
EAST ASIA JOINT SEMINARS
on Statistical Physics 2025
Date October 14-17, 2025
Place Rm.1503 (5F), KIAS, Seoul, Korea
INVITED SPEAKERS
Yuansheng Cao Tsinghua University
Carlo V. Cannistraci Tsinghua University
Kun Chen ITP/CAS
Qun-Li Lei Nanjing University
Zhaoru Sun Shanghai Tech
Peng Tan Fudan University
Lei-Han Tang Westlake University
Zhi-Qin John Xu Shanghai Jiao Tong University
Yifan Yang Westlake University
Hai-Jun Zhou ITP/CAS
Cheng-Hung Chang National Yang-Ming Chiao-Tung University
Hsuan-Yi Chen National Central University
Yonggun Jun National Central University
Pik-Yin Lai National Central University
Yi-Hung Liao National Central University
Fu-Lai Wen National Central University
Chikara Furusawa Tokyo & Riken
Yoshifumu Nakata YITP
Daiki Nishiguchi Science Tokyo
Yoshihiko Nishikawa Kitazato
Masayuki Ohzeki Tohoku & Science Tokyo
Kazuki Sone Tsukuba
Kazuaki Takasan Tokyo
Kazumasa A. Takeuchi Tokyo
Tan Van Vu YITP
Miho Yanagisawa Tokyo
Yongjoo Baek Seoul National University
Hyun-Myung Chun KIAS
Junghyo Jo Seoul National University
Deok-Sun Lee KIAS
Jae Sung Lee KIAS
Jae Dong Noh University of Seoul
Hye Jin Park Inha University
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Lei-Han Tang Westlake University
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Jae Dong Noh University of Seoul
KIAS

Introduction

The East Asia Joint Seminars on Statistical Physics 2025(EAJSSP2025） is the 7th of the series of international meetings in the field of statistical physics with the joint efforts of scientists from East Asia. This meeting will cover some of the major advances in the field of statistical physics and its interdisciplinary applications, achieved by colleagues from the East Asia region, in the latest few years.

Invited Speakers

Chikara Furusawa (Tokyo & Riken)
Yoshifumu Nakata (YITP)
Daiki Nishiguchi (Science Tokyo)
Yoshihiko Nishikawa (Kitazato)
Masayuki Ohzeki (Tohoku & Science Tokyo)
Kazuki Sone (Tsukuba)
Kazuaki Takasan (Tokyo)
Kazumasa A. Takeuchi (Tokyo)
Tan Van Vu (YITP)
Miho Yanagisawa (Tokyo)

Cheng-Hung Chang (National Yang-Ming Chiao-Tung University)
Hsuan-Yi Chen (National Central University)
Yonggun Jun (National Central University)
Pik-Yin Lai (National Central University)
Yi-Hung Liao (National Central University)
Fu-Lai Wen (National Central University)

Yuansheng Cao (Tsinghua University)
Carlo V. Cannistraci (Tsinghua University)
Kun Chen (ITP/CAS)
Qun-Li Lei (Nanjing University)
Zhaoru Sun (Shanghai Tech)
Lei-Han Tang (Westlake University)
Zhi-Qin John Xu (Shanghai Jiao Tong University)
Yifan Yang (Westlake University)
Hai-Jun Zhou (ITP/CAS)

Yongjoo Baek (Seoul National University)
Hyun-Myung Chun (KIAS)
Junghyo Jo (Seoul National University)
Deok-Sun Lee (KIAS)
Jae Sung Lee (KIAS)
Jae Dong Noh (University of Seoul)
Hye Jin Park (Inha University)
Su-Chan Park (Catholic University of Korea)
Sunghan Ro (Havard University)

Organizers

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Jae Dong Noh (University of Seoul)

Program Schedule

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

Time	14 Oct (Tue)	15 Oct (Wed)	16 Oct (Thur)	17 Oct (Fri)
08:30-09:00	Sandwich	Sandwich	Sandwich	Sandwich
09:00-09:30	Opening at 09:20			
09:30-10:00	**Chair: H. Park**	**Chair: H. Hayakwa**	**Chair: P.-Y. Lai**	**Chair: H.-J. Zhou**
	J. D. Noh	L.-H. Tang	D. Nishiguchi	P.-Y. Lai
10:00-10:30	Y. Jun	Y. Nishikawa	K. A. Takeuchi	C.-H. Chang
10:30-11:00	Coffee break			
11:00-11:30	**Chair: H.-Y. Chen**	**Chair: K. A. Takeuchi**	**Chair: D.-S. Lee**	**Chair: L.-H. Tang**
	Z. Sun	M. Ohzeki	H.-J. Zhou	K. Sone
11:30-12:00	C. Furusawa	Y. Yang	C. V. Cannistraci	S.-C. Park
12:00-12:30	Y. Nakata	F.-L. Wen	J. Jo	J. S. Lee
12:30-13:00	Lunch	Lunch	Photo Session	Closing
13:00-13:30			Lunch	Lunch
13:30-14:00				
14:00-14:30	**Chair: J. D. Noh**	**Chair: J. S. Lee**		
	Q.-L. Lei	T. V. Vu	Excursion	
14:30-15:00	Y. Baek	H.-M. Chun		
15:00-15:30	M. Yanagisawa	K. Takasan		
15:30-16:00	Coffee break			
16:00-16:30	**Chair: C. B. Hyun**	**Chair: C. V. Cannistraci**		
	S. Ro	H. J. Park		
16:30-17:00	Y.-H Liao	D.-S Lee		
17:00-17:30	Y. Cao	K. Chen		
17:30-18:00	H.-Y. Chen	Z.-Q. J. Xu		
18:00-20:00	Poster (Pizza & Beer)	Banquet	Dinner	

Day 1 – October 14 (Tue)

08:30-09:20	Registration/Coffee & Sandwiches	
09:20-09:30	Opening	
	Morning Session Ⅰ	Chair : H. Park
09:30-10:00	J. D. Noh	Polar order in active Ising model
10:00-10:30	Y. Jun	Anomalous Diffusion of Passive Tracers in Crowded and Filamentous Bacterial Swarming
10:30-11:00	Break	
	Morning Session Ⅱ	Chair : H.-Y. Chen
11:00-11:30	Z. Sun	From Proton Mobility to Excitons: The Role of Hydrogen Bond Networks
11:30-12:00	C. Furusawa	Analysis of evolutionary constraints using bacterial experimental evolution
12:00-12:30	Y. Nakata	Quantum Error Correction and Quantum Chaos in Hamiltonian Systems
12:30-14:00	Lunch	
	Afternoon Session Ⅰ	Chair : J. D. Noh
14:00-14:30	Q.-L. Lei	Liquid-Gas Criticality of Hyperuniform Fluids
14:30-15:00	Y. Baek	Pattern formation of fuel-consuming and chemokinetic active particles
15:00-15:30	M. Yanagisawa	Exploring ultra-polydisperse systems through jammed droplets and linear polymers
15:30-16:00	Break	
	Afternoon Session Ⅱ	Chair : M.Ohzeki
16:00-16:30	S. Ro	Multipole-Conserving Diffusion

16:30-17:00	Y.-H. Liao	Second Law-abiding account of heat engines in active bath
17:00-17:30	Y. Cao	Energy dissipation enhances information transmission in biological trigger waves
17:30-18:00	H.-Y. Chen	How do incorrect ligands help detect a correct ligand?
18:00-20:00	Poster Session	

Day 2 – October 15 (Wed)

08:30-09:30	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : H. Hayakawa
09:30-10:00	L.-H. Tang	Domain-wall statistics and mixed order transition in the random bond Ising model
10:00-10:30	Y. Nishikawa	Lattice glass model in three spatial dimensions: Statics and dynamics at low temperatures
10:30-11:00	Break	
	Morning Session Ⅱ	Chair : K.A. Takeuchi
11:00-11:30	M. Ohzeki	Duality analysis on Fisher zeros
11:30-12:00	Y. Yang	A Mathematical Theory of Aging and Its implications for Healthspan Extension
12:00-12:30	F.-L. Wen	Mechanobiological mechanism of cyclic stretch-induced cell columnarization
12:30-14:00	Lunch	
	Afternoon Session Ⅰ	Chair : J. S. Lee
14:00-14:30	T. V. Vu	Thermodynamics of Precision in Open Quantum Systems
14:30-15:00	H.-M. Chun	Fluctuation–Response Inequalities for Nonequilibrium Steady States
15:00-15:30	K. Takasan	Activity-induced quantum phase transitions: A proposal for quantum active matter
15:30-16:00	Break	
	Afternoon Session Ⅱ	Chair : C. V. Cannistrati
16:00-16:30	H. J. Park	General Theory for Group Resetting with Application to Avoidance
16:30-17:00	D.-S. Lee	Equilibrium-preserving Laplacian renormalization group

17:00-17:30	K. Chen	Mechanism of the Emergent System-2 Reasoning in LLMs: A Complex Network Perspective
17:30-18:00	Z.-Q. J. Xu	Understanding memorization and reasoning of language model through neuron condensation
18:00-20:00	Banquet	

Day 3 – October 16 (Thu)

08:30-09:30	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : P. Y. Lai
09:30-10:00	D. Nisiguchi	Reversals and oscillations as a precursor of bacterial active turbulence
10:00-10:30	K. A. Takeuchi	Designing topological edge localization in bacterial active matter
10:30-11:00	Break	
	Morning Session Ⅱ	Chair : D. S. Lee
11:00-11:30	H.-J. Zhou	Statistical mechanics of lateral predictive coding: energy--information tradeoff, feature detection, and discontinuous phase transitions
11:30-12:00	C. V. Cannistraci	Complex network science for brain-inspired sparse artificial network training to develop efficient and sustainable AI
12:00-12:30	J. Jo	Data augmentation using diffusion models to enhance inverse Ising inference
12:30-12:40	Photo Session	
12:40-14:00	Lunch	
14:00-20:00	**Excursion & Dinner**	

Day 4 – October 17 (Fri)

08:30-09:30	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : H.-J. Zhou
09:30-10:00	P.-Y. Lai	Second-Law violating events are not Rare in Non-equilibrium non-steady states
10:00-10:30	C.-H. Chang	High-Efficiency Stochastic Engines: A Dynamical Systems Perspective
10:30-11:00	Break	
	Morning Session Ⅱ	Chair : L.-H. Tang
11:00-11:30	K. Sone	Nonlinearity-induced topological phase transition and chaos transition in nonlinear topological insulators
11:30-12:00	S.-C. Park	Finite-size scaling of the Kuramoto model
12:00-12:30	J. S. Lee	Coherence enhanced by dynamic oscillators: Breaking π-reflection symmetry
12:30-14:00	**Closing & Lunch**	

[Talk 1]

Polar order in active Ising model

Jae Dong Noh

Department of Physics, University of Seoul, Seoul, 02504, Korea

We revisit the controversy over long-range polar order in the active Ising model with discrete Z_2 symmetry. The active Ising model has been regarded as a minimal model exhibiting long range polar order. However, a recent work reports that the polar order is metastable due to spontaneously nucleated droplet excitations. Despite its importance, dynamics of the droplets has not been investigated thoroughly. It turns out that the droplets display rich dynamical behaviors including growth, evaporation, and pinning. We present the details of the dynamical behavior and discuss the implication on the polar order.

[Talk 2]

Anomalous Diffusion of Passive Tracers in Crowded and Filamentous Bacterial Swarming

Yen Chiu, Yu-Jo Chai, and Yonggun Jun
Department of Physics and Center for Complex Systems, National Central University, Taoyuan 320, Taiwan

Passive tracers in the bacterial swimming bath show enhanced diffusion caused by hydrodynamic coupling and direct interaction with active matter. Our work moves the focus to bacterial swarming, a system where interactions are dominated by direct physical collisions rather than hydrodynamics. In this talk, we present our study on the dynamics of passive tracers in a dense two-dimensional swarming of filamentous bacteria. Our analysis reveals that the displacement probability density function is characterized by two-scaled non-Gaussian tails for short time intervals, but as the lag time increases, they evolve to a single exponential distribution and asymptotically to the Gaussian function. Furthermore, the observed non-Gaussian behavior results from significant heterogeneity between different trajectories as well as dynamic heterogeneity within individual trajectories. Our findings offer new insights into how the physical interactions within a dense active medium control the transport of passive matter.

[Talk 3]

From Proton Mobility to Excitons: The Role of Hydrogen Bond Networks

Yueqi Zhao, Weiyu Li, Zhaoru Sun
School of Physical Science and Technology, ShanghaiTech University

The hydrogen bond network denotes the extended and dynamic arrangement of hydrogen bonds among water molecules and between water and solutes. Constantly reorganizing on the picosecond timescale through bond breaking and reformation, this network governs solvation structures, ion hydration, and dielectric properties. In this talk, I will present our recent wo rks on how the topology and fluctuations of the hydrogen bond network critically influence proton transport, acid dissociation, as well as the electronic structure and excitonic properties of aqueous systems.

[1] Yueqi Zhao, Feifei Tian, and Zhaoru Sun. Sci. Adv. 11, eadu6525 (2025)
[2] Weiyu Li, Zhaoru Sun. J. Phys. Chem. Lett. 16, 503 (2025)
[3] Zhaoru Sun, Lixin Zheng, Mohan Chen, Michael L. Klein, Francesco Paesani, and Xifan Wu, Phys. Rev. Lett. 12, 137401 (2018).

[Talk 4]

Duality analysis on Fisher zeros

Masayuki Ohzeki

Graduate School of Information Sciences, Tohoku University
Department. of Physics, Institute of Science Tokyo
Research and Education Institute for Semiconductors and Informatics, Kumamoto University
Sigma-i, Co., Ltd.

Duality analysis is a well-established method for pinpointing critical points. Originally formulated by Kramers and Wannier and mathematically reformulated by Wu and Wang, it enables the precise determination of critical points across a variety of spin systems, both with and without randomness.

Even today, statistical-mechanical models—particularly spin glass models—offer fundamental insights in many fields. In this presentation, we spotlight several emerging applications of these models in quantum computing. In quantum computation, we employ various unitary operators, whose time evolutions can be characterized by the action of the corresponding Hamiltonian. When directly manipulating these operators, we often encounter complex-valued interactions in statistical-mechanical models, prompting the question of whether standard approaches from statistical mechanics still apply.
The critical points in complex-valued interactions reminds us the existence of the Fisher's zeros in partition functions.
Revisiting the issue of Fisher’s zeros, we demonstrate that duality analysis reproduces well-known results and provides a fresh avenue for analytically examining quantum computation from a statistical-mechanical standpoint. Notably, the framework can be extended to assess quantum error correction involving both incoherent (real-valued) and coherent (complex-valued) errors by leveraging duality analysis.

[Talk 5]

Quantum Error Correction and Quantum Chaos in Hamiltonian Systems

Yoshifumi Nakata[1] and Masaki Tezuka[2]
[1]*Yukawa Institute for Theoretical Physics, Kyoto University*
[2]*Department of Physics, Kyoto University*

Quantum chaos, information scrambling, and quantum error correction (QEC) are the central topics in the intersection between quantum many-body physics and quantum information science. While these concepts have long been speculated to be deeply connected, rigorous studies have remained limited. In this talk, we explore the interplay using the Hayden-Preskill model, a canonical toy model for QEC, in various Hamiltonian systems. We address two key questions. First, what specific types of "chaotic" Hamiltonian dynamics would be useful for QEC? Second, what insights could the QEC approach offer to better understanding many-body physics? We numerically show a crucial distinction between conventional notion of quantum chaos and the QEC-achieving dynamics. Furthermore, we demonstrate that the investigation of the QEC properties in Hamiltonian systems provides new perspectives on information scrambling in terms of the out-of-time-ordered correlators, especially for those based on global operators that have been rarely addressed so far.

[1] Hayden-Preskill recovery in Hamiltonian systems, Y.N. and M. Tezuka, Phys. Rev. Research 6, L022021 (2024).

[Talk 6]

Liquid-Gas Criticality of Hyperuniform Fluids

Shang Gao[1], Hao Shang[1], Hao Hu[2], Yu-Qiang Ma[1] and Qun-Li Lei[1]
[1]*School of Physics, Nanjing University, Nanjing 210093, China*
[3]*School of Physics and Optoelectronic Engineering, Anhui University, Hefei 230601, China*

In statistical physics, it is well established that the liquid-gas (LG) phase transition with divergent critical fluctuations belongs to the Ising universality class. Whether non-equilibrium effects can alter this universal behavior remains a fundamental open question. Here, we theoretically investigate LG criticality in a hyperuniform (HU) fluid of active spinners, where phase separation is driven by dissipative collisions. Strikingly, at the critical point the HU fluid displays normal Gaussian density fluctuations rather than the expected divergence, while the compressibility still diverges. The system is thus calm yet highly susceptible, in fundamental violation of the conventional fluctuation-dissipation theorem. Consistently, we observe anomalous zero-range correlation functions coexisting with quasi-long-range response functions. Based on a generalized model B and renormalization-group analysis, we show that hyperuniformity reduces the upper critical dimension from d_c=4 to d_c=2, and the system exhibits anomalous finite-size scaling in density fluctuations, energy fluctuations, and the Binder cumulant. Furthermore, the HU fluid undergoes non-classical spinodal decomposition, where the decomposition time diverges but the characteristic length scale remains finite as criticality is approached. The origin of these anomalies lies in the center-of-mass-conserving dynamics of the spinners, which endows the system with a scale-dependent effective temperature, $T_{eff} \propto q^2$, underlying a generalized fluctuation-dissipation relationship. These findings establish a striking exception to classical paradigms of critical phenomena and illustrate how non-equilibrium forces can fundamentally reshape universality classes.

[1] S. Gao1, H. Shang, H. Hu, Y.-Q. Ma and Q.-L. Lei arXiv:2507.06023 (2025)

[Talk 7]

Pattern formation of fuel-consuming and chemokinetic active particles

Yongjoo Baek, Euijoon Kwon, and Yongjae Oh
Department of Physics and Astronomy, Seoul National University

Motility-induced phase separation (MIPS) is a well-studied nonequilibrium collective phenomenon observed in active particles. Recently, there has been growing interest in how coupling the self-propulsion of active particles to chemical degrees of freedom affects MIPS. Although the effects of chemotaxis on MIPS have been extensively studied, little is known about how chemokinesis affects MIPS. In this study, we demonstrate that various patterns can be induced when active particles consume chemicals and exhibit chemokinesis, where higher chemical concentrations enhance self-propulsion without causing alignment with the chemical gradient. We discover that MIPS is intensified if chemical consumption is proportional to particle density (as in the basal metabolic regime), but it is suppressed if chemical consumption is closely tied to particle motion (as in the active metabolic regime). While the former produces large-scale phase separation via coarsening, the latter suppresses the coarsening process, leading to microphase separation and oscillating patterns. We also derive a hydrodynamic theory that describes these findings.

[1] Euijoon Kwon, Yongjae Oh, and Yongjoo Baek, Communications Physics 8, 288 (2025).

[Talk 8]

Exploring ultra-polydisperse systems through jammed droplets and linear polymers

Daisuke S. Shimamoto1, Naoya Yanagisawa1, Miho Yanagisawa1
1Komaba Institute for Science, Graduate School of Arts and Sciences, Institute of Science, The University of Tokyo

Perfectly monodisperse particles are rare in nature, whereas polydisperse systems are ubiquitous, encompassing both thermal particles such as biomolecules in cells and athermal particles such as gravel [1]. In particular, particles generated by impact fracture frequently exhibit a power-law size distribution. To gain deeper insight into such ultra-polydisperse systems, we introduce two experimental model systems in which particle sizes follow a power law with a tunable exponent [2,3]. The first system consists of oil-in-water droplets, where the power-law size distribution is realized through repeated "injection and impact fracture" [2]. We examine the jammed configurations of these droplets confined in a quasi-two-dimensional geometry. The second system is a polymer solution of linear polyethylene glycol (PEG) chains with different molecular weights [3]. We investigate the phase behavior and rheological properties of this solution. Strikingly, in both systems we observe systematic deviations from the behavior of their monodisperse counterparts, occurring within a well-defined range of power-law exponents. In this presentation, we will introduce these findings and discuss possible underlying mechanisms.

[1] M. Yanagisawa, K. Fujiwara, Macromolecules, in press.
[2] D. S. Shimamoto, M. Yanagisawa, Phys. Rev. Res., 5, L012014. (2023).
[3] N. Yanagisawa, D. S. Shimamoto, M. Yanagisawa, in preparation.

[Talk 9]

Multipole-Conserving Diffusion

Jung Hoon Han[1] Ethan Lake[2] and Sunghan Ro[3]
[1]*Department of Physics, Sungkyunkwan University*
[2]*Department of Physics, University of California Berkeley*
[3]*Department of Physics Harvard University*

In normal diffusion, particles move randomly while conserving their total number. What would happen when additional constraints, such as the conservation of the center of mass, are imposed? In this talk, I will show that the dynamic exponent of diffusion with center of mass conservation in d dimension changes to z = d+4, and that the equilibrium distribution is exponentially localized in the presence of a hard wall. I will also extend these results to multipole-conserving diffusion.

[1] J. H. Han, E. Lake, and S. Ro, Phys. Rev. Lett. 132, 137102 (2024).

[Talk 10]

Second Law-abiding account of heat engines in active bath

Yi-Hung Liao[1], Jerard Vincent Ang[1], Pik-Yin Lai[1,2], and Yonggun Jun[1]

[1]*Department of Physics and Center for Complex Systems,*
National Central University, Taoyuan, Taiwan

[2]*Physics Division, National Center for Theoretical Sciences, Taipei, Taiwan*

We revisit the thermodynamic energetics of a colloidal heat engine immersed in a heat bath containing both white noise and Ornstein–Uhlenbeck (OU) active noise. Previous studies treated active noise with hidden degrees of freedom (DoFs) and reported efficiencies exceeding the Carnot limit, which contradicts the second law. Several explanations have been proposed to avoid violating the second law by introducing effective temperatures. In this work, we instead treat OU noise with explicit DoFs. The original two-dimensional system is modeled as a two-particle one (the colloidal particle and the active noise) coupled to four independent white noise baths.

We demonstrate both theoretically and experimentally that the Langevin equations can be analytically solved to obtain the interacting energetics between the colloidal particle and the OU noise. Without introducing effective temperatures, our results show nonnegative entropy production, engine efficiency bounded above by the Carnot limit, and validity of conventional thermodynamic uncertainty relation (TUR). This study offers a crucial perspective by resolving the apparent contradiction between active noise and the thermodynamic second law.

[Talk 11]

Energy dissipation enhances information transmission in biological trigger waves

Yuansheng Cao[1], Yuping Chen[2], Shengyao Luo[1]

[1]*Department of Physics, Tsinghua University*

[2]*State Key Laboratory of Quantitative Synthetic Biology, Shenzhen Institute of Synthetic Biology, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences.*

Biochemical trigger waves are widespread in living systems, including neuronal action potentials and calcium waves in tissues. Despite their diverse origins, these waves share common dynamics that enable rapid and reliable information transmission across long distances. However, because they arise from biochemical reactions, they are subject to fluctuations that limit transmission fidelity. An effective trigger wave system must suppress spontaneous excitation at rest while preserving spatiotemporal order during propagation.

Using stochastic thermodynamics applied to the FitzHugh–Nagumo model, we identify two distinct forms of energy dissipation: dissipation at rest, which suppresses spontaneous excitation, and dissipation during propagation, which enhances wave coherence. We derive analytic relationships between these dissipation terms and validate them in simulations of Belousov–Zhabotinsky reaction and also in experimental systems.

Our framework provides a quantitative basis for analyzing the spatiotemporal coherence of biochemical traveling waves and shows how energy dissipation enhances the fidelity of information transmission. These results yield testable predictions for future experimental studies.

[Talk 12]

How do incorrect ligands help detect a correct ligand?

Yan-Ru Chen[1], Kwan-tai Leung[2], and Hsuan-Yi Chen[1,2]
[1]*Department of Physics and Center for Complex Systems, National Central University, Taiwan*
[2]*Institute of Physics, Academia Sinica, Taiwan*

We consider a small cluster of receptors in a two-dimensional lattice that binds reversible to two types of ligands with nearest-neighboring binding state coupling. Specific enzymes activate receptors in the bound states, while another type of enzyme deactivates receptors in the free states. Our numerical simulations indicate that, for a range of parameters, incorrect ligands alone cannot activate the receptors; however, the presence of one correct ligand is sufficient to activate many receptors. The response time of the system and the amplification of the signal both increase as the inter-receptor binding state coupling strength increases. The similarity and difference between our simple model and the activation of T cell receptors (TCRs) in immunological cells are discussed, and our model suggests a possible mechanism for speedy, specific response to very few ligands in biological as well as artificial systems.

[Talk 13]

Domain-wall statistics and mixed order transition in the random bond Ising model

Yi Liu[1,2], Ding Wang[1], Dao-Xin-Yao[2], Leticia Cugliandolo[3] and Lei-Han Tang[1]

[1]*Center for Interdisciplinary Studies, Westlake University*

[2]*School of Physics, Sun Yat-Sen University*

[3]*Sorbonne Université, Laboratoire de Physique Théorique et Hautes Energies*

The $\pm J$ random-bond Ising model is a paradigmatic example of a frustrated spin system, where a ferromagnetic phase exists only when the fraction p of ferromagnetic bonds is sufficiently high. Despite extensive studies, the nature of the transition out of this phase remains unresolved, particularly below the Nishimori line. Using an entropic sampling scheme, we investigate the model on square $(d = 2)[1]$ and simple cubic $(d = 3)[2]$ lattices by tracking the evolution of magnetization-resolved ground states and low-energy excited states while gradually decreasing the number of ferromagnetic bonds. Around a critical value $p_c = 0.9$ for the square lattice and 0.79 for the simple cubic lattice, the largely ferromagnetic ground state abruptly fragments into two opposing but compact domains of comparable size. As p decreases further, a cascade of ever-smaller domains follows. We propose that the "first-order-like" behavior is driven by a domain-wall energy $E(L) = \gamma(p)L^{d-1} + aL^{\omega}$, where $\gamma(p)$ vanishes linearly at p_c, $a > 0$, and $\omega(d)$ is the energy exponent of directed surfaces in a disordered medium[3]. The first instance of vanishing domain-wall energy occurs at the largest scale permitted by the system size L, marking the onset of domain fragmentation process. To confirm this scenario and extend the analysis to finite temperatures, we compute the free energy difference $\Delta F(p, T, L)$ under periodic and anti-periodic boundary conditions, using the same bond configuration for both [1, 2]. Our findings also suggest a physical understanding of the complex order in the spin glass state.

[1] Yi Liu, Ding Wang, Xin Wang, Dao-Xin Yao, and Lei-Han Tang, *Communications in Theoretical Physics* **77**, 125603 (2025).
[2] Yi Liu, Ding Wang, Dao-Xin Yao, L. F. Cugliandolo, and Lei-Han Tang, in preparation.
[3] S. Brazovskii and T. Nattermann, *Advances in Physics* **53**, 177 (2004).

[Talk 14]

Lattice glass model in three spatial dimensions: Statics and dynamics at low temperatures

Yoshihiko Nishikawa [1,2]
[1]Department of Physics, Nagoya University
[2]Department of Physics, Kitasato University

The origin of the drastic dynamical slowing down upon approaching the glass transition has been a subject of debate over decades. There are many theories that can describe the observed dynamical features of glasses but are based on completely different physical pictures, including the Adam-Gibbs, the dynamical facilitation (DF), and the random-first order transition (RFOT) theories. Despite recent advances in experiments and numerical simulations [1], we still have not been able to disentangle those theoretical scenarios for the glass transition due to the very long timescales and thus have not reached a complete understanding of the origin of the slow glassy dynamics.

In Ref. [2], we proposed a lattice glass (LG) model as a simple toy model for the glass transition. In the model, particles can lie only on lattice sites, in contrast to off-lattice, atomistic models. Yet, the model shows the slow glassy dynamics typically found in fragile supercooled liquids, such as the super-Arrhenius growth of the relaxation time and the strong dynamical heterogeneity without any quenched disorder. Interestingly, the LG model in three dimensions has static properties that are similar to those observed in the mean-field limit, e.g. a first-order transition in the coupled system and a rapid drop in the specific heat. The LG model should be thus useful for a crucial test of the RFOT theory in physical dimensions.

Here, we study the equilibrium dynamics of the LG model deep inside the glassy temperature regime using Monte Carlo simulations [3]. At very low temperature, the dynamics is highly heterogeneous, even stronger than that found in off-lattice models, with narrow spatial channels in which particles are much more mobile than those in the other regions. In the mobile regions, clusters of a few lattice sites with small energy barriers emerge and each can travel a large distance within a time much shorter than the structural relaxation time. We find that the facilitation process caused by the clusters governs the early stage of the relaxation, and they eventually trigger the subsequent collective motion of particles. Whereas this relaxation process is qualitatively the same as that observed in atomistic models [4], some static lengthscales grow as fast as the dynamic lengthscales contrary to such models, suggesting the dynamical slowing down of the model is controlled by the growing thermodynamic lengthscales. Our results provide a possible *reconciliation* between the RFOT and the DF scenarios for the glass transition, which we believe is a key to understanding the physical origin of the glass transition.

[1] M. D. Ediger, J. Chem. Phys. 147, 210901 (2017); A. Ninarello *et al.*, Phys. Rev. X 7, 021039 (2017).

[2] Y. Nishikawa and K. Hukushima, Phys. Rev. Lett. 125, 065501 (2020).

[3] Y. Nishikawa and L. Berthier, Phys. Rev. Lett. 132, 067101 (2024).

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[Talk 15]

Analysis of evolutionary constraints using bacterial experimental evolution

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Biological systems undergo changes to evolve and adapt to varying environmental conditions. Despite the importance of characterizing the biological capacity to adapt and evolve, research on phenotypic/genotypic plasticity and constraint has yet to be limited to qualitative analyses. To investigate the quantitative nature of phenotypic/genotypic evolution, we conducted a high-throughput experimental evolution of E. coli under various stress environments using an automated system we developed. Our study aimed to provide a detailed analysis of the physical and genetic changes that occur in response to environmental stresses. Our phenotypic/genotypic analyses showed that the observed changes in the evolved E. coli strains were constrained to a relatively low-dimensional dynamics [1], which was consistent with our theoretical prediction [2].

The observation of low dimensionality in phenotypic evolution implies that evolution can be predictable and controllable. To explore this possibility, we began developing methods to predict and control phenotypic evolution based on the high-throughput experimental evolution we conducted. In our first approach, we developed a method to estimate the phenotype-based fitness landscape for antibiotic resistance. Our study involved quantifying multidimensional phenotypic changes, specifically time-series resistance data for eight drugs, starting from multiple initial strains. We used appropriate dimension reduction techniques and machine learning to infer fitness landscapes in two-dimensional phenotype space [3]. We found that the fitness landscape sometimes has multiple peaks, which correspond to different drug resistance mechanisms. We then analyzed how inferred phenotype-fitness landscapes could contribute to the prediction and control of evolution. Additionally, we are developing a method to achieve an evolutionary trajectory towards a desired target phenotype on the multidimensional phenotype space using feedback regulation to the selection pressure. Based on these results, we will discuss the nature of phenotypic plasticity and constraints in bacterial evolution, as well as potential strategies for predicting and controlling evolutionary dynamics.

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[Talk 16]

A Mathematical Theory of Aging and Its implications for Healthspan Extension

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A century of work has catalogued myriad molecules, pathways, and physiological states that modulate aging, yet an integrative quantitative theory of why organisms age is still missing. We argue that the way forward is to coarse grain biological complexity into a small set of universal, predictive, and interpretable variables.
We have now realized this crucial step [1–6]. Longitudinal measurements in mice [1] and single *E. coli* cells [2] reveal that the dynamics of physiological damage in both organisms obey the same low dimensional stochastic differential equation [3] . This model—with no retraining—accurately forecasts human survival curves [1], age related disease incidence [4], and the effects of interventions [5,6].
Going forward, the resulting framework provides a unified mathematical lens through which decades of aging research can be systematically integrated and reevaluated. As an example, I will show how it uncovers a surprising quantitative link between health-span and lifespan inequality and how that insight guides the search for interventions that not only lengthen life but also compress morbidity [5], a central goal of longevity research.

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[Talk 17]

Mechanobiological mechanism of cyclic stretch-induced cell columnarization

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Tissues consist of many cells that work together to perform a specific function for the living organism. While cells within a tissue are constantly perturbed by time-varying mechanical forces from the surroundings, they are capable of maintaining their structure required for execution of normal functions. To understand how cells respond to a dynamic mechanical stimulation, we subjected MDCK cells (a canine kidney epithelial cell line) to a persistent uniaxial cyclic stretch (CS), and found that MDCK cells autonomously transformed from a cuboidal to a columnar shape with increased cell height and reduced cell width. In particular, the CS-induced cell shape transformation is shown to be associated with the remodeling of intracellular cytoskeletons and intercellular junctions. Through atomic force microscopy (AFM) measurements and mathematical modeling analyses, we further confirmed that these molecular remodeling processes result in increase of tensile forces at both the apical and the basal sides of cells, which in turn promote the shape transformation. Our findings thus reveal a mechanobiological mechanism by which epithelial cells sense and adapt to a dynamic mechanical stimulation.

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[Talk 18]

Thermodynamics of Precision in Open Quantum Systems

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Achieving high precision in quantum technologies, ranging from clocks and sensors to thermal machines, inevitably incurs a thermodynamic cost. This trade-off is captured by thermodynamic and kinetic uncertainty relations, which constrain the fluctuations of currents and counting observables in terms of entropy production and dynamical activity. In the quantum regime, however, coherence, entanglement, and system-environment correlations complicate these relations, raising the question of how precision is fundamentally limited in realistic open quantum dynamics.

In this talk, I will present recent progress on the thermodynamics of precision in open quantum systems, spanning both Markovian and non-Markovian regimes. For Markovian dynamics, quantum extensions of thermokinetic uncertainty relations reveal how coherence can relax classical bounds, allowing enhanced precision at reduced thermodynamic cost [1]. Going beyond the weak-coupling and memoryless limit, I will introduce universal precision bounds valid for general open quantum systems subjected to two-point measurements [2]. These bounds demonstrate that the relative fluctuations of time-antisymmetric currents are limited not only by entropy production but also by a forward-backward asymmetry term, which reflects the time-reversal symmetry breaking caused by dynamical factors such as quantum coherence and quantum entanglement. For generic observables, precision is instead constrained by a generalized activity term, which quantifies changes in the environment.

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[Talk 19]

Fluctuation–Response Inequalities for Nonequilibrium Steady States

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In this talk, I present a unified framework of fluctuation–response inequalities (FRIs) for Markov jump processes, derived from the Cramér–Rao bound. These inequalities generalize conventional fluctuation–response relations by linking the fluctuations of a wide class of observables, including both current-like and state-dependent ones, to the system's response under perturbations of transition rates. Unlike static relations restricted to steady-state currents, the FRIs remain valid for finite observation times and capture dynamic responses. Known results also emerge as limiting cases, which clarifies their scope within a broader structure. The framework is further extended to open quantum systems governed by Lindblad dynamics, where a quantum FRI arises and dynamical activity constrains the system's response. Numerical illustrations in both classical and quantum settings demonstrate the robustness of the inequalities across different system topologies and timescales.

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[Talk 20]
Activity-induced quantum phase transitions: A proposal for quantum active matter

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Active matter is an ensemble of self-propelled entities, such as flocks of birds and schools of fish, that has attracted much attention because of phase transitions and pattern formation not present in equilibrium systems [1]. While the physics of active matter has been studied extensively in statistical physics and biophysics, most studies have been limited to classical systems, and the possibility of active matter in quantum systems has rarely been considered. However, recent developments in atomic, molecular, and optical systems allow us to study the complex dynamics of quantum many-body systems in a highly controlled manner, and it may be possible to design quantum many-body systems that behave like active matter. Stimulated by this, the study of a quantum analog of active matter has only recently begun [2–8]. In particular, we have studied quantum phase transitions analogous to the nonequilibrium phase transitions of active matter [2,8].

In this talk, I would like to present our work on quantum active matter. We have studied two-component (spin-1/2) hard-core bosons with spin-dependent asymmetric (non-Hermitian) hopping, corresponding to the motility of each active particle. This is expected to be realized with ultracold atoms in a dissipative optical lattice. We have shown that this model can be regarded as a quantum generalization of classical active matter models defined on a lattice, and that it exhibits various phase transitions, including nonequilibrium phase transitions unique to active matter, such as motility-induced phase separation [2]. In more recent work [8], we have shown that the combination of activity and repulsive interactions induces ferromagnetism, based on both numerical and analytical analyses. This activity-induced ferromagnetism can be considered as a quantum counterpart of flocking. While the flocking transition in classical systems requires a microscopic alignment interaction, this mechanism does not require such an interaction and thus may be unique to quantum active matter.

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[Talk 21]

General Theory for Group Resetting with Application to Avoidance

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We introduce a theoretical framework for group resetting dynamics in multi-particle systems under a drift potential. While classical resetting models typically reset a single particle, even when many are present, our formulation integrates information from all particles and resets them to the same position according to a predefined protocol—capturing how group behavior governs resetting events. Inspired by recent applications of resetting as a regulatory tool, such as stabilizing water levels or mitigating financial risks, we extend this concept to group dynamics, with implications for bacterial evolution.

By combining renewal theory and extreme-value statistics, we derive a Fokker–Planck equation for the group's center of mass, treated as an effective particle, and obtain analytical expressions for key observables: stationary mean, variance, and a dimensionless risk measure. Our results reveal how group size and resetting rate shape the probability of avoiding danger regions. This framework opens new perspectives for designing optimal group-level strategies for search, regulation, and avoidance through resetting [1].

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[Talk 22]

Equilibrium-preserving Laplacian renormalization group

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Diffusion-based Laplacian Renormalization Group(LRG) provides a principled framework for defining spatiotemporal scales and coarse-graining complex networks. However, its original formulation relied on an ad hoc procedure lacking a rigorous foundation. We present an equilibrium-preserving LRG[1] that systematically derives renormalized Laplacians via a proper, quasi-complete basis transformation, ensuring that the renormalized diffusion equation retains its equilibrium solution. Using equilibrium-state flows, we further construct renormalized adjacency matrices that preserve mean connectivity and effective diffusion dynamics. Applying this framework recursively to hypergraphs, we uncover distinct classes of structural flows: in hypertrees with low spectral dimensions, vertex-degree and hyperedge-cardinality distributions converge toward Poissonian forms, whereas in hypergraphs lacking finite spectral dimensions, initially narrow distributions broaden toward power-law forms. These results establish a robust theoretical foundation for renormalization on networks and hypergraphs and reveal how informational, structural, and dynamical scale-invariances are interrelated.

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[Talk 23]

Mechanism of the Emergent System-2 Reasoning in LLMs: A Complex Network Perspective

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Large Language Models (LLMs) represent a new frontier for complex systems physics, where emergent cognitive abilities arise from trillions of interacting parameters. A profound example is the development of multi-step "System-2" reasoning when models are trained with reinforcement learning using verifiable rewards (RLVR), yet the underlying mechanism remains opaque. We propose a complex-network account in which reasoning corresponds to policy-guided traversals on a latent graph of concepts. To make these dynamics tractable, we introduce a minimal model (CoNet) where problem-solving is a Markovian random walk on a K-regular random graph. Under multi-task RLVR, CoNet reproduces a robust two-stage trajectory also seen in full-scale LLMs : an initial fast-learning phase that discovers efficient but isolated reasoning paths , followed by a slow plateau during which those paths interconnect into a large, linked—and ultimately frustrated—concept web. Crucially, this reorganization is phase-transition-like at the level of a single question–answer instance. The framework explains key empirical signatures, including the lengthening of correct reasoning chains , a trade-off between performance and diversity , and a collapse of policy entropy as probability mass concentrates on reinforced paths. Finally, drawing on these insights, we propose an "annealed-RLVR" protocol: periodically inserting brief Supervised Fine-Tuning phases to “melt” the concept web by reintroducing lost paths, followed by RLVR phases that allow the system to reconsolidate into a more optimal state. Our study connects the emergence of reasoning in LLMs to familiar statistical-physics notions of network formation, frustration, and critical-like transitions, and yields concrete, testable predictions for learning curves and internal connectivity during RLVR.

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[Talk 24]

Understanding memorization and reasoning of language model through neuron condensation

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Reasoning ability is important to LLMs. In this talk, I will show initialization is critical to reasoning ability of Transformer networks by studying compositional functions. Small initialization, which leads to neuron condensation phenomenon, biases towards more reasoning while large initialization towards memorizations.

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[Talk 25]

Reversals and oscillations as a precursor of bacterial active turbulence

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Bacteria swimming at high density form spatiotemporally chaotic flows and vortices, called active turbulence, even at low Reynolds numbers. In contrast to conventional Navier-Stokes turbulence, active turbulence, occurring for essentially zero Reynolds numbers, is characterized by the well-defined characteristic length scale. The existence of the typical vortex size allows transforming bacterial motion into stable vortex arrays under geometrical confinements or in the presence of obstacles [1]. However, how these vortical orders get destabilized and eventually lead to turbulence was not well characterized.

In this talk, we first elaborate our experiments on the self-organizations of bacterial active turbulence into stable vortical structures in microscopic pillar arrays [1]. We experimentally inferred the boundary conditions and incorporated them into a continuum description of the bulk unconstrained active turbulence [2]. This numerical scheme with these boundary conditions has successfully reproduced the emergent macroscopic vortex order and the topology of the flow field around a pillar observed in the experiments. Next, by combining large-scale experiments, computer modeling, and analytical theory, we have uncovered the basic instability mechanism that destabilize the vortical order, leading to a reversing vortex pair and then a pulsating four-vortex state [3,4]. This mechanism characterizes a universal route to well-developed active turbulence. Our findings provide insights into how geometrical confinements orchestrate spatiotemporal organization in a broad class of active systems. The controls and rectification of vortices in confined active matter may open up new possibilities for engineering and utilizing active matter for e.g. mixing at the microscale.

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[Talk 26]

Designing topological edge localization in bacterial active matter

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Besides its potential relevance to the life sciences, active matter also manifests as a novel, intrinsically non-equilibrium kind of matter, endowed with collective properties and functions absent in ordinary matter. As an example, active liquid composed of swimming bacteria was reported to turn a gear [1], which would be forbidden for ordinary liquid by the second law of thermodynamics. A challenge is how to control and design such functions of active matter. In this context, topology has emerged as a useful tool for designing robust collective phenomena in condensed matter physics [2]. However, experimental realizations of topological phenomena in active matter have thus far relied on the chirality of the active particles, which limits design capabilities.

Here we report a controlled realization of topological edge localization in dense bacterial suspension [3], induced by microfabricated geometry instead of the bacteria's chirality. First we demonstrate that we can rectify bacterial collective motion in a channel by using its asymmetric shape. Then we construct networks made of such asymmetric channels and show that we can control the emergence of topological edge localization through the network design. Through modelling and experiments, we discuss what properties of the network and the bacterial flow are crucial to the observed topological phenomenon. We expect our results may pave the way for establishing a control and design principle of topological transport in such active matter systems.

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[Talk 27]

Statistical mechanics of lateral predictive coding: energy--information tradeoff, feature detection, and discontinuous phase transitions

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The brain may adopt the strategy of lateral predictive coding (LPC) to construct optimal internal representations for salient features in input sensory signals, reducing the energetic cost of information transmission. Here we first consider the task of detecting one non-Gaussian signal by lateral predictive interactions from Gaussian background signals of the same magnitude, which is intractable by principal component decomposition. We study the emergence of feature detection function from the perspective of tradeoff between energetic cost E and information robustness, and implement this tradeoff by a thermodynamic free energy. We define E as the mean $L1$-norm of the internal state vectors, and quantify the level of information robustness by an entropy measure S. There are at least three types of optimal LPC matrices, one type with very weak synaptic weights and S close to zero, and two functional types either with low energy E or with high entropy S in which one single unit selectively responds to the non-Gaussian input feature. Energy--information tradeoff induce two discontinuous phase transitions between these three types of optimal LPC networks. We then extend the discussion to detecting and distinguishing between two non-Gaussian input features and observe similar discontinuous phase transitions.

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[Talk 28]

Complex network science for brain-inspired sparse artificial network training to develop efficient and sustainable AI

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Abstract

Complex network science is an emerging interdisciplinary discipline at the intersection of physics, mathematics, computer science, and data science. While its intellectual roots lie in statistical physics, the field has rapidly evolved into a global scientific framework, shaping research across biology (gene regulation, protein interactions, brain networks), computer science (internet topology, algorithms), socioeconomic sciences (social dynamics, mobility), and engineering (infrastructure and power grids). Network science theory and modelling can guide the design of next-generation artificial intelligence systems, where sparse network architectures are harnessed for both efficiency and performance.

Artificial neural networks (ANNs) are foundational to contemporary artificial intelligence (AI), however their conventional fully connected architectures are computationally inefficient. Contemporary large language models consume vast amounts of power at rates over 100 times that of the human brain. In contrast, the brain's inherently sparse connectivity facilitates exceptional capabilities with minimal expenditure: learning with just a few watts.

Brain-inspired network science offers a promising pathway towards low-consumption, high-efficiency deep learning. Developing new theories for an ecological and sustainable approach to AI requires inspiration from the physics of brain connectivity and its complex systems biology. At the Center for Complex Network Intelligence (CCNI) within the Tsinghua Laboratory of Brain and Intelligence (THBI), our research focuses on three pivotal features of brain networks that contribute to efficient computation: (1) Connectivity Sparsity: training a dynamic sparse connectivity to reduce computational overhead while maintaining performance; (2) Connectivity Morphology: exploring the spatial patterns of neural connections to optimize information processing; (3) Neuro-Glia Coupling: investigating the interactions between neurons and glial cells to enhance computational efficiency.

This talk will introduce the Cannistraci-Hebb Training soft rule (CHTs), a brain-inspired

network science theory that employs a gradient-free network-informed approach to emulate the growth of new connection during synaptic turnover. Relying solely on network topology to predict sparse connectivity during dynamic sparse training, CHTs have demonstrated the potential to achieve ultra-sparse networks with approximately 1% connectivity, outperforming fully connected networks in various tasks.

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[Talk 29]

Data augmentation using diffusion models to enhance inverse Ising inference

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Identifying model parameters from observed configurations poses a fundamental challenge in data science, especially with limited data. Recently, diffusion models have emerged as a novel paradigm in generative machine learning, capable of producing new samples that closely mimic observed data. These models learn the gradient of model probabilities, bypassing the need for cumbersome calculations of partition functions across all possible configurations. We explore whether diffusion models can enhance parameter inference by augmenting small datasets. Our findings demonstrate this potential through a synthetic task involving inverse Ising inference and a real-world application of reconstructing missing values in neural activity data. This study serves as a proof-of-concept for using diffusion models for data augmentation in physics-related problems, thereby opening new avenues in data science.

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[Talk 30]

Second-Law violating events are not Rare in Non-equilibrium non-steady states

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For non-equilibrium systems in which fluctuations are important, it is well-established that there can be events that violate the Second Law of thermodynamics on the trajectory level. For non-equilibrium steady-states, these Second-Law violating events are rare, but this may not be true for far-from-equilibrium non-steady processes. In the paradigm system of a Brownian particle trapped under a time-dependent compressing potential, we demonstrate that Second-Law violating trajectories can outnumber the Second-Law obeying ones[1]. In particular, for abruptly compressed harmonic and anharmonic potentials, analytic expressions for the total entropy production distribution and the fraction of Second-Law violating events are derived to show explicitly that Second-Law violating events can be of significant majority. These results are further confirmed in experiments. Furthermore, one can view the Second Law abiding or violating trajectories, respectively, as winning or losing in a gambling process in which a negative (positive) total entropy production is regarded as a winning (losing) scenario. Together with the decision to stop the process when the cumulative work exceeds some assigned threshold, one can describe the stochastic stopping process of a non-equilibrium trajectory as the action of a gambling demon, which has been realized experimentally[2,3]

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[Talk 31]

High-Efficiency Stochastic Engines: A Dynamical Systems Perspective

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We investigate a stochastic Stirling engine operating in various active baths governed by a large number of stochastic dynamical systems and derive conditions under which active engines can outperform their passive counterparts, as notably demonstrated in a recent experiment with a bacterial bath. Our analysis attributes such enhanced performance to either a restoring effect in noise or to a significant dissipation kernel. We further examine its impact on the maximum power output, Carnot efficiency, and Curzon-Ahlborn efficiency. These findings provide insights into the origins of the reported superior performance of active heat engines, offer strategies for harvesting energy from active noise, and illuminate the role of nonequilibrium temperature in stochastic thermodynamics.

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[Talk 32]

Nonlinearity-induced topological phase transition and chaos transition in nonlinear topological insulators

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Since the quantum Hall effect was discovered, band topology has attracted much interest in condensed matter physics. The principle of the bulk-edge correspondence guarantees the oneby-one correspondence between the nonzero bulk topological invariants and the existence of gapless edge modes that are localized at the edge of the sample. Recent studies have extended the notion of topology to classical systems, such as fluids, optics, and active matter, by constructing an analogy between their linearized dynamics and the Schrödinger equations. However, the governing equations of classical dynamics are often nonlinear, and it has been unclear whether the bulk-edge correspondence of topological insulators can be extended to such nonlinear systems.

We reveal that topological invariants and their bulk-edge correspondence are extended to nonlinear systems via the nonlinear extension of the eigenvalue problem [1]. We find that the nonlinear topological invariants depend on the norm of the nonlinear eigenvector, which enables us to predict the nonlinearity-induced topological phase transition under moderately strong nonlinearity. In contrast, if we consider further stronger nonlinearity, topological edge modes can exhibit spatial chaos transitions [2], which induce the breakdown of the bulk-edge correspondence. These nonlinearity-induced transitions and chaos transitions can be understood from the nonlinear extension of transfer matrices [3], i.e., spatial dynamics in a unified way.

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[Talk 33]

Finite-size scaling of the Kuramoto model

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The asymptotic scaling behavior of the Kuramoto model with finite populations has been notably elusive, despite comprehensive investigations employing both analytical and numerical methods. In this paper, we explore the Kuramoto model with "deterministic" sampling of natural frequencies, employing extensive numerical simulations and reporting the asymptotic values of the finite-size scaling exponents, which deviate significantly from the previously reported values in the literature. Additionally, we observe that these exponents are sensitive to the specifics of the sampling method. We discuss the origins of this variability through the self-consistent theory of entrained oscillators.

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[Talk 34]

Coherence enhanced by dynamic oscillators: Breaking π-reflection symmetry

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We study a generalized Kuramoto model in which each oscillator carries two coupled phase variables, representing a minimal swarmalator system. Assuming perfect correlation between the intrinsic frequencies associated with each phase variable, we identify a novel dynamic mode characterized by bounded oscillatory motion that breaks the π-reflection symmetry. This symmetry breaking enhances global coherence and gives rise to a non-trivial mixed state, marked by distinct degrees of ordering in each variable. Numerical simulations confirm our analytic predictions for the full phase diagram, including the nature of transition. Our results reveal a fundamental mechanism through which non-entrained dynamic oscillators can promote global synchronization, offering broad insights into coupled dynamical systems beyond the classical Kuramoto paradigm.

[P1]

Deep learning complex intracellular calcium oscillations

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Calcium ions (Ca^{2+}) are essential intracellular messengers whose diverse dynamical patterns reflect key physiological states linked to both health and disease. Deterministic nonlinear models have shown how biochemical parameters give rise to different dynamical behaviors such as steady states, oscillations, bursting, chaos, and multi-periodicity states. However, in reality, small biological cells are inherently stochastic due to finite molecular populations, raising the question of whether these organizational principles of Ca^{2+} dynamics persist under intrinsic fluctuations and remain biologically meaningful. To address this, we use a large-kernel convolutional neural network (LKCNN) tailored to capture dynamical features of Ca^{2+} across noise levels. Our LKCNN model achieves ~90% accuracy in classifying eight distinct dynamical states despite fluctuations. When validated against experimental Ca^{2+} trajectory data from pancreatic β-cells, WT-HEK293, STIM-KO, and ORAI TKO cells, accuracy shows ~97%. These findings demonstrate that deterministic organizational signatures of Ca^{2+} dynamics are preserved under realistic biological noise, suggesting that parameter-dependent dynamical structures constitute robust principles governing cellular function.

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[P2]

An Observable Capacity Bound for Force Inference: MMSE Upper Bounds, Optimal Sampling, and Generic Fluctuation Laws

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Inferring latent forces from stochastic trajectories is a fundamental problem across physics and beyond. We introduce stochastic force alignment that quantifies the local agreement between hidden forces and their inferred counterparts. We prove that its expectation upper-bounds the minimum mean square error of force inference, which, when combined with finite time discretization error, implies a unique optimal sampling interval. Finally, we uncover a set of generic statistical properties of stochastic force alignment, integral and detailed fluctuation theorems and extremal statistics identities, that hold independently of the system's dynamics, the force form, and stationarity.

[P3]

Analyzing the Association Between Transaction Diversity and Regional Mobility/Consumption: An Inflow–Outflow Perspective

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Using credit-card transaction records for 250 regions from January 2019 to August 2022, we quantify spending heterogeneity with an entropy-based measure and define transaction diversity (TD) as the mean entropy of the spending-amount distribution. We evaluate TD separately for inflow (purchases within a region by nonresidents) and outflow (purchases outside the home region by residents), providing a flow-aware view of regional economic activity. We then examine how TD co-varies with government interventions, a fear index, regional industry composition, and observed mobility and consumption. Cross-regional differences in inflow and outflow TD indicate that interregional mobility responded asymmetrically to the COVID-19 shock. These results suggest that comparing inflow- and outflow-side TD offers a compact, entropy-based indicator of mobility and consumption sensitivity during the pandemic, and can inform policy evaluation and the design of crisis-response scenarios.

Keywords: COVID-19; credit-card transactions; entropy; inflow–outflow mobility; transaction diversity

[P4]

Length heterogeneity drives efficient bacterial swarming

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Swarming refers to the collective motion of flagella-driven, rod-shaped bacteria for rapid translocation. Recently, there have been many studies focusing on the collective behavior of bacteria; however, the impact of intra-strain phenotypic variation on the swarming dynamics remains an open question, even though this variation is common in nature. To address this gap, we present the dynamics of monolayer swarming of a single strain of *Vibrio alginolyticus* to understand how cell length heterogeneity confers functional advantages through multiscale dynamics. Our results show that longer cells exhibit greater motility and directional persistence, form the swarming clusters, and facilitate coordinated movement. On the contrary, shorter cells reverse more frequently, and thus, disrupt motion memory and modulate complex clusters' interaction. These behaviors collectively enhance overall swarming efficiency. Our findings connect statistical physics with microbiological complexity and help incorporate phenotypic variability into the model of active matter.

[P5]

Global Entropy Production in Langevin Dynamics in Terms of a Single Mutual Information: Theory and Application

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The entropy production (EP) of a system in a non-equilibrium steady state is a key measure of its thermodynamic irreversibility. While various formulations for EP exist, a fundamental representation rooted in information theory for general stochastic systems has remained a significant challenge. In this work, we establish a rigorous equality connecting thermodynamics and information theory: the **global entropy production rate** in general nonlinear **Langevin dynamics** with constant diffusion is exactly given by a single **mutual information** rate.

Specifically, we prove that the global EP is proportional to the rate of mutual information between a particle's infinitesimal displacement (dx) and the midpoint of its path (xm), i.e., I(dx:xm)/dt. This finding opens new avenues for applying various information-theoretic tools—such as the Data Processing Inequality (DPI), Partial Information Decomposition (PID), the information chain rule, and Shapley decomposition— in the theoretical study of EP. Furthermore, it is expected to pave the way for novel methodologies for measuring entropy production.

[P6]

Revealing Underlying Dynamics from Noisy Observations: An Unsupervised Reservoir Computing Approach

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We introduce a novel, unsupervised framework for separating deterministic signals from complex noise, a fundamental challenge in analyzing physical systems. Our approach uses Reservoir Computing to learn and extract predictable dynamics directly from a single, noisy time-series without prior assumptions about the signal or noise structure. We first establish the method on univariate signals and then extend it to high-dimensional, multivariate systems by uniquely utilizing the estimated correlation structure of the noise itself to enhance signal reconstruction. Validated on data from spatiotemporal chaotic systems, our framework demonstrates robust performance even in severe noise conditions, providing a powerful, data-driven tool for revealing the true underlying dynamics in experimental and observational data.

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[P7]

Collective dynamics of autonomously steering microswimmers: swarming, turbulence, clusters, vortices

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Cognition-based interactions between self-propelled particles, like alignment and cohesion, often govern collective behavior in active matter. Such adaptive self-steering gives rise to a variety of fascinating phenomena, ranging from large-scale swarming as observed in mammalian herds and schools of fish, or even cell layers and tissues, to the formation of bacterial biofilms. Typically on microscales, hydrodynamics plays a critical role, e.g., by destabilizing a polar state in systems with alignment interactions, as indicated by a stability analysis. Using large-scale simulations, we explore self-organization in systems of cognitive self-propelled particles with hydrodynamic interactions [1,2]. Our simulations disclose rich dynamical patterns, including active turbulence, the emergence of pulsatile vortex rings, and worm-like swarming, which illustrate novel forms of self-organization. In particular, alignment amplifies hydrodynamic interactions, leading to chaotic advection of microswimmers [3], while cohesion facilitates spatial heterogeneity, thereby regulating density-dependent interparticle interactions [4]. The clustering tendency is more pronounced in systems of front-actuated microswimmers (pullers), whereas rear-actuated microswimmers (pushers) generally exhibit vortical advection.

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[P8]

Entropy Production in Non-Gaussian Active Matter: A Unified Fluctuation Theorem and Deep Learning Framework

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We present a general framework for deriving entropy production (EP) rates in active matter systems driven by non-Gaussian active fluctuations. Employing the probability flow equivalence technique, we rigorously derive an EP decomposition formula. By introducing three distinct irreversibility concepts—trajectory, flow and process irreversibilities, we demonstrate that the EP, Δs_{tot}, satisfies the integral fluctuation theorem $\langle \exp[-\Delta s_{tot} + \mathrm{B}_{act}]\rangle = 1$ and the generalized second law of thermodynamics $\langle \Delta s_{tot}\rangle \geq \langle \mathrm{B}_{act}\rangle$, where B_{act} quantifies the difference between trajectory- and ensemble-level active entropy production rates (in terms of trajectory irreversibility); the difference between trajectory- and ensemble-level active heat dissipation (in terms of flow irreversibility); and, in terms of process irreversibility, the disparity between process and flow irreversibilities. Our result holds generally for arbitrary initial conditions, encompassing both steady-state and transient finite-time regimes. In the limiting case where active fluctuations are absent (i.e., $\mathrm{B}_{act} \equiv 0$), the theorem reduces to the well-established results in stochastic thermodynamics. Building on the theoretical foundation, we propose a deep learning-based methodology to efficiently compute the EP, utilizing the Lévy score we proposed. To illustrate the validity of this approach, we apply it to a representative system: a Brownian particle in a periodic active bath. And we verify the generalized second law in this example. Our results provide a unified framework for analyzing EP in active matter systems while offering practical computational tools for investigating complex nonequilibrium behaviors.

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[P9]

Measuring Condensation through Gini Index

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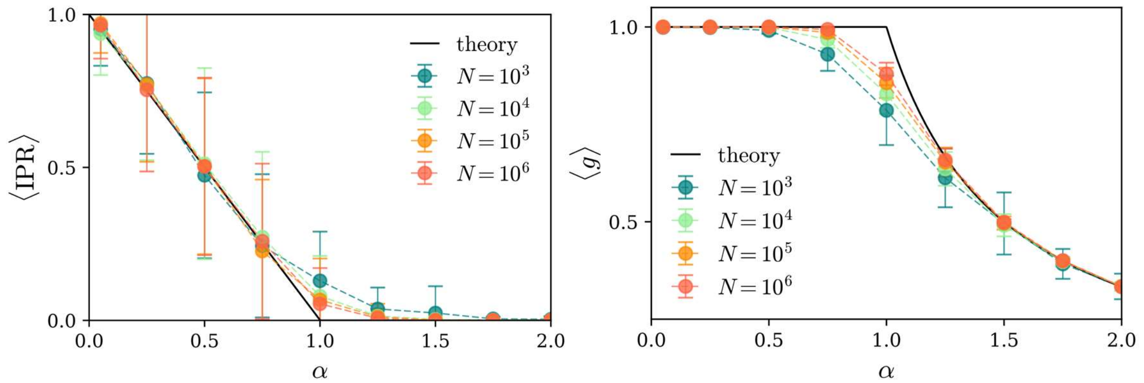
We investigate the condensation transition on power-law tailed distributions by comparing two condensation measures: the inverse participation ratio (IPR) and the Gini index. While the IPR has been widely used to characterize condensation in extreme value statistics [1], ensemble average of IPR does not show system size dependence. In contrast, we demonstrate that the Gini index provides a consistent system size dependence and, in particular, size effect analytically tractable for Pareto distribution. The Bouchaud–Mézard (BM) model [2] on Erdős–Rényi (ER) network is representative wealth dynamics model that generating power-law tailed distribution and exhibits wealth condensation transition over control parameter $2J/\beta^2$. Through numerical simulations of the BM model on ER network, we show that the Gini index exhibits consistent size effect and follows scaling behavior over control parameter. Our findings suggest that the Gini index is a more reliable measure than IPR for detecting condensation, especially in finite-size systems, and open pathways for applying this framework to broader models such as urn processes and percolation systems.



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[P10]

Percolation in degree-size correlated hypergraphs

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Recent studies encoding complex systems into hypergraphs have provided insights into how higher-order interactions affect large-scale connectivity; yet systematic investigations of higher-order correlations remain scarce. In particular, empirical hypergraphs of real-world systems commonly exhibit pronounced degree–size correlation, where a node's degree (the number of hyperedges it belongs to) correlates with the hyperedge's size (the number of nodes it contains). The impact of degree–size correlation on percolation in hypergraphs remains largely unexplored; in this work, we embark on a systematic analysis. We compute the giant component size, which characterizes global connectivity and reveals percolation properties, as a function of degree-size correlation by using both an analytic approach—extending the generating-function framework to incorporate joint degree-size distribution—and numerical Monte Carlo simulations based on the configuration model. Our results show that positive correlation helps in forming a core of high-degree nodes (hubs), which facilitates large-scale connectivity when the mean degree is low, while negative correlation helps in promoting low-degree nodes into the giant component, enhancing connectivity when the mean degree is high. These findings demonstrate how the degree–size correlation can modulate the percolation properties of hypergraphs.

[P11]

System-Specific Information Transfer Patterns and Inference

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We found that the distribution $p(\mathbb{T})$ of transfer entropy (TE), $\mathbb{T}$, which quantifies information transfer between data, exhibits system-dependent variations. Specifically, while the distribution $p(\mathbb{T})$ obtained from earthquake data follows a power-law form $p(\mathbb{T}) \sim \mathbb{T}^{-\alpha}$, the distribution derived from stock price fluctuations follows an exponential form $p(\mathbb{T}) \sim \exp(-\mathbb{T}/\tau)$. To investigate the origin of such differences across datasets, we analyzed time series generated from the Ising model under various conditions. From this analysis, we discuss the influence of criticality and interaction structure on $p(\mathbb{T})$, and propose a method to infer the underlying interaction structure based on the statistical properties of the TE distribution.

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[P12]

Non-reciprocal Dynamics in a Rock-Paper-Scissors Vicsek Model: Emergence of Collective Patterns

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This study analyzes a rock-paper-scissors (RPS) type interaction system of self-propelled particles, by incorporating the Vicsek model. The conventional Vicsek model describes the collective motion of self-propelled particles that align their direction with neighboring particles while being influenced by noise. Depending on the particle density and noise level, the system exhibits various macroscopic phenomena such as disordered motion and parallel alignment. To extend the conventional model into the RPS-type system, we introduce the cyclic competition among three different species characterized by the two parameters α and β: α represents the extent to which a species pursues ($\alpha>0$) or avoids ($\alpha<0$) its prey and β determines the response to its predator (chasing ($\beta>0$) or escaping ($\beta<0$) from the predator). We investigate the collective patterns in the α-β plane. In particular, we focus on the dynamic behavior in the presence of the non-reciprocal interaction. Our findings provide insights into predator-prey relationships observed in biological systems and contribute to understanding the formation of collective motion patterns driven by non-reciprocal interactions.

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[P13]

The Role of Punishment in Indirect Reciprocity under Incomplete Observation

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One of humanity's enduring aspirations is to build cooperative societies where mutual aid drives progress. Within game theory, indirect reciprocity has emerged as an important framework for understanding the maintenance of cooperation. While most theoretical studies focus on two actions—cooperation (helping others at a personal cost) and defection (withholding help)—empirical evidence suggests that individuals also engage in costly punishment, where they incur a personal cost to penalize others. Despite its relevance, the theoretical role of punishment remains underexplored. In this study, we extend existing models by considering environments in which reputations are observable only with probability q, reflecting imperfect information. Using analytical methods, we identify social norms that support cooperative Nash equilibria and demonstrate that incorporating costly punishment expands the parameter space in which cooperation can be sustained. These results underscore the significant role punishment can play in fostering cooperation when reputational cues are limited.

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[P14]

Improving the generalization performance of the perturbed gradient descent via anticorrelated noise

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Adding stochasticity to deterministic learning algorithms can improve its generalization performance. In particular, the perturbed gradient descent (PGD), which adds artificial noise to the conventional gradient descent, has been found to achieve even better performance when the injected noise is anticorrelated in time (anti-PGD). To systematically investigate how an anticorrelated noise affects the generalization performance, we propose a class of PGD variants whose noise follows an Ornstein-Uhlenbeck process and has tunable magnitude of anticorrelation, which can interpolates between the PGD and anti-PGD. We analytically show that anticorrelation induces a Hessian-dependent effective loss, which introduces an implicit bias towards the flatter minima, potentially improving generalization ability. In addition, using generalized Fox's method, we analytically show that anticorrelated noise facilitates escape from sharper minima. In numerical studies on real CiFAIR and CIFAR data, varying the magnitudes of anti-correlation across the PGD and anti-PGD continuum revealed that performance is optimized at an intermediate value, which demonstrate that our algorithms improve upon existing methods.

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[P15]

Bacterial trail in entangled polymer solutions

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Active particles can leave behind time-varying heterogeneities in their trail that change another particle's motility. In the natural habitat of microbes, viscoelastic fluids, the homogenization time scale of such environmental cues is comparable to the inter-arrival time of cells to the same region. To investigate the remote interactions of bacteria via heterogeneities in a controlled environment, we introduced genetically modified bacteria, engineered to lack chemotactic sensing abilities, into an entangled polymer solution. In this purely physical system, our results show bacteria chasing other bacteria at distances of up to a few hundred microns along the same trajectories. The chasing bacteria also experienced increased velocity compared to the non-chasing state. We showed that this interaction diminishes when the polymer concentration is lowered. Thus, our study suggests that cells sharing no chemical cues can still interact remotely and enhance bacterial diffusion.

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[P16]

Thermodynamic control of active system and its application on a self-aligning particle under harmonic confinement

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We study the thermodynamic control of a self-aligning active particle in a harmonic trap, aiming to minimize the work required to drive it between nonequilibrium steady states. Unlike passive systems, where only the excess work depends on the protocol, both quasistatic and excess work are protocol-dependent in active systems. This breaks the conventional geometric framework, where optimal protocols follow geodesics in a Riemannian space. Using a nonequilibrium linear response theory, we derive generalized friction tensors and identify effective magnetic-like forces, leading to loop-shaped optimal trajectories. At short durations, excess work dominates and scales inversely with time; at longer durations, quasistatic and excess contributions compete. We numerically solve the Euler-Lagrange equation using semi-analytic expressions for the friction tensor and effective magnetic field.

[P17]

Cell-Cell Adhesion Drives Solidification and Fluidization of a Tissue

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Cells undergo collective motions during morphogenesis, which are controlled by fluidization or solidification of biological tissues. Fluid-like tissues show enhanced cell movement and frequent cell neighbor exchanges, while cells in solid-like tissues experience more constrained motions. Studies on simplified models of epithelial tissues, such as vertex and Voronoi models, have suggested that these tissue-level behaviors are governed by a single geometric parameter called the shape index, defined as the perimeter divided by the square root of the area. If the shape index exceeds or falls below a certain threshold, leading to more pentagonal or hexagonal cell shapes, tissues become fluidized or solidified, respectively. However, it remains still unclear whether a larger shape index, often attributed to a stronger cell-cell adhesion, leads to the fluidization of a tissue in more realistic settings. Intuitively, adhesion, which functions as an attractive force between cells, should rigidify a tissue, which may not be fully captured in the simplified epithelial models proposed before.

Here, we aim to address this adhesion-induced rigidity transition through a model that allows arbitrary packing fraction as well as cell shapes. We leverage the computational framework introduced in [1], where the contour of each cell is represented as a series of Fourier coefficients. We incorporated cell-cell adhesion with steric repulsion and deformability in this framework, which allowed us to reproduce the contact angle between two adhesive cells. We are currently exploiting this model to simulate the collective dynamics of adhesive cells within a tissue, with the goal of resolving the apparent contradiction between geometry-driven tissue fluidization and adhesion-driven tissue rigidification.

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[P18]

Dynamical systems perspective on KaiABC circadian rhythm

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Circadian rhythms in living organisms are temporal orders emerging from biochemical circuits driven out of equilibrium. Here, we study how the rhythmicity of a biochemical clock is shaped using the KaiABC system. A phase diagram constructed as a function of KaiC and KaiA concentrations reveals a sharply bounded limit-cycle region, which naturally explains arrhythmia upon protein over-expression. Beyond the Hopf bifurcation, intrinsic noise enables regular oscillation via coherence resonance. Within the limit-cycle region, greater rhythmic precision incurs a higher energetic cost, following the thermodynamic uncertainty relation. The cost-minimizing period of the KaiABC clock (~21-hr) is close enough to entrain to 24-hr cycle of environment. Our study substantiates universal physical constraints on the robustness, precision, and efficiency of noisy biological clocks.

[P19]

Stretching cross-linked polymer necklaces: binding via transverse fluctuations, crossover via quantum analogy

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We discuss the binding behavior of a directed-polymer pair with reversible cross-links, in both the freely jointed and wormlike chain models. In each model, we first revisit the partition function of a single chain and calculate the transverse fluctuations in the strong stretching (or weakly bending) regime. By showing that the projected transverse excursions follow a two-dimensional random walk, we introduce a *Gaussian slinky* representation of the polymer necklace, which enables an analytical treatment of the binding statistics. In the thermodynamic limit, we delineate two asymptotic regimes (weakly bound *vs* strongly bound) and evaluate the mean occupation number as a function of stretching force for each case. Furthermore, to characterize the crossover between the two regimes, we map the polymer trajectory onto a fictitious quantum particle in two dimensions, propagating in imaginary time. Through this quantum mechanical analogy, the binding free energy density is estimated from the lowest eigenvalue of an effective Schrödinger equation, allowing us to quantitatively predict the crossover force.

[P20]

Phase separation of active particles with chemokinetic effects

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Motility-induced phase separation (MIPS) is a well-studied nonequilibrium collective phenomenon observed in active particles. Recently, there has been growing interest in how coupling the self-propulsion of active particles to chemical degrees of freedom affects MIPS. Previous studies have shown that incorporating **chemotaxis** and production/consumption of chemicals by active particles results in various pattern formations, such as arrested phase separation and traveling waves. In this study, we demonstrate that similar phenomena can be induced when active particles consume chemicals and exhibit **chemokinesis**, where higher chemical concentrations enhance self-propulsion without causing alignment with the chemical gradient. We discover that MIPS is intensified if chemical consumption is proportional to particle density but is suppressed if chemical consumption is closely tied to particle motion. This leads to a broader range of collective behaviors, including arrested phase separation and oscillating patterns. Our findings are based on a hydrodynamic theory derived from a particle-based model via standard methods.

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[P21]

Independence of Correlation Functions from Odd Diffusivity in Odd-Diffusive Systems

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When both time-reversal and chiral symmetries are broken, transport tensors such as mobility and diffusion tensors can contain antisymmetric off-diagonal components. In particular, diffusive dynamics with an antisymmetric part in the diffusion matrix, known as odd-diffusive systems, exhibit motion that differs significantly from conventional Brownian diffusion, characterized by non-white noise with singular time correlations. Previous studies have reported several anomalous behaviors in autocorrelation-related quantities in such systems, which have been attributed to the presence of odd-diffusivity. However, in this presentation I will show that the correlation function of any observables is, in fact, independent of the antisymmetric part of the diffusion matrix. Instead, it is the antisymmetric part of the mobility tensor that plays the relevant role, giving rise to transverse forces and nonreciprocal interactions. Our findings enable the accurate calculation of correlation functions, both analytically and numerically, in odd-diffusive systems where traditional approaches fail. As a straightforward consequence, we also find that several universal relations associated with autocorrelation functions remain valid in odd-diffusive systems without modification. These results are verified through simple toy models as well as molecular dynamics simulations of hard-core odd-diffusive particles.

[P22]

How Wikipedia Article Connections Influence Editing Patterns

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This study investigates how hyperlinks, which connect related articles in Wikipedia, influence editors' editing patterns. While prior research has focused on individual article histories [1, 2] or editor-article networks [3], the role of direct article-to-article connections has been largely overlooked. We analyze the inter-event times between two pages and find that hyperlinked articles are edited more quickly and frequently than random pairs. To understand this behavior, we compare editor trajectories with a hyperlink-based network, using the Jaccard index to quantify the similarity between them. Based on their entropy—which measures the distribution of contributions across communities—we classify editors. Low-entropy editors, who focus on specific topics, show a high Jaccard similarity, indicating they follow hyperlink structures. In contrast, high-entropy editors and bots show a much lower tendency to follow these links. Our findings suggest that this hyperlink-driven editing behavior is a crucial factor in understanding Wikipedia's growth.

[1] O. Kwon, W.-S. Son, and W.-S. Jung, The double power law in human collaboration behavior: The case of Wikipedia, Physica A 461 (2016) 85.

[2] J. Choi, T. Hiraoka, and H.-H. Jo, Individual-driven versus interaction-driven burstiness in human dynamics: The case of Wikipedia edit history, Physical Review E 104 (2021) 014312.

[3] F. Ogushi, J. Kert´esz, K. Kaski, and T.Shimada, Ecology of the digital world of Wikipedia, Scientific Reports 11 (2021) 18371.

[P23]

Thermodynamic anomalies in overdamped systems with time-dependent temperature

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One of the key objectives in investigating small stochastic systems is the development of micrometer-sized engines and the understanding of their thermodynamics. However, the primary mathematical tool used for this purpose, the overdamped approximation, has a critical limitation: it fails to fully capture the thermodynamics when the temperature varies over time, as the velocity is not considered in the approximation. Specifically, we show that heat dissipation and entropy production calculated under the overdamped approximation deviate from their true values. These discrepancies are termed thermodynamic anomalies. To overcome this limitation, we analytically derive expressions for these anomalies in the presence of a general time-varying temperature. One notable feature of the result is that high viscosity and small mass, though both leading to the same overdamped dynamic equations, result in different thermodynamic anomaly relations. Our results have significant implications, particularly for accurately calculating the efficiency of heat engines operating in overdamped environments with time-varying temperatures, without requiring velocity measurements. Additionally, our findings offer a simple method for estimating the kinetic energy of an overdamped system.

[1] Awasthi, S., Park, H., & Lee, J. S. (2025). Thermodynamic anomalies in overdamped systems with time-dependent temperature. *arXiv preprint arXiv:2503.22367*.

[P24]

Mutual percolation with tunable long-range connectivity and edge overlap

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Mutual percolation displays on random multiplex networks discontinuous hybrid phase transitions. However, specific structural properties can lead to continuous transitions. For instance, when nodes are embedded in low-dimensional spaces and both intra- and inter-layer connections are sufficiently short-ranged, the transition becomes continuous [1]. Similarly, overlapping edges also facilitate continuous transitions [2]. Here, we study one-dimensional multiplex networks with tunable long-range connectivity and edge overlap. In particular, we find that reducing overlapping edges shrinks the continuous-transition regime. Beyond this regime, we further investigate the nature of discontinuous transitions. Finally, we discuss our results from the effective-dimension perspective [3].

[1] K.-K. Kleineberg et al., Phys. Rev. Lett. 118, 218301 (2017)
[2] G. J. Baxter et al., Phys. Rev. E 94, 012303 (2016)
[3] A. P. Millan et al., Phy. Rev. Res. 3, 023015 (2021)

[P25]

Violation of kinetic uncertainty relation in maser heat engines: Role of spontaneous emission

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We investigate the kinetic uncertainty relation (KUR)—a fundamental trade-off between dynamical activity and current fluctuations—in two configurations of a maser heat engine. We find that KUR violations arise only in one model. This asymmetry originates from spontaneous emission, which breaks the structural symmetry between the configurations and modifies their coherence dynamics. While we analyze several contributing factors—including statistical signatures such as the Fano factor and the ratio of dynamical activity to current—our results show that the decisive mechanism is the slower decoherence in one configuration, which enables quantum violations of the classical steady-state KUR bound. By contrast, the faster coherence decay in the other configuration suppresses such violations, driving it closer to classical behavior. These findings highlight the critical role of decoherence mechanisms in determining fundamental thermodynamic bounds and provide insights for the design of quantum heat engines in which the control of decoherence is central to suppressing fluctuations and enhancing reliable performance.

[1]V. Singh, E. Kwon, and J. S. Lee, arXiv:2508.18619 (2025).

[P26]

Machine learning-based analysis of electrode calcination factors and performance prediction

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This study trained a machine learning model on limited experimental data to predict battery performance and analyze key manufacturing factors. [cite_start]Using SHAP analysis, the model identified the 2nd step sintering temperature as the most critical variable. [cite_start]It also revealed that the Lithium ratio strongly influences initial capacity, while the Manganese ratio significantly impacts the retention ratio. [cite_start]Based on these insights, a large synthetic dataset was generated to explore new material compositions, leading to the discovery of high-performing candidates for experimental validation.

[P27]

The freely jointed chain with a two-state hinge

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In our recent works, we have analyzed the stretching and bending elasticity of the freely jointed chain with hinges, where the hinges can be open or closed. This two-state-hinge model captures a specific degree of freedom associated with the local bending stiffness of the polymer. In this presentation, we focus on comparing the effects of two different types of disorder on the hinges: annealed (reversible Freely Jointed Chain, qFJC) or quenched (quenched Freely Jointed Chain, qFJC). It turns out that, as expected, those different types of disorder yield qualitatively different behaviors. For finite-size systems, we obtain a recurrence relation, which allows us to calculate the exact force-extension relation numerically for an arbitrary size of the system for both systems. In the thermodynamic limit, when the contour length is much larger than the persistence length, we obtain an exact expression for the force-extension relation. The difference between the two systems still exists in the thermodynamic limit.

[1] M. Yi, D. Lee and P. Benetatos, J. Chem. Phys. 161 (23): 234908 (2024)
[2] M. Yi and P. Benetatos, J. Stat. Mech. 073501 (2025)

[P28]

Generative Adversarial Networks for Conditional State Space Modeling in Complex Physical Systems

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We introduce a novel deep generative model, the Factor-Conditional Generative Adversarial Network (FC-GAN), to enhance the prediction of state-space dynamics in complex physical systems. Our model uniquely incorporates established physical parameters—such as temperature, pressure, and external fields—directly into its generator and discriminator. This conditioning enables the FC-GAN to effectively learn the joint probability distribution of system configurations aligned with these physical constraints.

Using data from a simulated Ising model, we conduct a comparative analysis against benchmark computational methods, including traditional Monte Carlo simulations. Our empirical results demonstrate that FC-GAN achieves superior performance in both generating realistic system states and predicting macroscopic properties like magnetization and specific heat. Furthermore, ablation studies underscore the essential roles of factor conditioning and spectral normalization in achieving model stability and predictive power, particularly near phase transition points.

Our findings present the FC-GAN as a powerful and scalable solution for merging physical factor insights with advanced generative modeling techniques, offering a new avenue for both predictive analysis and the exploration of complex physical phenomena.

[1] Wang, Jiawei, and Zhen Chen. "Factor-GAN: Enhancing stock price prediction and factor investment with Generative Adversarial Networks." *Plos one* 19.6 (2024): e0306094.
[2] Eckerli, Florian, and Joerg Osterrieder. "Generative adversarial networks in finance: an overview." *arXiv preprint arXiv:2106.06364* (2021).

[P29]

Flocking with random non-reciprocal interactions

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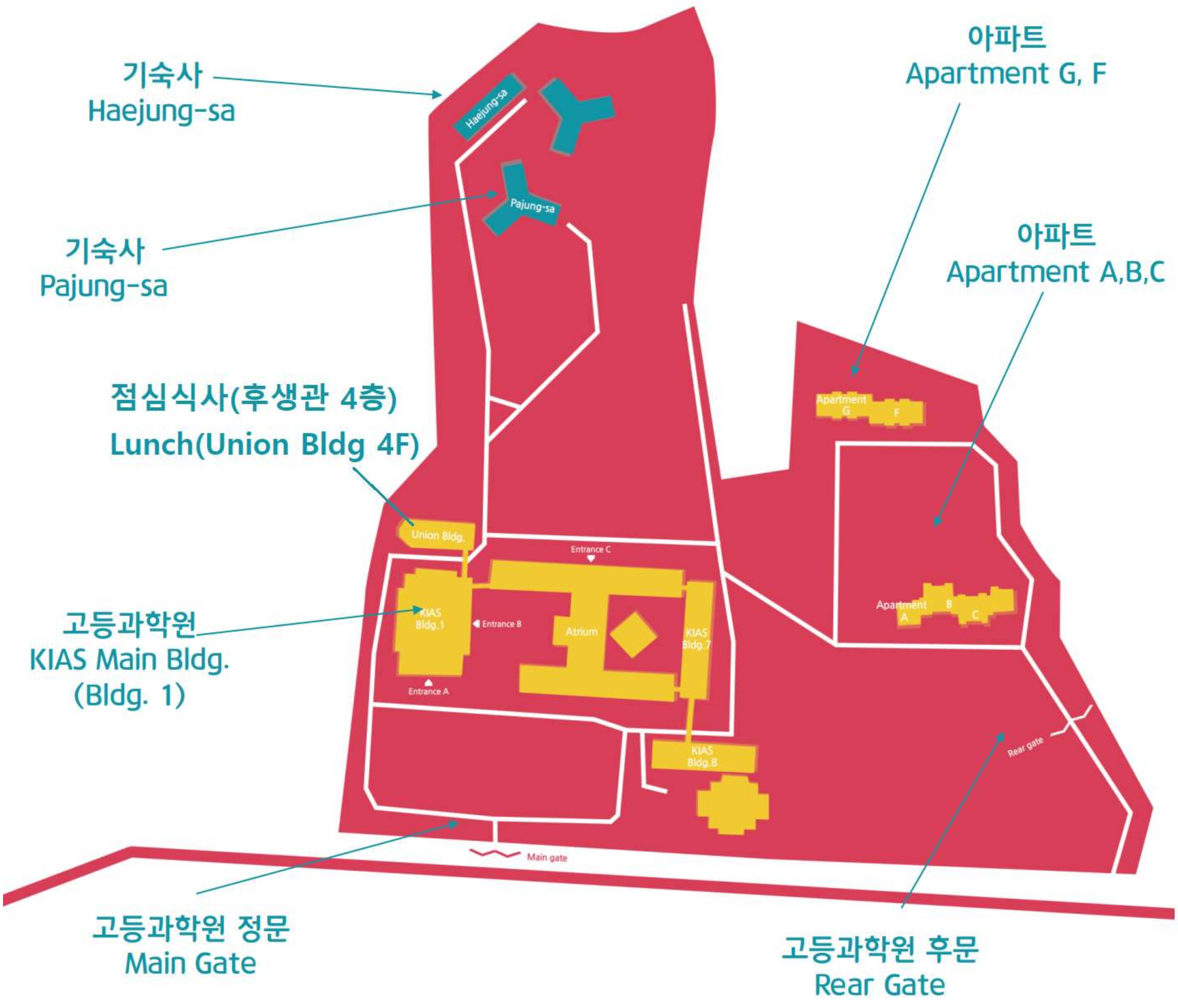
Flocking is ubiquitous in nature and emerges due to short- or long-range alignment interactions among self-propelled agents. Two unfriendly species that anti-align or even interact non-reciprocally show more complex collective phenomena, ranging from parallel and anti-parallel flocking over run-and chase behavior to chiral phases. Whether flocking or any of these collective phenomena can survive in the presence of a large number of species with random non-reciprocal interactions remained elusive so far. As a first step here the extreme case of a Vicsek-like model with fully random non-reciprocal interactions between the individual particles is considered. For infinite-range interaction, as soon as the alignment bias is of the same order as the random interactions the ordered flocking phase occurs, but deep within this phase, the random non-reciprocal interactions can still support global chiral and oscillating states in which the collective movement direction rotates or oscillates slowly. For short-range interactions, moreover, even without alignment bias self-organized cliques emerge, in which medium size clusters of particles that have predominantly aligning interactions meet accidentally and stay together for macroscopic times. These results may serve as a starting point for the study of multi-species flocking models with non-random but complex non-reciprocal inter-species interactions.

[1] Jiwon Choi, Jae Dong Noh, Heiko Rieger, arXiv:2506.22060 (2025).

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
Main gate
Apartment G F
Apartment A B C
Rear gate