structure connects to hierarchical organization and emergent ultrametricity *a la* Parisi, and how this viewpoint sharpens the intuition behind peculiar temperature chaos [2].

I will close by linking these ideas to an older theme from our 2007 PRL work on the Kuramoto model [3]: in both spin glasses and coupled oscillators, quenched disorder can produce "peculiar" mean-field behavior, while finite-dimensional systems reveal equally important, and sometimes counterintuitive, corrections driven by spatial structure. Hyunggyu has always insisted on rigor while I keep trying to dig underneath for the physics—so I like to think we have uncovered many good bricks in the 2D RBIM, and that after his formal retirement he will have the spare time to assemble them into proper mansions.

[1] Yi Liu, Ding Wang, Xin Wang, Dao-Xin Yao, and Lei-Han Tang, *Comm. Theor. Phys.* **77**, 125603 (2025).
[2] H Nishimori, M Ohzeki, and M Okuyama, *Phys. Rev. E* **112**, 044140 (2025).
[3] Hyunsuk Hong, Hugues Chaté, Hyunggyu Park, and Lei-Han Tang, *Phys. Rev. Lett.* **99**, 184101 (2007).

[Talk 20]

Finite-time Information Erasure (in Classical and Quantum Systems)

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Finite-time information erasure is of interest in both classical and quantum problems. Slow erasure protocols that begin from an equilibrium state pay a thermodynamic cost equal to the Landauer bound per bit of information, but this is no longer the case for faster erasure protocols or protocols that begin from an out-of-equilibrium state. What sort of bounds exist for such scenarios is a topic of current interest. In this talk, we will discuss some of our recent work on this problem, where information erasure is caused by the time-dependent stiffening of a harmonic trap which takes any initial state to the equilibrium state in the final trap configuration. This problem (in different guises) has been extremely well studied in the past and we will discuss some of our new results in comparison to what was known earlier. Some interesting aspects of information erasure in a qubit will also be discussed.

[1] D. Gupta, K.S. Olsen and S. Krishnamurthy, Comm. Phys, 8, 355 (2025).
[2] P. Nayak, S. K. Manikandan, T. Van Vu and S. Krishnamurthy, arXiv:2602.00227 (2026)

[Talk 21]

An information engine with high performance and efficiency

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Information engines, a modern realization of the Maxwell-demon thought experiment, use feedback to extract work from a single heat bath. A 1929 variant proposal by Leo Szilard can extract energy from a heat bath and then store it as work, at an efficiency that can seemingly approach 100%. Previous experimental information engines have either demonstrated efficient energy conversion but no storage or storage but low efficiency. In our version, a heavy colloidal particle diffuses in water in a horizontal optical trap. Favorable "up" fluctuations are captured by ratcheting up the trap center, thereby converting bath fluctuations into stored gravitational potential energy. We discuss how to optimize performance in response to challenges (measurement noise) and opportunities (extra fluctuations in a nonequilibrium bath). Then we present experimental results for a new engine design that separates the acquisition of information from its storage. This separation of the protocol into two distinct stages allows for efficient work conversion and energy storage. Our work implies that more heat dissipation than expected occurs during high-speed irreversible computation.

[Talk 22]
Frequency-domain fluctuation–response relation as a diagnostic tool for nonequilibrium spectra

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[2]*School of Physics, Korea Institute for Advanced Study*

Fluctuation–response relations provide a central route to connecting spontaneous fluctuations, external responses, and dissipation in nonequilibrium systems. While conventional formulations often focus on time-domain observables or zero-frequency limits [1,2], many experiments and simulations naturally characterize dynamics through power spectra. This raises a simple question: can a fluctuation spectrum be decomposed into physically meaningful response channels?

In this talk, I will present a frequency-domain fluctuation–response relation for Markov jump and overdamped Langevin systems [3]. For Markov jump networks, the relation decomposes the power spectrum of an observable into contributions from individual transition edges. For Langevin systems, it gives a spatial decomposition in terms of local force-response contributions. These decompositions turn a global spectrum into a diagnostic map of the underlying dynamics.

I will illustrate the theory with two examples. First, in a two-conformation Markov motor with hidden substeps, the edge-resolved decomposition identifies which transition channels dominate different frequency regimes and reveals a finite-frequency window where the thermodynamic uncertainty relation becomes tight. Second, in a tilted periodic potential, the spatial decomposition shows which regions of the state space contribute to the velocity spectrum and how finite-band perturbations can reconstruct the main spectral features. The same information can guide the choice of perturbations entering response uncertainty bounds.

These results show that the frequency-domain fluctuation–response relation is not only a formal identity, but also a practical tool for diagnosing nonequilibrium spectra and identifying relevant channels, spatial regions, and frequency windows for fluctuation–response and thermodynamic bounds.

[1] E. Kwon, H.-M. Chun, H. Park, and J. S. Lee. Phys. Rev. Lett. 135 (9), 097101
[2] H.-M. Chun, E. Kwon, H. Park, and J. S. Lee. arXiv:2601.16387
[3] E. Kwon, H.-M. Chun, H. Park, and J. S. Lee. arXiv:2605.05038

[Talk 23]

Energy Conversion and Fluctuation Relations in Levy Active Matter

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[1]*Asia Pacific Center for Theoretical Physics, Pohang*

Stochastic thermodynamics successfully quantifies energy exchange in fluctuating environments, yet its standard formulation relies crucially on continuous Gaussian noise. Here, we establish a stochastic thermodynamic framework for systems driven by non-Gaussian pure-jump Levy fluctuations, which naturally arise in strongly intermittent biological and synthetic active matter. By extending trajectory-level energetics to discontinuous dynamics, we identify an active entropy production that quantifies irreversibility induced solely by jump-driven probability redistribution [1]. Using a conditioning path-integral formulation for jump processes, we derive non-trivial generalized forms of the Clausius inequality, Crooks fluctuation theorem, and Jarzynski equality. We further show that active entropy production systematically modifies the thermodynamic bounds of cyclic energy converters, yielding generalized power-efficiency trade-off relations and enhanced apparent efficiencies relative to passive thermal engines. These predictions are further illustrated numerically for an active Brownian particle driven by Poisson shot noise. Our results establish heavy-tailed active fluctuations as a genuine thermodynamic resource for nonequilibrium energy conversion.

[1] Y. Huang, C. Liu, B. Miao, X. Zhou. Phys. Rev. Lett. 136 (6), 068302 (2026).
[2] Y. Huang, J-M. Park, Energy Conversion and Fluctuation Relations in Levy Active Matter. Soon in arXiv.

[Talk 24]

Ornstein-Uhlenbeck Process Driven by Multiple Dichotomous Noises

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[4]*Nanotech-CNR, Rome, Italy*

[5]*Asia Pacific Center for Theoretical Physics, Pohang, Republic of Korea*

We discuss the stationary properties of a generalized Ornstein--Uhlenbeck process driven by a superposition of K independent dichotomous noises with arbitrary fixed amplitudes and switching rates. Unlike the classical Ornstein--Uhlenbeck process driven by equilibrium Gaussian white noise, the present system is governed by bounded non-equilibrium fluctuations with finite correlation times. We obtain exact expressions for the stationary position distribution and all cumulants, and show that the stationary state possesses an unexpectedly rich structure, including compact support, algebraic branch-point singularities, edge divergences, and multiple extrema. We establish a mapping onto a heterogeneous random-flight process with bounded jumps, yielding a transparent probabilistic interpretation of the stationary measure. We further analyze several limiting regimes, including the crossover to Gaussian statistics for large numbers of noise sources. For ensembles with exponentially-distributed quenched amplitudes, we derive exact disorder-averaged stationary distributions and show that disorder fundamentally alters the stationary state, producing exponential tails decorated by algebraic prefactors, with exponents non-trivially dependent on the switching rates.

[Talk 25]

Inference of fluctuating information flow via machine learning

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[2] *School of Physics, Korea Institute for Advanced Study*

Stochastic information flow (SIF) quantifies information flow at the trajectory level, overcoming the limitations of conventional symmetric, ensemble-averaged measures. However, computational difficulties have hindered the empirical application of the SIF. In this work, we propose a scalable deep-learning method for estimating the SIF from general time-series data. Its applications to an exactly solvable two-particle model, Kuramoto oscillators, and empirical trajectories of interacting motile cells demonstrate the utility of SIF as a data-driven indicator of cooperative structures.

[1] Y. Oh, E. Kwon, and Y. Baek, arXiv:2605.13509.

[Talk 26]

Exact Results in Stochastic Processes with Division, Death, and Diffusion

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We consider a generic class of stochastic particle-based models whose state at an instant in time is described by a set of continuous degrees of freedom (e.g. positions), and the length of this set changes stochastically in time due to birth-death processes. Using a master equation formalism, we write down the dynamics of the corresponding (infinite) set of probability distributions: this takes the form of coupled Fokker-Planck equations with model-dependent source and sink terms. We derive the general expression of entropy production rate for this class of models in terms of path irreversibility. To demonstrate the practical use of this framework, we analyze a biologically motivated model incorporating division, death, and diffusion, where spatial correlations arise through the division process. By systematically integrating out excess degrees of freedom, we obtain the marginal probability distribution, enabling exact calculations of key statistical properties such as average density and correlation functions. We validate our analytical results through numerical Brownian dynamics simulations, finding excellent agreement between theory and simulation. Our method thus provides a powerful tool for tackling previously unsolved problems in stochastic birth-death dynamics.

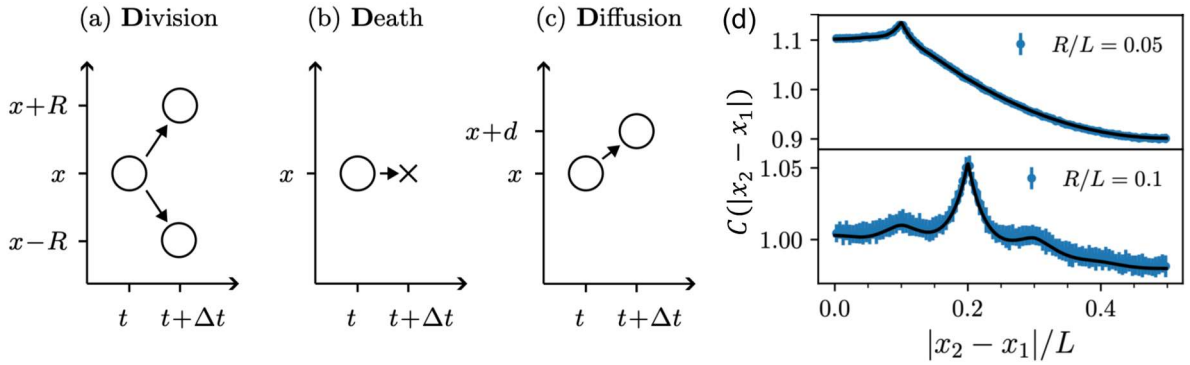

Figure: Schematic of (a) division, (b) death, and (c) diffusion processes in our model. (d) Two-body correlation function in the steady state. Markers are numerical results and solid lines are analytic results.

[1] S. Cameron, and E. Tjhung, Phys. Rev. E. 112, 034109 (2025).

[Talk 27]

Neural Estimation of Entropy Production in Coarse-Grained Systems via Trajectory Snippets: Application to Molecular Catenane Motors

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Estimating entropy production is essential for uncovering the non-equilibrium energetics of biophysical systems, yet traditional inference is often challenged by high levels of coarse-graining and sparse experimental data. We present a recurrent neural network (RNN)-based estimator that leverages the framework of trajectory snippets (trajectories between recurring Markovian events) to provide a fundamental lower bound on entropy production, even when underlying dynamics are partially hidden. By training a compact and computationally efficient RNN architecture to learn irreversibility from snippets, our method demonstrates superior data efficiency, capturing complex history dependencies in time-series data with significantly fewer dataset than conventional estimators. We apply it to a synthetic molecular Catenane motors, a prominent real-world model for autonomous chemically fueled small-molecule motor. Notably, under conditions of current reversal induced by varying track geometries, our neural estimator successfully extracts underlying entropy production and uncovers the explicit the physical origins of entropy production by identifying which localized shuttling ring currents drive the system's irreversibility. This extensible framework provides a robust and scalable diagnostic tool for characterising energy dissipation, thermodynamic efficiency, and free energy landscapes directly from limited experimental time series data, such as single-molecule force spectroscopy or fluorescence trajectories.

[Talk 28]

Dynamically Emergent Correlations

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The goal of this talk is to show that strong correlations between particles may emerge dynamically due to a common stochastically fluctuating environment, even when there is no direct built-in interaction between particles. These correlations grow with time, eventually driving the system into a `strongly correlated' nonequilibrium stationary state with nontrivial properties. I will demonstrate this in an exactly solvable model of noninteracting Brownian particles in a harmonic trap whose stiffness switches between two values at a constant rate. This model has been recently realized experimentally in optically trapped colloidal particle systems. Experimental results agree very well with theoretical predictions.

[1] . M. Biroli, H. Larralde, S. N. Majumdar, G. Schehr,
``Extreme Statistics and Spacing Distribution in a Brownian Gas
Correlated by Resetting",Phys. Rev. Lett. 130, 207101 (2023)
[2] M. Biroli, M. Kulkarni, S. N. Majumdar, G. Schehr,
``Dynamically emergent correlations between particles in a
switching harmonic trap", Phys. Rev. E 109, L032106 (2024)
[3] M. Biroli, S. Ciliberto, M. Kulkarni, S.N. Majumdar, A. Petrosyan, G. Schehr,
``Experimental evidence for strong emergent correlations between particles in a switching trap “, arXiv: 2508.07199
[4]G. De Mauro, M. Biroli, S. N. Majumdar, G. Schehr,
``Dynamically emergent correlations in Brownian particles subject to simultaneous non-Poissonian resetting protocols", Phys. Rev. E 113, 014120 (2026).
[5] S. N. Majumdar, G. Schehr, ``Dynamically Emergent Correlations”, arXiv: 2603.03162

[P1]

Memory-aware feedback enhances power in active information engines

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We study an information engine operating in an active bath, where a Brownian particle confined in a harmonic trap undergoes feedback-driven displacement cycles. Unlike thermal environments, active baths exhibit temporally correlated fluctuations, introducing memory effects that challenge conventional feedback strategies. Extending the framework of stochastic thermodynamics to account for such memory, we analyze a feedback protocol that periodically shifts the potential minimum based on noisy measurements of the particle's position. We show that conventional feedback schemes, optimized for memoryless thermal baths, can degrade performance in active media due to the disruption of bath-particle memory by abrupt resetting. To overcome this degradation, we introduce a class of memory-preserving feedback protocols that partially retain the covariance between the particle's displacement and active noise, thereby exploiting the temporal persistence of active fluctuations. Through asymptotic analysis, we show how the feedback gain—which quantifies the strength of positional shifts—nontrivially shapes the engine's work and power profiles. In particular, we demonstrate that in active media, intermediate gains outperform full-shift resetting. Our results reveal the critical interplay between bath memory, measurement noise, and feedback gain, offering guiding principles for designing high-performance information engines in nonequilibrium environments.

[1] S. Bahng, J. S. Lee, and C. M. Ghim, Phys. Rev. E 112, 054134 (2025).

[P2]

Escort-Driven Network Condensation, Anti-Condensation, and Nonequilibrium Cycles

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Condensation in statistical physics is often tied to conserved transport or to growth. Here we study a different mechanism: a fixed heterogeneous network on which new mass is repeatedly injected according to the current occupation profile and then redistributed by a fixed mixing matrix. The injection rule is an escort, or power-normalized, map with exponent θ. This single parameter acts as an inverse temperature for reinforcement. For $\theta > 0$, the dynamics favors already large components and selects a hub-biased phase; for $\theta < 0$, it favors small components and pushes injection toward the periphery; at $\theta = 0$, injection is uniform. Thus the same network can support condensation or anti-condensation without changing its topology and without conserving mass.

The feedback looks history-dependent, but its asymptotic behavior reduces to a nonlinear map on the probability simplex. In the stable regime $|\theta| < 1$, this map contracts the Hilbert projective metric and gives a unique attracting steady profile. The resulting state is not simply localized or delocalized. On heavy-tailed networks the steady injection is a degree tilt, and the inverse participation ratio can enter an anomalous-scaling regime before any few-node condensate appears. The transition is set by the degree-tail exponent, while assortativity mainly changes the amplitude of the selected bias. The model also separates two observables that are usually conflated: injection and accumulated stock. Through escort duality, negative reinforcement can inject mass toward the periphery while the accumulated stock remains hub-biased.

Directed, non-reversible networks add a nonequilibrium layer. The steady state carries edge currents, so localization may first appear on channels rather than on node marginals. Entropy production for the endogenous reverse process separates reversible relaxation from circulating steady flow. Beyond the stable regime, in the zero-temperature limit $|\theta| \to \infty$, the smooth dynamics reduces to an argmax/argmin map on vertices; cycles of this limiting map lift to rotating condensates in the original system. The framework therefore connects hub condensation, peripheral anti-condensation, current localization, and time-dependent concentrated states within one escort-driven dynamics on fixed complex networks.

[P3]

Steady-state Response Theory in Noisy Network Dynamics

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Many complex interacting systems in physics, biology, and engineering can be modeled as network dynamics under stochastic noise. Examples include neural networks, ecological interactions, and epidemic networks. Depending on the interplay between network topology and local dynamics, these stochastic network systems often converge to a stable steady state. Noise sources can be treated as environmental factors. To understa nd the influence of perturbations on complex networks, we applied the linear response theory (LRT), which is a powerful tool in statistical mechanics, to predict the syste m's response. Considering that most real systems are in nonequilibrium steady states (NESS), although there has been some research about linear response near NESS, its extension to complex networks is much less discussed. In this work, we develop a st eady-state and time-dependent linear response framework for noisy network dynamics near stable fixed points [1]. The network is modeled as a set of coupled stochastic d ynamical variables with intrinsic node dynamics f_i, weighted directed interactions W, and Gaussian white noise η:

$$\dot{x}_i = f_i(x_i; r_i) + \sum_{m \neq i} W_{im} h(x_i, x_m) + \eta_i(t), \qquad i = 1,2, \dots, N,$$

where asymmetric couplings $W \neq W^T$ and heterogeneous noise break detailed balance and lead to NESS. To verify our theoretical results, we quantify the network response by measuring the equal-time covariance $\langle \delta\vec{x}(t)\delta\vec{x}(t) \rangle$ on the unperturbed and perturb ed trajectories. We derive response functions for perturbations in node parameters and coupling strengths [2] and show that these responses can be expressed in terms of co rrelation functions of the unperturbed steady state. Our findings establish a generalized steady-state linear response theory for noisy network dynamics, applicable to both eq uilibrium and nonequilibrium steady states, and we derive explicit results for steady o r non-steady (time-dependent) response functions subject to parameter(s) changes, whic h are verified by implementing numerical simulations.

[1] C. Kwon, P. Ao, and D. J. Thouless, "Structure of stochastic dynamics near fixed points," *Proc. Natl. Acad. Sci. U.S.A.* **102**, 13029–13033 (2005).

[2] M. Doi, *Soft Matter Physics* (Oxford University Press, Oxford, 2013).

[P4]

Joint Component Size Distributions in Hypergraphs with Higher-Order Interactions

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[2]*Department of Computer Science, Middlesex University, London*
[3]*School of Computational Sciences, Korea Institute for Advanced Study*

To fully understand the structural properties of complex systems with higher-order interactions, it is essential to look beyond simple pairwise graphs and analyze hypergraph structures. In this study, we establish a rigorous theoretical framework to analyze connected components in higher-order networks by introducing a dual measurement for component size as a pair (s, m), where s denotes the number of nodes (users/authors) and m denotes the number of hyperedges (books/papers). Using a generating function framework combined with Cauchy's integral formula, we derive a general analytical solution for the joint probability distribution $\pi_{s,m}$ that a randomly selected node belongs to a component of an exact size (s, m) in uncorrelated hypergraphs. We show that the joint distribution decomposes into independent node and hyperedge contributions, allowing us to obtain explicit closed-form expressions or asymptotic behaviors for various classical topologies, including Delta, Poisson, Geometric, and Power-law (Zeta) distributions. Furthermore, we validate our analytical framework against extensive numerical simulations and demonstrate its practical utility by applying it to empirical datasets, such as library book loan networks and co-authorship databases. Our work provides a complete dual characterization of structural density and scales in higher-order networks, distinguishing between popular, core, and highly specialized components within complex systems.

[1] M. E. J. Newman, *Random graphs with arbitrary degree distributions and their applications*, Phys. Rev. E **64**, 026118 (2001).

[P5]

Symmetry breaking chirality of an achiral gear in an active fluid

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Ratchet currents provide a fundamental route by which nonequilibrium fluctuations are rectified into directed motion. Recent studies have shown that feedback between the motion of an immersed body and an active bath can generate spontaneous ratchet-like currents even without explicit geometric bias[1]. Motivated by this perspective, we study an achiral symmetric gear immersed in a bath of active Brownian particles. Although neither the gear nor the bath imposes a handedness, the coupled gear–bath dynamics allows clockwise and counterclockwise rotation to emerge as two symmetry-related chiral states.

To understand the mechanism behind this spontaneous chirality, we focus on boundary-localized nonequilibrium currents near the gear surface. In the co-rotating frame of the gear, these edge currents provide a local probe of how active particles accumulate, slide, and circulate along the boundary, transferring angular momentum from persistent self-propulsion to the gear. We combine this current-based analysis with active-passive comparisons and small-angular-velocity response measurements. This allows us to test whether the onset of rotation can be understood as an effective negative rotational drag, where the active bath amplifies rather than damps an incipient rotation.

At finite angular velocities, the same framework provides a way to analyze nonlinear torque response, rotational saturation, and the possible formation of a bimodal angular-velocity distribution. Our work reframes spontaneous gear rotation as an edge-ratchet-current problem: the central object is not only the global angular velocity, but the local nonequilibrium circulation that encodes how an achiral active fluid can generate macroscopic handedness.

[1] K. -W. Kim, Y. Choe, and Y. Baek, Phys. Rev. E 109, 014614 (2024).

[P6]

Fluctuation-response theory for non equilibrium Langevin Dynamics

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In this poster, I present a unified fluctuation–response framework for Langevin dynamics. By identifying the common mathematical structure behind fluctuations and responses of empirical density and current, the framework extends the fluctuation–dissipation theorem from equilibrium to nonequilibrium systems. The resulting relation connects global fluctuations of observables with local responses to perturbations in force, mobility, and temperature. Finite-time fluctuation–response inequalities are also derived, leading to response uncertainty relations that provide practical bounds on nonequilibrium responses. Together, these results clarify the hierarchical relationship among fluctuation–response relations, fluctuation–response inequalities, the fluctuation–dissipation theorem, and thermodynamic uncertainty relations. The framework is illustrated using an F_1-ATPase molecular motor model, where response-based bounds constrain the long-time diffusion coefficient.

[1] H.-M. Chun, E. Kwon, H. Park, and J. S. Lee, arXiv:2601.16387 (2026).

[P7]

Effective Uniqueness for Renewal-Type Potentials on Mixing S-Gap Shifts

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We study quantitative stability of equilibrium states for renewal-type potentials on one-sided mixing S-gap shifts. These symbolic dynamical systems arise naturally in nonequilibrium statistical mechanics as compact renewal models: the first return map to a distinguished cylinder is conjugate to a full shift on a countable alphabet, while the original system need not be a shift of finite type. For a Holder renewal-type potential, the induced equilibrium measure is Bernoulli, determined by a single pressure equation analogous to the stationarity conditions appearing in stochastic thermodynamics and driven lattice systems.

Assuming the topological pressure strictly exceeds the value at the fixed point and that the induced weights satisfy an exponential moment condition, we prove existence and uniqueness of the equilibrium state and establish a square-root pressure-gap stability estimate for Holder observables. Specifically, if an invariant measure has free energy close to maximal, it must be quantitatively close to the equilibrium state when tested against Holder functions. This yields an explicit effective uniqueness theorem on a compact symbolic renewal model that lies strictly outside the classical finite-state Markov setting.

The proof combines two ingredients. First, a self-contained square-root pressure-gap inequality on the induced renewal shift is derived via a telescoping decomposition of Holder observables and conditional relative entropy, in a spirit analogous to entropy-production bounds in stochastic thermodynamics. Second, the estimate is transferred back to the original compact S-gap shift by decomposing the induced observable into an unbounded roof term and a bounded Holder remainder. The roof mean is controlled via a direct pressure-gap estimate using one-coordinate relative entropy and the exponential moment hypothesis, reflecting the role of return-time fluctuations in renewal-type nonequilibrium dynamics.

The result bridges classical finite-state and countable-state Markov theories of effective uniqueness and the broader uniqueness theory for symbolic systems beyond the finite-type setting, showing that the renewal structure of mixing S-gap shifts is rigid enough to support a quantitative pressure-gap inequality on the original compact system.

[1] S. Kadyrov, Effective uniqueness of Parry measure and exceptional sets in ergodic theory, Ergodic Theory Dynam. Systems 35 (2015), 2672–2686.
[2] R. Ruhr, Pressure gap and effective uniqueness for Gibbs measures on countable Markov shifts, Israel J. Math. 244 (2021), 521–560.
[3] V. Climenhaga and D. J. Thompson, Intrinsic ergodicity beyond specification: beta-shifts, S-gap shifts, and their factors, Israel J. Math. 192 (2012), 785–817.

[P8]

Distance Decay and Hub Dominance in Korea's Card-Transaction Consumption Network: An Intra- versus Inter-Regional Self-Containment Analysis

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We study the spatial organization of consumer spending in Korea as a directed, weighted interaction network reconstructed from credit- and debit-card transactions (2019–2022). Treating monthly offline spending flows between regions as a mobility-to-consume process, we fit a gravity law in which the directed flow decays with geographical distance, and use the deterrence exponent β as a structural descriptor of each region. Because online consumption carries no geographic deterrence, restricting to offline flows isolates the distance-dependent component of consumption interaction.

We decompose the consumption gravity into an intra-regional (within-region) and an inter-regional (cross-boundary) component, and find that their ratio behaves as a self-containment order parameter that sharply separates the Seoul metropolitan core from peripheral regions: non-metropolitan regions show strong intra-regional gravity together with rapidly decaying inter-regional flow, while the metropolitan core exhibits the opposite asymmetry and acts as a dominant absorbing hub. The Seoul-to-periphery gravity ratio is systematically distinct and tracks regional structural fundamentals (consumption infrastructure, industrial composition, GRDP).

We benchmark the gravity law against the parameter-free radiation model, identify where each deterrence form succeeds and fails, and track the response of β and of network structure across the COVID-19 perturbation.

We close by mapping the heterogeneity of the deterrence exponent and the self-containment parameter across industries and age groups, yielding a network-level fingerprint of metropolitan concentration in Korea.

Keywords: human mobility; gravity law; radiation model; spatial networks; core–periphery; econophysics

[1] Anderson, J. E., & van Wincoop, E. (2003). Gravity with Gravitas: A Solution to the Border Puzzle. American Economic Review, 93(1), 170-192.
[2] McCallum, J. (1995). National Borders Matter: Canada–U.S. Regional Trade Patterns. American Economic Review, 85(3), 615-623.
[3] Head, K., & Mayer, T. (2014). Gravity Equations: Workhorse, Toolkit, and Cookbook. In G. Gopinath, E. Helpman & K. Rogoff (Eds.), Handbook of International Economics, Vol. 4, pp. 131-195. Elsevier.
[4] Huff, D. L. (1963). A Probabilistic Analysis of Shopping Center Trade Areas. Land Economics, 39(1), 81-90.
[5] O. H. Kwon, I. Hong, W. S. Jung, and H. H. Jo, Multiple gravity laws for human mobility within cities, EPJ Data Science 12, 57 (2023).

[P9]

Percolation process with cluster-size dependent recovery

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To investigate the robustness of the complex network systems, permanent nodes failure has been assumed and the size of the giant cluster has been measured. However, many real-word phenomena involve recovery processes, either natural or artificial, i.e. repair, self-healing. To capture these types of phenomena, we study a percolation model with cluster-size dependent recovery process. In this model, failed clusters are recovered with cluster size s dependence recovery probability distribution $\rho(s)$. We then measure the size of the giant cluster Φ which consists of the connected activated nodes and recovered nodes. For instance, if $\rho(s)$ is step function $\Theta(s_c - s)$ with $\Theta(0) = 1$, all the failed clusters that its size is less than or equal to size threshold s_c are recovered and activated nodes and recovered nodes can merge into the giant cluster. We calculate analytical solutions using generating function methods and obtain numerical results from Monte Carlo simulations. This study suggests insights into the robustness and the resilience of complex systems.

[P10]

Power-Efficiency Trade-off in a Quantum Otto Engine Coupled to a Squeezed Thermal Reservoir: A Phase-Space Approach

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Nonequilibrium reservoirs offer thermodynamic advantages beyond the Carnot limit, but their effect on the power-efficiency trade-off at finite time is not well understood. We examine a quantum Otto engine coupled to a squeezed thermal bath and derive, via a quasiprobability phase-space approach, a power-efficiency trade-off valid for arbitrary driving protocols. The efficiency is bounded above by a squeezing-enhanced value exceeding the Carnot efficiency, and power vanishes as this bound is approached. Further, the conditions for saturation of this bound are identified.

[P11]

Fluid Dynamics of Nationwide Traffic: Simulating the Korean Highway Network via Macroscopic Traffic Flow Model

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Macroscopic traffic flow models offer a powerful framework for understanding congestion by treating vehicle movement analogously to fluid dynamics. A prominent example is the classic Lighthill–Whitham–Richards (LWR) model, which captures these dynamics through a one-dimensional continuity equation. However, while extensively studied, applications of the LWR model have historically been confined to idealized single-road sections and small-scale test networks, leaving real, nationwide-scale transportation systems largely unexplored. In this study, we construct an LWR-based simulation framework to analyze traffic congestion on the Korean highway network and identify congestion-vulnerable roads that play a significant role in propagating congestion throughout the network. Utilizing highly reliable, empirical network data provided by the Korea Expressway Corporation, we implement cutting-edge road network simplification algorithms to effectively capture the system's topology while preserving critical transport dynamics. The resulting simulation spans the entire national highway system, encompassing nearly 50 highways totaling over 5,000 km in physical length, enabling a large-scale description of traffic dynamics in terms of density and flow. Using the proposed framework, we evaluate currently planned highway expansion projects and explore alternative network interventions that may provide greater congestion-relief benefits.

[P12]

Assortativity and the breakdown of a common assumption in network dynamics

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A wide range of models for dynamics on networks—from epidemic spreading to percolation and opinion formation—rely on relationships between the degrees of neighboring nodes, and many implicitly assume that the mean degrees of nearest and next-nearest neighbors coincide. We show that this assumption breaks down systematically in real networks, and we identify assortativity, the tendency of nodes to connect to others of similar degree, as a primary cause. As degree correlations vary, the gap between the mean degrees of nearest and next-nearest neighbors grows in a predictable way, with direct consequences for the accuracy of dynamical predictions built on the equal-degree assumption. By tracing this discrepancy to a single, measurable structural property, our results offer a route to more accurate models of how networks shape the processes running on them.

[P13]

Crypto vs. Stock Markets: A Visibility Network Approach

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While cryptocurrency markets share macroscopic stylized facts (such as heavy tails and volatility clustering) with traditional stock markets, this resemblance does not necessarily imply dynamical equivalence under extreme stress. As these digital assets integrate into traditional portfolios, understanding this distinction is vital for managing systemic risks. To address this, we analyze one-minute returns of Bitcoin, Ethereum, Ripple, and E-mini S&P 500 futures (hereafter S&P 500) from 2020 to 2025 using a surrogate-controlled framework combining the complexity-entropy causality plane (CECP) and directed horizontal visibility graphs (directed HVGs).

Applying this framework, we find that during ordinary fluctuations, cryptocurrencies exhibit weaker temporal organization, operating as highly noisy and disorganized systems relative to the stock market benchmark. In contrast, under extreme positive-return stress, cryptocurrencies exhibit a robust, dynamically irreversible directional asymmetry, wherein upward shocks couple more strongly with pre-event history than subsequent recovery. In addition, surrogate controls preserving marginal distributions and linear temporal correlations fail to replicate this feature, whereas the S&P 500 remains largely consistent with these baseline models.

To test the reproducibility of this empirical phenomenon, we examine whether networks constructed from data incorporating key stylized facts can replicate the observed directional asymmetry under extreme conditions. Our preliminary framework focuses on whether standard generative features are sufficient to trigger this irreversibility, or if additional microscopic constraints are required. This approach provides a benchmark to assess whether conventional complexity models can fully account for the unique dynamical structure of cryptocurrency markets during financial distress.

[1] R. Cont, Quant. Finance 1, 223-236 (2001).

[2] O. A. Rosso et al., Phys. Rev. Lett. 99, 154102 (2007).

[3] L. Lacasa et al., Eur. Phys. J. B 85, 217 (2012).

[4] R. Flanagan and L. Lacasa, Phys. Lett. A 380, 1689-1697 (2016).

[P14]

Density-dependent transition in bacterial self-organization driven by confinement and aerotaxis

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Microorganisms explore and respond to heterogeneous environments. For example, certain motile bacteria migrate up an oxygen gradient by modulating their tumbling rate, a process called aerotaxis. Here, we investigate the response of aerotactic bacteria geometrically confined within a thin liquid film in the presence of a controlled oxygen concentration gradient. Our experimental results reveal that the total bacterial number density determines which effect dominates: confinement prevails at low bacterial density, whereas the aerotactic effect becomes apparent as bacterial density increases. To elucidate the underlying mechanisms, we develop a coupled continuum model of oxygen and bacteria, in which the bacteria interact hydrodynamically with the confining wall and exhibit Keller-Segel-based chemotactic migration in response to the oxygen gradient. Our model reproduces the density-dependent transition observed in experiments and provides insights into the collective behavior of bacteria in response to external stimuli, such as an oxygen gradient and confinement. These findings shed light on microorganism-environment interactions and the resulting self-organization, with implications for microbial control and the early stages of biofilm formation.

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[P15]

Thermodynamic Cost of Giant Transport in a Random-Protocol Flashing Ratchet

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We study the thermodynamic efficiency of a flashing ratchet driven by a random compound Poisson protocol, using stochastic thermodynamics for non-Gaussian jump processes [1]. In jump-diffusion systems, the insertion of a periodic barrier can counterintuitively induce a giant enhancement of particle transport, even though barriers usually suppress motion [2,3]. This raises a central question: how efficiently useful work can be extracted from transport enhanced by a random protocol that neither observes nor feedback-controls the system?

We model an overdamped Brownian particle in a periodic potential whose phase is instantaneously shifted by compound-Poisson jumps. From the steady-state thermodynamic balance, we derive an efficiency bound containing an information flow term. In this system, the protocol itself is random, and the particle distribution statistically adapts to the randomly shifting potential landscape. This adaptive response makes information flow to the system non-negative, which tightens the second law bound and lowers the maximum achievable thermodynamic efficiency.

At the same time, this information flow is closely related to protocol-induced transport: without sufficient adaption to the protocol, the enhanced current and the resulting output power would vanish. However, a larger information flow does not necessarily imply larger power. We therefore investigate the relation between information flow and output power in order to clarify when random non-Gaussian driving can efficiently enhances transport and generates useful work.

[1] Y.Huang, C. Liu, B. Miao and X. Zhou, Phys. Rev. Lett. 136, 068302 (2026)
[2] K. Białas and J. Spiechowicz, Phys. Rev. E 107, 064120 (2023).
[3] K. Białas, J. Łuczka, and J. Spiechowicz, Phys. Rev. E 107, 024107 (2023).

[P16]

Power spectral density of free and confined active Ornstein–Uhlenbeck particle trajectories

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The power spectral density (PSD) is a fundamental quantity for characterizing stochastic processes in the frequency domain. While its properties are well understood for Brownian and anomalous diffusion processes, the spectral signatures of active nonequilibrium processes remain largely unexplored. Here, we develop an exact theory for the PSDs of active Ornstein–Uhlenbeck particles (AOUPs) in free space and under harmonic confinement. For free AOUPs, activity does not alter the Brownian f^{-2} spectrum, but only modifies its amplitude and introduces a crossover at the persistence frequency. Under confinement, the spectrum exhibits a rich variety of behaviors governed by the interplay among persistence, trap relaxation, and activity strength. In particular, we identify two characteristic signatures that are absent in both thermal systems and free AOUPs: a two-plateau structure arising from a double-trapping mechanism associated with two distinct noise sources, and a novel f^{-4} spectral scaling associated with transient ballistic motion. We further investigate the finite-time effects through the finite-time PSD, and show that the low-frequency plateau and high-frequency oscillation exhibit distinct dependences on the observation time T in free and confined systems. Finally, we discuss our results in connection with previously reported experimental studies of active systems. Our results provide an analytically tractable framework for interpreting active fluctuations in such systems.

[P17]

Dynamical Phase Transitions in monitored Clifford circuits with symmetry-preserving feedback

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Intermittent measurements and feedback controls on random quantum circuits can provide an alternative platform for studying non-equilibrium phase transitions. In this work, we present a measurement-feedback protocol that can purify scrambling dynamics into two equivalent absorbing states. We demonstrate our protocol using random hybrid Clifford circuits consisting of probabilistic two-qubit projective measurements and subsequent gate controls based on the classically stored measurement outcomes to preserve the symmetry. The quantum state undergoes two phase transitions controlled by the measurement rate: the entanglement transition between the volume-law and area-law phases, and the absorbing-state phase transition between the active and inactive absorbing phases of spin polarization.

Here we focus on the absorbing-state phase transition occurring at the higher measurement frequency. We develop quantum and classical order parameters to characterize dynamical criticality in the nonequilibrium evolution of quantum states from three different initial states under periodic and open boundary conditions. Regardless of these details, we find that all estimates of critical exponents are consistent with the directed Ising universality class in one dimension, suggesting a classical-quantum analogy between branching-annihilating random walks with even number of offsprings and quantum dynamics in monitored random circuits with symmetry-preserving feedback.

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[P18]

Common Noise-Induced Group-Level Synchronization Between Uncoupled Groups of Oscillators

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We investigate group-level synchronization between oscillator groups induced by common noise in the absence of inter-group coupling. Each group receives a common noise shared by all its oscillators and independent local noise inputs to individual oscillators. The same common noise is applied to all groups. The system is studied with both identical and nonidentical oscillators, and with and without intra-group coupling. In the nonidentical case, natural frequencies are drawn from the same distribution for both groups, making them statistically equivalent. Through numerical simulations of this system, we find that the degree of synchronization within each group, measured by the absolute value of a complex Kuramoto order parameter, typically shows significant temporal fluctuations. Importantly, the complex order parameters representing the collective oscillations of the groups synchronize when the groups are driven by the same common noise. By deriving a phase density evolution mapping, we analytically explain how this group-level synchronization is achieved in the absence of intra-group coupling.

[1] T.-W. Ko, arXiv:2605.29529 (2026).

[P19]

Metal Substitution in Semi-constrained Systems: DFT Study on a Metalloenzyme

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Metal complexes with constrained or semi-constrained geometry play a crucial role in the coordination chemistry of metalloenzymes by imposing structural limits on the ligands. These constraints result in a pre-distorted coordination geometry, forming an entatic state of the protein. The entatic state of a metalloenzyme directly influences the thermodynamic and kinetic aspects across a broad range of chemical reactions by facilitating faster electron transfer and reaction kinetics. In this work, we selected the catalytic active center of human carbonic anhydrase II (CA II) and its four metal variants containing Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+} as the model system and conducted a density functional theory (DFT) study on their coordination chemistry. We imposed structural constraints on the active site to mimic the entatic state of the protein and tested various functional and basis set combinations to find the optimal combination for reproducing the experimental structures. We found that the native metal ion in metalloenzymes does not always exhibit the strongest binding, but the trend follows the Irving-Williams series, and that structural constraints make the energy landscape of the metal complexes more rugged. We anticipate that our findings can be utilized to design and tune the entaticity of the active site in artificial metalloenzymes.

[1] Rajeev Kumar et al., “DFT investigation of metal coordination and reactivity in minimal metalloenzyme models”, Journal of Inorganic Biochemistry, 272, 113018 (2025)
[2] Jin Kyun Kim et al., “Elucidating the role of metal ions in carbonic anhydrase catalysis”, Nature Communication, 11, 4557 (2020).
[3] Dicke, B., Hoffmann, A., Stanek, J. et al., “Transferring the entatic-state principle to copper photochemistry”, Nature Chemistry, 10, 355 (2018).
[4] Peter Comba et al., “Coordination compounds in the entatic state”, Coordination Chemistry Reviews, 200, 217 (2000).

[P20]

Tunable Mpemba effect in a polymer–bead system with inertia

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Designing protocols that accelerate relaxation toward equilibrium is a central challenge in nonequilibrium physics. The Mpemba effect, whereby a system prepared at a higher temperature cools faster following a thermal quench, provides a natural framework for addressing this problem. Here, we propose a minimal model in which a stretched polymer is coupled to an underdamped bead, allowing the Mpemba effect to be tuned through the bead's mass. Specifically, we consider a polymer undergoing a denaturation transition whose force–extension curve exhibits a plateau that slows relaxation when the applied stretching force is only slightly weaker than the restoring force in the plateau regime. When prepared at a higher initial temperature, the larger kinetic energy of the bead enables more rapid traversal of this plateau, giving rise to the Mpemba effect. Increasing the bead mass broadens the range of initial temperatures over which this mechanism operates. Our results demonstrate a simple and experimentally accessible strategy for controlling Mpemba behavior through inertia.

[P21]

Quantifying information flow along a stochastic trajectory

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Stochastic information flow (SIF) quantifies information flow at the trajectory level, overcoming the limitations of conventional symmetric, ensemble-averaged measures. However, computational difficulties have hindered the empirical application of the SIF. In this work, we propose a scalable deep-learning method for estimating the SIF from general time-series data. Its applications to an exactly solvable two-particle model, Kuramoto oscillators, and empirical trajectories of interacting motile cells demonstrate the utility of SIF as a data-driven indicator of cooperative structures.

[1] E. Kwon, Y. Oh and Y. Baek, *arXiv preprint*, arXiv:2605.13509 (2026).

[P22]

Oxygen-mediated self-organization in a bacterial–microalgal active suspension

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Active suspensions of living microorganisms provide a versatile platform for studying nonequilibrium statistical physics, where local energy consumption generates self-propulsion, enhanced fluctuations, and spatial organization. Here, we study a mixed suspension of motile bacteria, *Bacillus subtilis*, and immotile but photosynthetic microalgae, *Chlorella vulgaris*, under illumination. In this system, microalgae act as oxygen sources, while bacteria consume oxygen and exhibit oxygen-dependent motility. This coupling establishes a dynamic feedback loop between the chemical environment and bacterial active motion. We examine how oxygen-mediated motility regulation can induce heterogeneous bacterial density and the redistribution of microalgal cells in an initially homogeneous mixture. We quantify the dynamics using particle tracking and density-field analysis. The observed behavior suggests that light-controlled oxygen production can regulate bacterial activity and promote phase-separation-like spatial organization in a living active system. Our results provide a simple experimental model for connecting chemical-field-mediated motility control with collective nonequilibrium behavior in active matter.

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[P23]

Free energy dissipation of periodically driven chemical reaction network

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Many biological oscillators are modeled as autonomous systems. For such systems, the trade-off between energy dissipation and precision is constrained by the thermodynamic uncertainty relation (TUR), which sets a lower bound on the uncertainty product, $Q \geq 2$. Many biological oscillators, however, operate under external driving such as environmental signals, and can become entrained to periodic inputs. Previous studies of simplified models have shown that periodic driving can lower this bound while preserving clock precision. Yet applications of these ideas to realistic chemical and biochemical oscillators remain limited. Here, starting from a simple model reaction network, the Brusselator, we find that the entropy production rate exhibits nonmonotonic behavior depending on the frequency of periodic driving. A detailed theoretical analysis of the associated scaling behavior remains an important direction for future work.

[P24]

Information Erasure in Spatially Nonuniform and Time-Dependent Temperature Fields

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Landauer's principle establishes that the minimum energetic cost of erasing one bit of information is $k_B T \ln 2$, corresponding to the minimal heat dissipated into the environment during logically irreversible operations. In this work, we investigate the thermodynamic cost and physical mechanisms of information erasure in a double-well potential under the overdamped limit, subject to a spatiotemporally varying local Gaussian temperature field. Our study combines analytical derivations with numerical simulations.

For systems with inhomogeneous temperatures, the entropy production (EP) in the environment can be decomposed into regular and anomalous contributions. The anomalous term originates from the symmetry breaking of fast velocity degrees of freedom induced by temperature gradients and survives in the overdamped limit. In addition, we consider the Hatano–Sasa decomposition of EP into housekeeping and excess contributions.

We show that, in the quasi-static limit, the excess entropy production approaches the Landauer bound and coincides with the regular EP within the overdamped framework for the erasure protocol considered here. We further derive the finite-time Landauer bound under slow driving and demonstrate that the leading correction scales approximately as $1/\tau$.

These results provide a theoretical basis for designing optimal heating schemes for information erasure, deepen our understanding of non-isothermal information processing in small systems, and provide guidance for ongoing experimental efforts.

[P25]

Collective Dynamics and Curvature-Mediated Interactions of Active Ellipses in Deformable Vesicles

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We study self-propelled elliptical particles confined inside a deformable vesicle and investigate how particle shape, activity, and membrane rigidity affect the collective dynamics. Depending on the parameters, the system displays forward and chiral motion, which can occur either as single clusters or multiple clusters distributed along the boundary. We observe a reentrant transition between forward and chiral motion as the particle aspect ratio increases. The most common chiral states consist of evenly spread clusters, suggesting an effective long-range repulsion mediated by vesicle curvature. By analyzing the relative angular velocity between particles, we identify a linear restoring regime near the symmetric configuration and show that the effective trap stiffness agrees with predictions from fluctuation analysis and an Ornstein-Uhlenbeck description. Finally, we relate the observed phases to known swarmalator states, showing that this deformable active matter system provides a physical realization of coupled spatial and orientational self-organization.

[P26]

Mobility Anisotropy Reshapes Self-Propelled Motion

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Active particles with anisotropic translational mobility arise naturally in systems such as rodlike microswimmers, elongated colloids, and wheeled robotic agents. We investigate the nonequilibrium dynamics of a self-propelled particle with anisotropic mobility confined by a two-dimensional harmonic trap. Using an exact analytical approach, we characterize the transient and steady-state behavior through the mean displacement, mean-squared displacement (MSD), and fourth moment. We find that, in the high-persistence regime, the dynamics exhibits a quasi-steady plateau in the MSD, corresponding to a regime of strongly suppressed fluctuations. An exact calculation of the fourth moment reveals a negative excess kurtosis indicating a distinctly non-Gaussian steady state. The resulting position distribution remains strictly sub-Gaussian and displays an unusual accumulation of particles in regions of higher potential energy beyond the characteristic stationary contour set by activity and confinement. The crossover from the quasi-steady regime to the final stationary state is further reflected in the relaxation dynamics of the MSD. These results highlight the profound impact of mobility anisotropy on the statistics and confinement-induced behavior of active matter systems. Our results comprising non-Gaussian signatures are all experimentally accessible in existing systems — including elongated colloids, Janus swimmers in optical or magnetic traps, bacteria with anisotropic substrate interactions, and anisotropically driven robots in harmonic wells.

[1] A. Shee, and P. S. Pal, arXiv:2605.02148

[P27]

Advancing Financial Market Simulation with Generative Adversarial Networks: A Case Study on the KOSPI 200 Index

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Financial markets are complex systems whose macroscopic behavior cannot be reduced to a simple aggregation of microscopic events, limiting the reach of traditional parametric models and motivating data-driven approaches that capture nonlinear dynamics and abrupt regime shifts. Such methods, however, are constrained by data availability: the extreme, tail-driven episodes most relevant to risk are precisely those that are rarely sampled. We address this by training a Deep Convolutional Generative Adversarial Network (DCGAN)—whose convolutional structure captures the local temporal dependencies underlying volatility clustering—to generate synthetic daily return series for the KOSPI 200 Index. Rather than reproducing data, we ask whether the generator learns the emergent statistical regularities of the market: fat-tailed return distributions, negative skewness, the absence of linear return autocorrelation, and persistent volatility clustering. Fidelity is assessed quantitatively by comparing return distributions, tail indices, and the autocorrelation of squared returns against the empirical series. The results indicate to what extent GAN-based generation can serve as a realistic surrogate of the Korean equity market for simulation, stress-testing, and scenario analysis.

[1] Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A., & Bengio, Y. (2014). Generative adversarial nets. Advances in Neural Information Processing Systems (NeurIPS), 27, 2672–2680.

[2] Radford, A., Metz, L., & Chintala, S. (2016). Unsupervised representation learning with deep convolutional generative adversarial networks. International Conference on Learning Representations (ICLR). arXiv:1511.06434.

[3] Takahashi, S., Chen, Y., & Tanaka-Ishii, K. (2019). Modeling financial time-series with generative adversarial networks. Physica A: Statistical Mechanics and its Applications, 527, 121261. ScienceDirect

[4] Wiese, M., Knobloch, R., Korn, R., & Kretschmer, P. (2020). Quant GANs: deep generation of financial time series. Quantitative Finance, 20(9), 1419–1440. ACM Digital Library

[5] Cont, R. (2001). Empirical properties of asset returns: stylized facts and statistical issues. Quantitative Finance, 1(2), 223–236. IOPscienceSemantic Scholar

[6] Mantegna, R. N., & Stanley, H. E. (2000). An Introduction to Econophysics: Correlations and Complexity in Finance. Cambridge University Press.

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Investigating the Growth Kinetics of Biomolecular Condensates via Molecular Dynamics Simulations

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Biomolecular condensates are membraneless intracellular structures formed via liquid-liquid phase separation (LLPS) and play a critical role in organizing cellular processes spatiotemporally. While the growth rates of these condensates are key physical parameters governing their final size distribution, understanding their growth kinetics within complex nonequilibrium cellular environments remains a challenge under classical Brownian motion-based theories. In this study, we employed minimal-model molecular dynamics (MD) simulations to systematically investigate the growth kinetics of phase-separated clusters within an implicit solvent framework. Particularly, we performed a comparative analysis between NVT dynamics, which lacks solvent-induced viscous friction, and Langevin dynamics, which incorporates subunit-level friction. Our results reveal a distinct contrast between the two systems: while NVT dynamics maintains growth behavior close to the classical scaling prediction, Langevin dynamics exhibits a crossover in the scaling exponent, where the growth kinetics significantly slow down during the late coalescence-dominant stage. Our findings highlight that coarse-grained MD simulations performed under implicit solvent conditions may fail to accurately capture condensate coarsening dynamics unless appropriate solvent-friction effects are included.

[P29]

Competing heterogeneities shape ordering via higher-order interactions

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Higher-order interactions admit richer structural heterogeneity than pairwise networks. To understand how heterogeneity impacts collective phenomena we develop a framework based on the cavity method and apply it to the simplicial Ising model on heterogeneous hypergraphs. Unlike in homogeneous structures, group size and node degree play fundamentally different roles: size heterogeneity sharpens the transition via large-group unanimity, while degree heterogeneity softens it as hubs cooperatively seed ordering with non-hubs. Under either type of heterogeneity, continuous--discontinuous double transitions can arise, where the symmetry-breaking continuous transition is driven by pairs or by hubs, respectively. When both heterogeneities coexist, cross-order degree correlations further modulate the phase diagram, with anticorrelation delaying the group-driven discontinuous jump and broadening the hysteretic region. Our results reveal the intricate interplay between size and degree heterogeneities in collective phenomena beyond pairwise interactions.

[P30]

A universal method for deriving coarse-grained equations

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Goal — We develop a universal method for deriving coarse-grained equations and apply it to specific systems. Coarse-grained equations can be obtained from the underlying equations of motion by eliminating microscopic degrees of freedom. Hydrodynamic equations are representative coarse-grained equations because they can be derived from the equations of motion of atoms and molecules by eliminating microscopic details. Although coarse-grained equations are also used in quantum fluids and active matter, their derivation relies on properties specific to individual systems. Therefore, developing a universal method applicable to various systems would enable the systematic derivation of coarse-grained equations in these fields.

Theory — To derive coarse-grained equations, we employ a perturbative expansion based on the scale separation. Assuming macroscopic fluctuations with a length scale L much larger than the particle size a, we define the perturbative parameter $\varepsilon \equiv a/L \ll 1$. We expand the time-evolution equation for the full N-particle distribution function perturbatively in ε. In the course of solving the perturbative equations, divergent terms appear as $t \to \infty$. We derive coarse-grained equations by eliminating those divergent terms.

Results — We applied our method to stochastic systems as well as deterministic ones. For deterministic systems, the Navier-Stokes equations were derived from the equations of motion of atoms and molecules. Although the Navier-Stokes equations have been derived in previous studies, we confirmed that they can also be derived using our method. The methods used in previous studies cannot be applied to stochastic systems because they rely on properties specific to deterministic systems. In contrast, our method is applicable to stochastic systems because it does not rely on such properties.

Considering Langevin systems as stochastic processes, we derived new coarse-grained equations. Langevin systems can be classified into overdamped and underdamped cases. In the overdamped case, we derived the coarse-grained equations:

$$\frac{\partial \rho(\boldsymbol{r},t)}{\partial t} = \frac{1}{\gamma}\nabla^2 P(\boldsymbol{r},t) + \eta'\nabla^2\nabla^2\mu(\boldsymbol{r},t). \quad (1)$$

Here, $\rho(\boldsymbol{r},t)$ is the density field, γ is the friction coefficient, $P(\boldsymbol{r},t)$ is the pressure, and $\mu(\boldsymbol{r},t)$ is the chemical potential. The coarse-grained equations were also derived for the underdamped case:

$$\frac{\partial \boldsymbol{g}(\boldsymbol{r},t)}{\partial t} = -\boldsymbol{\nabla} P(\boldsymbol{r},t) - \boldsymbol{\nabla}\cdot[\boldsymbol{V}(\boldsymbol{r},t)\boldsymbol{g}(\boldsymbol{r},t)] - \frac{\gamma}{m}\boldsymbol{g}(\boldsymbol{r},t) + \eta\nabla^2\boldsymbol{V}(\boldsymbol{r},t) + \zeta\boldsymbol{\nabla}[\boldsymbol{\nabla}\cdot\boldsymbol{V}(\boldsymbol{r},t)], \quad (2)$$

where $\boldsymbol{g}(\boldsymbol{r},t)$ is the momentum density field, $\boldsymbol{V}(\boldsymbol{r},t)$ is the velocity field, m is the mass, η is t he shear viscosity, and ζ is the bulk viscosity.

[P31]

Two-Level Information Engines with Stochastic Measurement Intervals: Comparison with Fixed-Interval Engines

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An information engine extracts useful work from thermal fluctuations through repeated cycles of measurement and feedback. Most previous studies have focused on engines operating with a fixed measurement interval, while the impact of stochastic measurement intervals on engine performance remains largely unexplored. In this work, we study an analytically tractable two-state information engine model in which measurements occur according to a Poisson process with rate λ. We show that this setup is equivalent to a stochastic resetting process: the system is reset to its ground state upon measurement, extracting work in the process. Using this property, we first obtain the steady-state distribution and then derive expressions for the average extracted work, work variance, mutual information, and efficiency over a finite observation time as functions of the measurement rate. We compare the stochastic and deterministic protocols at equal average measurement count ($\lambda t = 1$). We identify two critical measurement rates, λ_L and λ_R, satisfying $\lambda_L < 1/t < \lambda_R$; the stochastic protocol outperforms the deterministic one in power only for $\lambda > \lambda_R$, and in efficiency only for $\lambda < \lambda_L$. At $\lambda = 1/t$, the deterministic protocol simultaneously exceeds the stochastic protocol in both power and efficiency. However, the stochastic protocol exhibits lower relative work fluctuations, indicating higher operational precision. These results reveal a three-way trade-off between power, efficiency, and precision in feedback-driven information engines, and quantify the thermodynamic cost of timing randomness.

[P32]

Biconnectivity in directed random networks

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Strongly Connected Components (SCCs) are widely used to define loop structure in directed networks. However, SCCs are highly susceptible to fragmentation upon the removal of even a single node. To address this limitation, we study Strongly Biconnected Components (SBCs), defined as sets of nodes connected by at least two mutually independent directed paths. We develop an analytic framework using generating function formalism to calculate the size of the largest SBC in random networks. Our results reveal that while SBCs emerge at the same percolation threshold as SCCs, their growth is significantly slower due to the more stringent connectivity requirements.

[1] S. N. Dorogovtsev, J. F. F. Mendes, and A. N. Samukhin, Giant strongly connected component of directed networks, Physical Review E 64, 025101 (2001).
[2] M. Newman and G. Ghoshal, Bicomponents and the robustness of networks to failure, Physical review letters 100, 138701 (2008).
[3] L. Georgiadis, G. F. Italiano, L. Laura, and N. Parotsidis, 2-vertex connectivity in directed graphs, Information and Computation 261, 248 (2018).

[P33]

Steady state distributions and the Green–Kubo formula in AOUP systems

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Purpose The present study focuses on whether active matter includes new physical laws, which differ from usual statistical mechanics. Active matter consists of spontaneously moving particles, such as microorganisms, and has different properties from those of passive matter (ex. molecules and colloidal particles). In passive matter, various physical laws have been established. Microscopic equilibrium distributions are given by canonical distributions, which provide methods of deriving macroscopic hydrodynamic equations from equations of motions for passive particles. The present study aims to clarify how these physical laws are modified in active matter, using a simple model of active matter.

Theory A simple model of active matter is given by active Ornstein–Uhlenbeck particle (AOUP) systems. Langevin equations of AOUP systems are written in the form

$$\dot{\mathbf{p}}_i(t) = -\gamma \mathbf{p}_i(t) - \nabla_i U(\{\mathbf{r}_i\}) + \mathbf{f}_i(t) \qquad \dot{\mathbf{f}}_i(t) = -\mathbf{f}_i(t)/\tau + \boldsymbol{\eta}(t),$$

where $\mathbf{r}_i$ and $\mathbf{p}_i$ are the position and momentum of particle i, and γ is the friction coefficient. In addition, $U(\{\mathbf{r}_i\})$ is the interaction potential between particles, and $\eta(t)$ is the white Gaussian noise associated with the heat bath temperature T. By expanding the Fokker–Planck equations derived from the above equations in powers of τ, one can obtain equations of N-particle distribution functions of $\mathbf{r}_i$ and $\mathbf{p}_i$. These equations provide steady state distributions, from which hydrodynamic equations are derived using a coarse-graining method developed by us.

Results In the AOUP system, the steady state distribution $\rho_{st}(\{\mathbf{r}_i,\mathbf{p}_i\})$ has been given by

$$\rho_{st}(\{\mathbf{r}_i, \mathbf{p}_i\}) = \frac{1}{Z} \exp[-\tilde{\beta} \sum_i^N \frac{\mathbf{p}_i^2}{2m} - \beta U(\{\mathbf{r}_i\})]$$

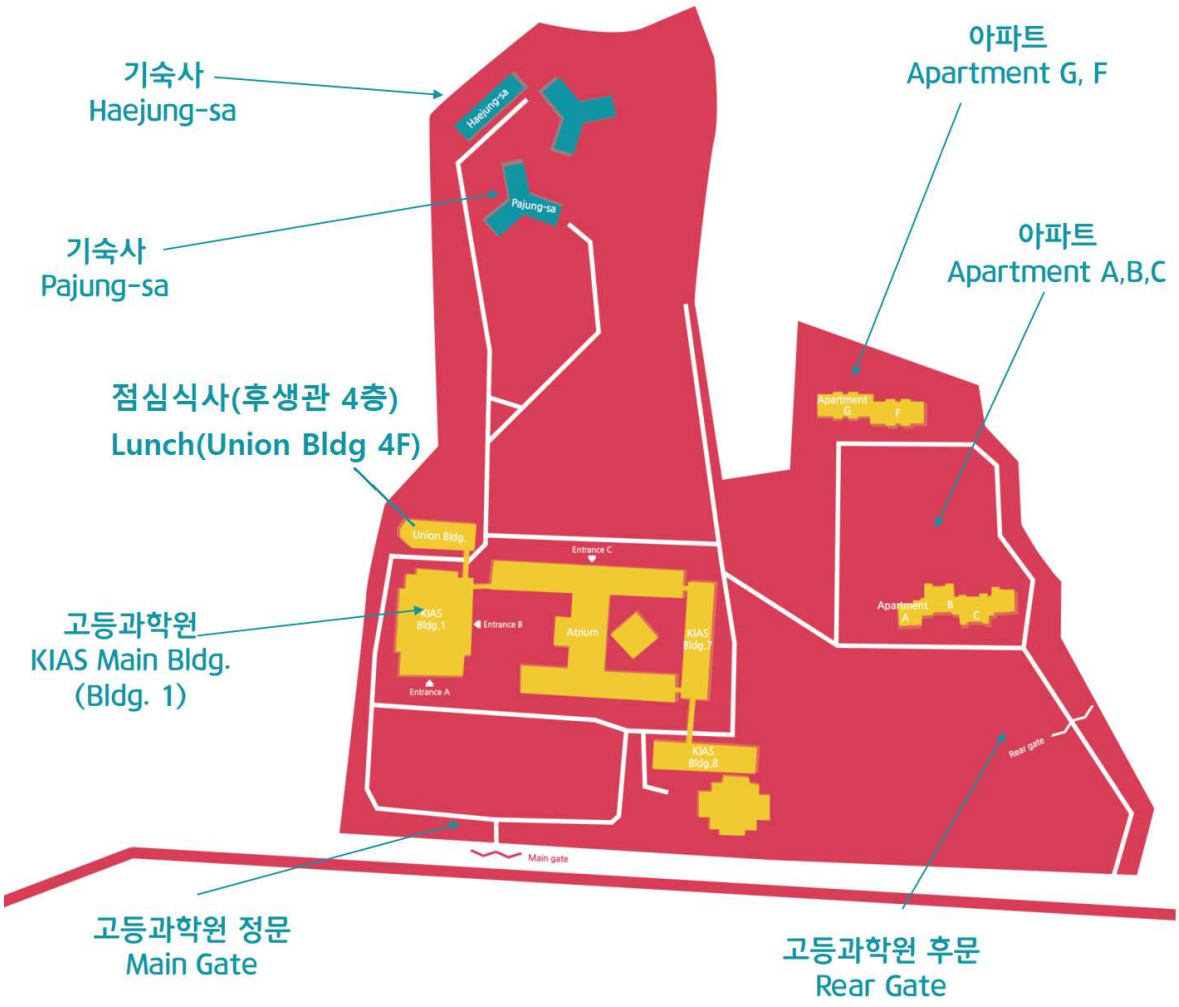
Here, Z is the normalization factor, m is the mass of a particle, and $\beta = 1/(k_B T)$. In addition, $\tilde{\beta}$ is defined by $\beta/(1-\gamma\tau)$, which differs from β.

This steady state distribution can give hydrodynamic equations. Although almost the same expressions as Navier–Stokes equations have been obtained, the Green–Kubo formula giving shear viscosity has a different expression from that in usual passive matter

$$\eta = \tilde{\beta} \int_0^\infty \int d\mathbf{r} \, \langle \tau^{xy}(0,\mathbf{r}) \tilde{\tau}^{xy}(t,\mathbf{r}) \rangle \, .$$

While $\tau^{xy}(0,\mathbf{r})$ is a usual stress tensor, $\tilde{\tau}^{xy}(t,\mathbf{r})$ is a different function from $\tau^{xy}(t,\mathbf{r})$. This difference shows the possibility of $\eta < 0$.

Campus Map


기숙사
Haejung-sa
기숙사
Pajung-sa
점심식사(후생관 4층)
Lunch(Union Bldg 4F)
고등과학원
KIAS Main Bldg.
(Bldg. 1)
고등과학원 정문
Main Gate
아파트
Apartment G, F
아파트
Apartment A,B,C
고등과학원 후문
Rear Gate
Haejung-sa
Pajung-sa
Union Bldg.
Entrance C
KIAS Bldg.1
Entrance B
Atrium
KIAS Bldg.7
Entrance A
KIAS Bldg.8
Apartment G
F
Apartment A
B
C
Rear gate
Main gate