Introduction

The conference is the 10th one of the biannual KIAS conferences on statistical physics since 2004. It aims to present new ideas in statistical physics and related fields and to facilitate scientific exchange and collaboration among leading scientists as well as students and postdocs. Please note that the NSPCS2020 was skipped due to the COVID-19 pandemic. Information on the past conferences can be found in the tab named Links.

Topics include

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

Organizers

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

Program Schedule

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

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Day 1 – July 22 (Mon)

08:30-08:50	Registration/Coffee & Sandwiches	
08:50-09:00	Opening	
Morning Session Ⅰ		Chair : H. Park
09:00-09:40	Satya Majumdar	Correlated Resetting Gas
09:40-10:20	J. D. Noh	Pinning Without Disorder in Active Ising Model
10:20-10:40	Break	
Morning Session Ⅱ		Chair : D. Mukamel
10:40-11:20	A. Pal	Homing as a resetting paradigm
11:20-11:40	F. Corberi	Phase-ordering kinetics in ferromagnetic systems with long-range interactions
11:40-12:00	Y. Bae	Mitigating Overfitting in Neural Networks with Stochastic Restarting under Noisy Labels
12:00-15:00	Lunch	
Afternoon Session Ⅰ		Chair : H. Quan
15:00-15:40	S. Gupta	Controlling attainment of spontaneous ordering in many-body interacting systems
15:40-16:20	H. Hong	Exploring collective behavior in a swarmalator system
16:20-16:40	Break	
Afternoon Session Ⅱ		Chair : J. S. Lee
16:40-17:00	S. Lahiri	Microscopic heat engine subjected to stochastic resetting
17:00-17:20	H.-M. Chun	Power-efficiency trade-off for finite-time quantum harmonic Otto heat engines
17:20-19:20	Poster Session	

Day 2 – July 23 (Tue)

08:30-09:00	Coffee & Sandwiches	
Morning Session Ⅰ		Chair : L.-H. Tang
09:00-09:40	K. Saito	Time-cost-error trade-off relation in stochastic thermodynamics: third-law like constraint
09:40-10:20	J. S. Lee	Unified Hierarchical Relationship Between Thermodynamic Tradeoff Relations
10:20-10:40	Break	
Morning Session Ⅱ		Chair : J. D. Noh
10:40-11:20	K. Brandner	Memory Effects in Micro and Nanoscale Systems
11:20-11:40	J.-M. Park	Unveiling the Invisible System-Bath Coupling Dependence in Microscopic System
11:40-12:00	C. Kwon	Dynamics of a small quantum system open to a bath with thermostat
12:00-15:00	Photo / Lunch	
Afternoon Session Ⅰ		Chair : Y. Baek
15:00-15:40	S. Ito	Minimum Entropy production rate for macroscopic systems
15:40-16:20	H. Quan	Scaling relations of excess work when quenching a system across phase transitions
16:20-16:40	Break	
Afternoon Session Ⅱ		Chair : É. Fodor
16:40-17:20	I. Pagonabarraga	Effective interactions and ordered phases in active systems
17:20-17:40	A. Saha	Flow Of Information In a Mechanically Quenched Confined Flock
17:40-18:00	Break	
18:00-20:00	Banquet	

Day 3 – July 24 (Wed)

08:30-09:00	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : K. Saito
09:00-09:40	D. Mukamel	Local drive (a pump or a battery) in interacting diffusive systems
09:40-10:20	Y. Baek	Phase separation of active matter coupled to chemical degrees of freedom
10:20-10:40	Break	
	Morning Session Ⅱ	Chair : S. Gupta
10:40-11:20	É. Fodor	Pulsating active matter
11:20-11:40	S. Goh	Collective behavior of self-steering polar microswimmers
11:40-12:00	P. Pal	Effect of activity on target search with resetting in thermal environment
12:00-14:00	Lunch	
14:00-19:00	**Excursion (Hiking) & Dinner**	

Day 4 – July 25 (Thu)

08:30-09:00	Coffee & Sandwiches	
	Morning Session Ⅰ	Chair : K. Brandner
09:00-09:40	H. Jeong	Understanding of complex systems through D.N.A.
09:40-10:20	H. Kwon	Microscopic reversibility in the quantum regime
10:20-10:40	Break	
	Morning Session Ⅱ	Chair : S. Majumdar
10:40-11:00	O. Shpielberg	The relaxation spectrum of interacting particle systems
11:00-11:20	S. Awasthi	Thermodynamic anomaly in overdamped systems with time-dependent temperature
11:20-12:00	L.-H. Tang	Emergence of hidden order and its dynamical evolution in the annealed Sherrington-Kirkpatrick model
12:00-15:00	**Closing & Lunch**	

[Talk 1] Correlated Resetting Gas

Satya Majumdar
CNRS, LPTMS, Universite Paris-Saclay, France

I will first discuss the equilibrium properties of a gas of N interacting particles on a line. I will then introduce a simple model of N independent Brownian particles that are subjected to simultaneous stochastic resetting with rate r. The simultaneous resetting generates an effective dynamical all-to-all attractions between particles that persist even at long times in its nonequilibrium stationary state (NESS). Despite the presence of strong correlations, many physical observables such as the average density, extreme statistics, order and gap/spacing statistics, full counting statistics etc. can be computed exactly in the NESS and they exhibit rich and interesting behaviors. The physical mechanism built in this simple model allows it to generalise and invent a whole class of solvable strongly correlated gases, some of which are experimentally realisable in optical trap systems.

[Talk 2] Pinning Without Disorder in Active Ising Model

Jae Dong Noh
Department of Physics, University of Seoul

We report a novel type of pinning transition in the active Ising model for self-propelled particle systems with discrete symmetry. Quenched disorder has been considered essential for pinning. We demonstrate that motility can induce pinning of interfaces between two groups of particles confronting each other. Due to this motility-induced pinning, the active Ising model undergoes a phase transition from a disordered unpinned phase to a globally pinned phase. We present numerical evidence for the phase transition, along with analytical arguments for the pinning mechanism and interface coarsening dynamics.

[Ref] Chul-Ung Woo and Jae Dong Noh, arXiv:2403.10106

[Talk 3] Homing as a resetting paradigm

Arnab Pal
The Institute of Mathematical Sciences, Chennai

A fundamental aspect crucial for the survival of various animal species is their ability to successfully return home, whether it involves migration, foraging for food, or locating a breeding site. This innate behavior, known as Homing, is surprisingly ubiquitous, allowing animals to navigate back from seemingly unfamiliar locations over considerable distances. In this talk, I will try to shed some light on this phenomena from the perspective of stochastic resetting.

[Talk 4] Phase-ordering kinetics in ferromagnetic systems with long-range interactions

Federico Corberi
Salerno University, Italy

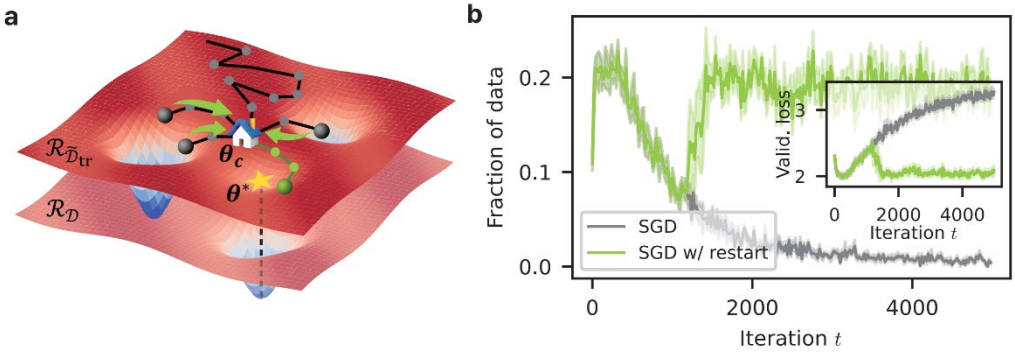
I will present a thorough discussion of the ordering kinetics of ferromagnetic systems with long-range interactions decaying with distance as $r^{-\alpha}$, for any α and in any spatial dimension d. I will consider two paradigmatic models: the voter model and the Ising one. The former is solvable in any dimension [1-3]. The latter can be studied analytically in one dimension using scaling arguments [4], or in a continuum (Ginzburg-Landau) approach [5,6]. Besides that, numerical simulations are also available. In general, the kinetics is characterized by the formation and growth of domains. In both models there is an upper critical value α_{SR} of α, such that for $\alpha>\alpha_{SR}$ the model behaves as the corresponding one with short-range interactions (e.g. among nearest-neighbors). In particular, the characteristic size L(t) of the coarsening domains grows as $L(t)\propto t^{1/2}$. There also exists a lower critical value α_{LR} such that some mean-field features (corresponding to $\alpha=0$) are displayed for $\alpha<\alpha_{LR.}$ In the voter model these amount to the presence of non-equilibrium stationary states whose lifetime diverges in the thermodynamic limit. In the Ising model, instead, the mean-field character is manifested by the presence of dynamical trajectories without formation of domains whereby the system approaches equilibrium by a fast exponential increase of the magnetization. For intermediate values of α, for $\alpha_{LR}<\alpha<\alpha_{,}$ there is an algebraic growth of the domains $L(t))\propto t^{1/z}$, with a non-trivial α-dependent value of the exponent z. A rich pattern of dynamical scaling violations are also observed as α and spatial dimension are varied.

[1] F. Corberi, and C. Castellano, arXiv:2309.16517 (to appear in J.Phys: Complexity, 2024).
[2] F. Corberi, and L. Smaldone, Phys. Rev. E **109**, 034133 (2024).
[3] F. Corberi, and L. Smaldone, arXiv:2402.11079 (to appear in J. Stat. Mech., 2024).
[4] F. Corberi, E. Lippiello, and P. Politi, J. Stat. Phys. **176**, 510 (2019).
[5] A.J. Bray, and A.D. Rutenberg, Phys. Rev. E **49**, R27 (1994).
[6]. A.D. Rutenberg, and A.J. Bray, Phys. Rev. E **50**, 1900 (1994).

[Talk 5] Mitigating Overfitting in Neural Networks with Stochastic Restarting under Noisy Labels

Youngkyoung Bae
[1]*Department of Physics and Astronomy, Seoul National University*

Capitalizing on the theoretical success of stochastic restarting, numerous algorithms incorporating the restarting strategy have begun to emerge in diverse fields. In this work, we demonstrate that restarting from a checkpoint can significantly improve generalization performance when training deep neural networks (DNNs) with noisy labels. In the presence of noisy labels, DNNs initially learn the general patterns of the data but then gradually overfit to the noisy labels. To combat this overfitting phenomenon, we developed a method based on stochastic restarting, which has been actively explored in the statistical physics field for finding targets efficiently. By approximating the dynamics of stochastic gradient descent into Langevin dynamics, we show that restarting can provide great improvements as the batch size and the proportion of corrupted data increase. We then empirically validate our conjecture, confirming the significant improvements achieved by restarting. An important aspect of our method is its ease of implementation and compatibility with other methods, while still yielding notably improved performance. We envision it as a valuable tool that can complement existing methods for handling noisy labels.



(a) Schematic of stochastic gradient descent (SGD) dynamics with stochastic restarting. The network parameters vector $\boldsymbol{\theta}$ evolves via SGD to find an optimal value $\boldsymbol{\theta}^*$ on the training risk landscape $\mathcal{R}_{\tilde{\mathcal{D}}_{\mathrm{tr}}}$ (upper colormap), which differs from the true risk landscape $\mathcal{R}_{\mathcal{D}}$ (lower colormap) due to corrupted data. Here, $\boldsymbol{\theta}$ resets to the checkpoint $\boldsymbol{\theta}_c$ (home icon) with the restart probability r and restarts from $\boldsymbol{\theta}_c$. (b) Fraction of correctly predicted data with wrong labels during training with SGD (gray) and SGD with restart (green). The inset shows the validation losses during training.

[Talk 6] Controlling attainment of spontaneous ordering in many-body interacting systems

Shamik Gupta
Tata Institute of Fundamental Research, Mumbai, India

Consider a thermodynamic system that shows a phase transition between an ordered and a disordered phase. The question we ask is: in the parameter regime in which the system exhibits a disordered phase, can we induce order by manoeuvring the system (i) either by forcefully establishing order in a small subset of the total number of degrees of freedom,(ii) or, by shuffling the inherent properties of the individual system constituents among themselves ? Within the ambit of the Kuramoto model, a paradigmatic nonlinear dynamical many-body system, we discuss both analytical and experimental results on how schemes (i) and (ii) lead to a rich dynamics and, most remarkably, establishing of macroscopic order even in parameter regimes in which the bare dynamics does not support any such ordering. An implication of our results is the proposition of an efficient mechanism for controlling attainment of ordering in many-body interacting systems.

[Talk 7] Exploring collective behavior in a swarmalator system

Hyunsuk Hong
Department of Physics and Research Institute of Physics and Chemistry, Jeonbuk National University, Jeonju 54896, Korea

In this talk, we introduce a system of swarmalators and explore their collective behavior. Swarmalators are a mobile version of phase oscillators that can sync in time and swarm through space. Our study focuses on an XY-type model of identical swarmalators moving on a one-dimensional ring and subject to thermal noise. We found that both interactions and thermal noise impact the behavior of swarmalators, leading to four distinct collective states. We will discuss these states and present a comprehensive phase diagram supported by Fourier mode analysis and numerical simulation results. Our model offers a minimal yet insightful representation of thermal systems that both synchronize and self-assemble.

[1] H. Hong, K. P. O'Keeffe, J. S. Lee, and H. Park, Phys. Rev. Research **5**, 023105 (2023).

[Talk 8] Microscopic heat engine subjected to stochastic resetting

Sourabh Lahiri and Shamik Gupta
Sourabh Lahiri Birla Institute of Technology

Quantum heat engines have been the subject of intense research in recent years. We explore the thermodynamics of stochastic heat engines in the presence of stochastic resetting. The setup comprises a Stirling engine whose working substance is a Brownian particle undergoing overdamped Langevin dynamics in a harmonic potential with a time-dependent stiffness . The position of the particle is reset at random times to a given location, and the resulting dynamics is observed to have a significant impact on the output power and efficiency. The effect of changing the reset position of the particle is also studied.

[Talk 9] Power-efficiency trade-off for finite-time quantum harmonic Otto heat engines

Hyun-Myung Chun
School of Physics, Korea Institute for Advanced Study

The performance of a heat engine is often characterized by two key quantities: power and efficiency. Although it has long been known that high power and high efficiency are incompatible due to thermodynamic constraints, the explicit formula for the trade-off between power and efficiency has been discovered only recently. We extend the power-efficiency trade-off derived for classical steady-state heat engines to that of the quantum harmonic Otto heat engine, a paradigmatic quantum cyclic heat engine. To this end, we employ the phase-space approach using quasi-probability distributions. The resulting trade-off is valid for cycles with an arbitrary protocol that connects two isobaric branches and with arbitrary finite operation time. We further show that the maximum power limited by the trade-off is achievable with the maximum (quasistatic) efficiency of the Otto engine.

[1] J.-M. Park, S. Lee, H.-M. Chun, and J. D. Noh, Phys. Rev. E **100**, 012148 (2019)
[2] J.-M. Park and H.-M. Chun, in preparation

[Talk 10] Time-cost-error trade-off relation in stochastic thermodynamics: third-law like constraint

Keiji Saito
Kyoto University

Elucidating fundamental limitations inherent in physical systems is a central quest in physics. For generic processes such as information erasure and cooling, resources such as time and energetic cost must be consumed to accomplish the task up to a predetermined error. In the present study, we uncover a three-way trade-off relation between time, cost, and error for this general class of thermodynamic processes, rigorously showing that these incompatible quantities cannot be simultaneously small. Remarkably, this relation leads to crucial implications in nonequilibrium thermodynamics, including a quantification for the third law of thermodynamics in the form of the unattainability principle, a limitation on the preparation of separate states, and a no-go theorem for exact classical copying. Furthermore, we generalize the findings to the quantum regime, including both Markovian and non-Markovian scenarios. The generalization implies that heat dissipation becomes infinite as the quantum system is exactly cooled down to the ground state or perfectly reset to a pure state, thereby resolving an open question regarding the thermodynamic cost of information erasure.

[Talk 11] Unified Hierarchical Relationship Between Thermodynamic Tradeoff Relations

Jae Sung Lee
School of Physics, Korea Institute for Advanced Study

Recent years have witnessed a surge of discoveries in the studies of thermodynamic inequalities: the thermodynamic uncertainty relation (TUR) and the entropic bound (EB) provide a lower bound on the entropy production (EP) in terms of nonequilibrium currents; the classical speed limit (CSL) expresses the lower bound on the EP using the geometry of probability distributions; the power-efficiency (PE) tradeoff dictates the maximum power achievable for a heat engine given the level of its thermal efficiency. In this study, we show that there exists a unified hierarchical structure encompassing all of these bounds, with the fundamental inequality given by a novel extension of the TUR (XTUR) that incorporates the most general range of current-like and state-dependent observables. By selecting more specific observables, the TUR and the EB follow from the XTUR, and the CSL and the PE tradeoff follow from the EB. Our derivations cover both Langevin and Markov jump systems, with the first proof of the EB for the Markov jump systems and a more generalized form of the CSL. We also present concrete examples of the EB for the Markov jump systems and the generalized CSL.

[1] E. Kwon, J.-M. Park, J. S. Lee, and Y. Baek, preprint arXiv:2311.01098.
[2] J. S. Lee, S. Lee, H. Kwon, and H. Park, Phys. Rev. Lett. 129, 120603 (2022).
[3] J. S. Lee, J.-M. Park, and H. Park, Phys. Rev. E 104, L052102 (2021).

[Talk 12] Memory Effects in Micro and Nanoscale Systems

Kay Brandner
School of Physics and Astronomy University of Nottingham Nottingham NG7 2RD United Kingdom

Memory effects are ubiquitous in small-scale systems. They emerge from interactions between accessible and inaccessible degrees of freedom and give rise to evolution equations that are non-local in time. If the characteristic time scales of accessible and inaccessible degrees of freedom are strongly separated, locality can be restored through the standard Markov approximation. Here, we show that this approach can be rigorously extended to a precisely defined weak-memory regime, where the relevant time scales can be of comparable order of magnitude. We provide explicit bounds on the error of the local approximation and a perturbative scheme for its systematic construction. Our theory is applicable to any non-local time evolution equation that is autonomous and linear in the observables of interest and provides a general framework to treat memory effects beyond the Markov approximation.

[Talk 13] Unveiling the Invisible System-Bath Coupling Dependence in Microscopic System

Jong-Min Park
Asia Pacific Center for Theoretical Physics

Microscopic systems are significantly affected by system-bath coupling, as shown by their highly fluctuating motions. However, the dynamics of microscopic systems are surprisingly well described by the Langevin equation which includes no system-bath coupling-dependent terms. We investigate why microscopic systems can exhibit coupling-independent dynamics even with significant coupling strengths. Starting from an explicit microscopic description of a composite system with an arbitrary interaction Hamiltonian, we derive the reduced system dynamics by applying time-scale separation. We find that the obtained equation contains coupling-dependent terms, which disappear regardless of the coupling strength under two specific conditions: (i) the translational invariance of the bath and (ii) the mutual independence of the system-bath interaction forces on each system particle. Our findings explain why the Langevin equation can successfully describe experimental observations, as these conditions are typically met in usual experimental setups. Finally, we validate our results both theoretically and numerically using toy models and molecular dynamics simulations.

[1] J.-M. Park, H. Park, J. S. Lee, arXiv:2309.15359 (2023).

[Talk 14] Dynamics of a small quantum system open to a bath with thermostat

Chulan Kwon
Department of Physics, Myongji University

We investigate dynamics of a small quantum system open to a bath with thermostat. We introduce another bath, called super bath, weakly coupled with the bath to provide it with thermostat, which has either the Lindblad or Redfield type. We treat the interaction between the system and bath via a rigorous perturbation theory. Due to the thermostat, the bath behaves dissipative and stochastic, for which the usual Born-Markov assumption is not needed. We consider a specific example of a harmonic oscillator system, and a photonic bath in a large container, and a super bath of the Caldeira-Legget oscillators distributed on the inner surface of the container. We use the *P*-representation for the total harmonic system. We derive the reduced time-evolution equation for the system by explicitly finding the correlation between the system and bath beyond the product state, that was not obtainable in the previous theory for the system and bath isolated from environment, and marginalizing bath degrees of freedom. Remarkably, the associated dynamic equation for the system density matrix is of the same form as the Redfield master equation with different coefficients depending on thermostat used. We find steady state does not depend on thermostat, but time-dependent state does, that agrees with common expectation. We expect to apply our theory to general systems. Unlike the usual quantum master equations, our reduced dynamics allows investigation for time-dependent protocols and non-equilibrium quantum stochastic dynamics will be investigated in future.

[1] C. Kwon and J-Y Gyhm, arXiv:2404.15568

[Talk 15] Minimum entropy production rate for macroscopic systems

Sosuke Ito[1,2]
[1]*the Universal Biology Institute, the University of Tokyo*
[2]*Department of Physics, the University of Tokyo*

The entropy production rate is decomposed into two contributions, the excess entropy production rate and the housekeeping entropy production rate. The excess entropy production rate, which is introduced by the 2-Wasserstein distance in the optimal transport theory for the Fokker-Planck equation or the master equation, is regarded as the minimum entropy production rate for a given state transition [1-4]. Based on a geometric structure in the optimal transport theory, we can discuss thermodynamic trade-off relations, such as thermodynamic uncertainty relations or speed limits for the excess entropy production rate. In this talk, we introduce the concept of the excess entropy production rate based on the optimal transport theory and discuss generalizations of the excess entropy production rate for two macroscopic systems, the reaction diffusion systems [5] and hydrodynamic systems [6]. We discuss thermodynamic trade-off relations for pattern formation and Couette flow.

[1] M. Nakazato and S. Ito, Phys. Rev. Research **3**, 043093 (2021).
[2] A. Dechant, S-I. Sasa and S. Ito, Phys. Rev. Research **4**, L012034 (2022).
[3] K. Yoshimura, A. Kolchinsky, A. Dechant and S. Ito, Phys. Rev. Research **5**, 013017 (2023).
[4] S. Ito, Information Geometry **7** (Suppl 1), 441-483 (2024).
[5] R. Nagayama, K. Yoshimura, A. Kolchinsky and S. Ito, arXiv:2311.16569 (2023).
[6] K. Yoshimura and S. Ito, Phys. Rev. Research **6**, L022057 (2024).

[Talk 16] Scaling relations of excess work when quenching a system across phase transitions

H. T. Quan[1,2,3]

[1]*School of Physics, Peking University, Beijing, 100871, China*

[2]*Collaborative Innovation Center of Quantum Matter, Beijing, 100871, China*

[3]*Frontiers Science Center for Nano-optoelectronics, Peking University, Beijing, 100871, China*

According to the maximum work principle, the average work spent during a driving process is always larger than the free energy difference associated with the initial and the final work parameters. Previously, it has been known that the excess work spent during a nonequilibrium driving process is proportional to the driving speed v in the isothermal processes, and proportional to the square of the driving speed v^{2} in the adiabatic processes, respectively. However, if quenching a system across a phase transition point, the excess work will exhibit various scaling behaviors with the quenching speed. When the system is quenched across a first-order phase transition, where hysteresis and metastable states makes the problem very involved, it is found that the excess work (enclosed area between the dynamical and static hysteresis) exhibits universal scaling behavior v^{2/3}. I will discuss the scaling relations of excess work in these situations and the crossovers between them when downsizing the system.

[1] Z. Fei, N. Freitas, V. Cavina, H. T. Quan, M. Esposito, Physical Review Letters 124 (17), 170603 (2020).

[2] F. Zhang, H. T. Quan, Physical Review E 105 (2), 024101 (2022).

[3] Y. X. Wu, J. F Chen, H. T. Quan, arXiv preprint arXiv:2401.15592

[Talk 17] Effective interactions and ordered phases in active systems

Ignacio Pagonabarraga
University of Barcelona

I will discuss the interactions between passive inclusions in an active suspension, where passive particles couple to the active suspension and quickly react to the active particles rearrangements. Hence, their relative dynamics plays an important role in the features that characterize the emergent interactions among the inclusions. Moreover, for systems where active particles develop long range polar order, the presence of passive obstacles triggers spontaneous macroscopic structures that give rise to non-reciprocal interactions. I will also discuss the susceptibility of polar active systems to small inclusions and the implications this has on the nature of their ordered phases.

[Talk 18] Flow Of Information In a Mechanically Quenched Confined Flock

Arnab Saha
University of Calcutta

Living entities in a group communicate and transfer information to one another for a variety of reasons. It might be for foraging food, migration, or escaping threats and obstacles, etc. They do so by interacting with each other and also with the environment. The tools from statistical mechanics and information theory can be useful to analyse the flow of information among the living entities modelled as active (i.e. self-propelling) particles. Here we consider the active particles confined in a circular trap. The self-organisation of the particles crucially depends on whether the trap boundary is soft or hard. We quench the trap boundary from soft to hard instantaneously. After the mechanical quench, the particles suddenly find themselves in a hard potential. The self-organised cluster of the active particles, which was stable when the boundary was soft, becomes unstable. The cluster undergoes extreme deformation after the quench to find another stable configuration suitable for the hard potential. Together with the structural relaxation, information regarding the quench also flows throughout the deforming cluster. Here, we quantify the flow of information by computing local transfer entropy. We find that the flow spans the whole cluster, propagating ballistically.

[Talk 19] Local drive in interacting diffusive systems

David Mukamel
The Weizmann Institute of Science

The long-range nature of the nonequilibrium steady state resulting from a local drive (a pump or a battery) in an interacting diffusive fluid is discussed. It is shown that off criticality the pump generates long-range modulation in the density profile of the form of a dipolar electric potential, and a current profile in the form of a dipolar electric field. The density profile is drastically modified when the fluid is at its critical point: here, in addition to the long-rage influence of the current generated by the battery, the fluid is dominated by its intrinsic long-range critical correlations. It is demonstrated that the resulting density profile is of the same form as that of a fluid in equilibrium but under the influence of dipolar ordering field. As a result, the nonequilibrium steady state density profile at criticality can be expressed in terms of the equilibrium critical exponents of the fluid. In contrast, the current is shown to retain it off critical dipolar field form.

[Talk 20] Phase separation of active particles coupled to chemical degrees of freedom

Yongjoo Baek
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. Studies[1–3] have shown that incorporating chemotaxis and the production or 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 wider range of collective behaviors, including arrested phase separation and traveling waves. Our conclusions are based on a hydrodynamic theory derived from a particle-based model via standard methods.

[1] B. Liebchen, D. Marenduzzo, I. Pagonabarraga, and M. E. Cates, Phys. Rev. Lett. **115**, 258301 (2015).
[2] B. Liebchen, D. Marenduzzo, and M. E. Cates, Phys. Rev. Lett. **118**, 268001 (2017).
[3] H. Zhao, A. Košmrlj, and S. S. Datta, Phys. Rev. Lett. **131**, 118301 (2023).

[Talk 21] Pulsating active matter

Étienne Fodor
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We propose two types of diffusive models where the internal states of particles are subject to a periodic drive. In the first model, inspired by biological tissues, the activity of dense repulsive particles drives periodic change in size [2]. We show that the competition between repulsion and synchronization triggers an instability which promotes a wealth of dynamical patterns, ranging from spiral waves to defect turbulence. In the second model, the discrete symmetry of states enforces an effective energy landscape which can counteract the drive to arrest the dynamics, and leads again to the emergence of spiral waves [3]. In both models, using analytical coarse-graining, we rationalize the emergence of dynamical patterns from the breakdown of a specific gauge invariance at the hydrodynamic level.

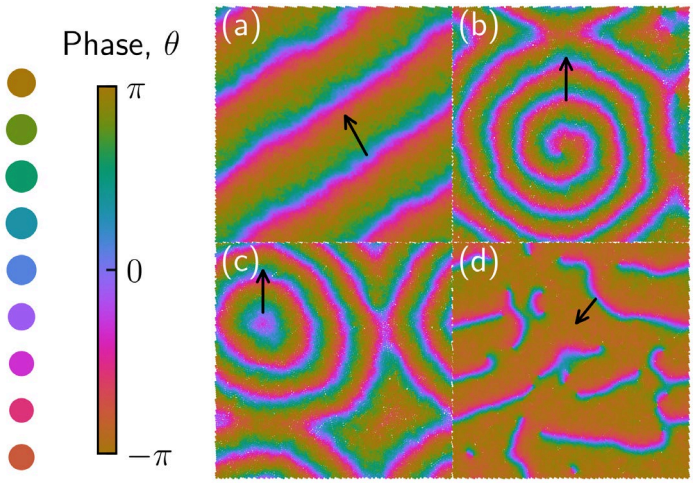

Figure 1: Repulsive particles with pulsating size yield contraction waves: (a) planar, (b) spiral, (c) circular, and (d) turbulent. Waves propagation (black arrows) stabilizes dynamical patterns reminiscent of reaction-diffusion systems [1].

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[Talk 22] Collective behavior of self-steering polar microswimmers

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"Cognitive" biological microswimmers and synthetic microbots are characterized by their ability to sense the environment, process this information, and adapt their motion accordingly. We aim to develop minimal models of such intelligent active agents [1,2,3], and analyze their emergent behavior. For the collective behavior of self-propelled particles, the adaptation of motion by alignment with neighbors has been shown to lead to long-range polar order in dry systems. However, in wet systems, hydrodynamic interactions between the active agents can destabilize both nematic and polar order. To unravel the self-organization and emergent dynamics of wet polar active matter, we propose a hydrodynamic extension of the Vicsek model in three dimensions, where microswimmers align by self-steering via adaptive actuation. We employ a mesoscale hydrodynamic simulation method, the multiparticle collision dynamics approach (MPC), where embedded microswimmers are modeled by self-steering squirmers with adaptive surface flow fields [3]. In contrast to dry polar systems with long-range order, our wet systems show only short-range polar order even for strong self-steering alignment [4]. Instead, the self-steering polar microswimmers exhibit chaotic dynamical patterns, characterized by a power-law decay in their kinetic energy spectra. Specifically, the systems of rear-actuated squirmers (pushers) feature active turbulence with suppressed density fluctuations and a Gaussian velocity distribution. In contrast, suspensions of front-actuated squirmers (pullers) exhibit a strong tendency for cluster formation as well as non-Gaussian velocity and vorticity distributions with fat tails, demonstrating that the chaotic advection of pullers is not active turbulence. Moreover, vortex rings and fluid jets emerge and decay in time [4]. Our results demonstrate that self-steering gives rise to novel collective phenomena.

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[Talk 23] Effect of activity on target search with resetting in thermal environment

P. S. Pal

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Stochastic resetting has recently emerged as an efficient target-searching strategy in various physical and biological systems. In particular, the strategy has been shown to be quite useful when the search is being conducted in a high noisy medium or in uncertain environmental conditions. Recent works have shown such effects in microscopic diffusive and other stochastic search processes. In this work, we explore the effects of stochastic resetting on an active system namely a self-propelled run and tumble particle immersed in a thermal bath. In particular, we assume that the position of the particle is reset at a fixed rate with or without reversing the direction of self-propelled velocity. Using standard renewal techniques, we compute the mean search time of this active particle to a fixed target and investigate the interplay between the activity and the thermal fluctuations. We find that the active search can outperform the Brownian search when the magnitude and flipping rate of self-propelled velocity are large and the strength of environmental noise is small. Notably, we find that the presence of environment via the thermal noise helps in reducing the mean first passage time of the run and tumble particle compared to the non-thermal one. Finally, we observe that reversing the direction of self-propelled velocity while resetting can also reduce the overall search time.

[Talk 24] Understanding of complex systems through D.N.A.

Hawoong Jeong
KAIST

In this talk, I will present some examples of how different methodologies (data science, network science, AI) are being used to understand complex systems, which are considered to be the challenges of the 21st century. Specifically, I will explain how data science can be used to determine the existence of the golden rule, how network science can be used to discover biological drugs, and how AI can be used to discover the laws of physics. Finally, I will discuss the future of the LLM, which is very popular these days, from a complex systems perspective.

[Talk 25] Microscopic reversibility in the quantum regime

Hyukjoon Kwon[1]
[1] *School of Computational Sciences, Korea Institute for Advanced Study*

The principle of microscopic reversibility lies at the core of fluctuation theorems, which have extended our understanding of the second law of thermodynamics to the statistical level. With the development of quantum information science, it has been actively studied how quantum coherence changes the laws of thermodynamics. We propose and experimentally test a quantum modification of the principle of microscopic reversibility, a symmetry relation between forward and backward state transitions when a system is interacting with a thermal heat bath. We show that this quantum modification plays a critical role in the low-temperature limit, while the quantum-to-classical transition occurs at high temperatures.

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[Talk 26] The relaxation spectrum of interacting particle systems

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A quantitative description of the relaxation to equilibrium dynamics is crucial to understanding important phenomena in statistical physics, e.g. meta-stability, cooling strategies, and first passage properties. In Markovian systems, where the system evolves according to a Liouvillian operator, the physics of relaxation is captured by the spectrum of the Liouvillian operator, i.e. the relaxation spectrum. For macroscopic interacting systems, with a large state space, extraction of the relaxation spectrum is restricted to integrable systems. Here, we present a novel approach for extracting the relaxation spectrum of interacting particle systems within the framework of the macroscopic fluctuation theory. We demonstrate the approach for the paradigmatic simple exclusion process.

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[Talk 27] Thermodynamic anomaly in overdamped systems with time-dependent temperature

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It is generally believed that for systems in which the temperature changes with time, the overdamped description breaks down. This feature is attributed to the fact that the velocity degree of freedom does not equilibrate within the overdamped time scales. In this talk, I am going to discuss about the discrepancies in the energetics of a thermodynamic system with temporally varying temperature when an overdamped approximation is used. In our recent work, we found that the overdamped approximation fails to capture the complete heat exchanged between the system and its surrounding bath. We also find that within this approximation the entropy production too deviates from its true value. This "thermodynamic anomaly" has far-reaching implications. In particular, the efficiency of heat engines needs to be suitably modified when studied with the overdamped description. Moreover, we also find a method of calculating kinetic energy changes for Langevin systems with large viscosity which outperforms the traditionally used experimental methods.

[1] Thermodynamic anomaly in overdamped systems with time-dependent temperature. *Shakul Awasthi, Hyunggyu Park, Jae Sung Lee* [Manuscript in preparation]

[Talk 28] Emergence of hidden order and its dynamical evolution in the annealed Sherrington-Kirkpatrick model

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Center for Interdisciplinary Studies, Westlake University

The concept of the hidden Mattis phase in annealed spin-glass models was first proposed by Kasai and Okiji 40 years ago [1], but it received little attention until recently. Although no thermodynamic transition is expected, the distribution of spin configurations acquires a Mattis-type order at low temperatures, associated with gap opening at the leading edge of the coupling matrix spectrum[2]. In this talk, I will discuss the dynamic consequences of the hidden Mattis order based on detailed numerical and analytical studies of the Sherrington-Kirkpatrick (SK) Ising spin-glass model with slowly evolving coupling constants[3]. Temporal evolution of spin autocorrelations is shown to follow a two-step process: at short times, spins equilibrate around a fixed principal eigenvector that defines the backbone of the spin condensate; the slow evolution of the coupling constants, on the other hand, yields diffusive motion of the eigenvectors and intermittent hybridization of states upon gap closures. Adapting the Dyson's se
minal work[4] to the present case, we show that the finite-size scaling properties of the gap dynamics can be derived analytically. Our work adds to the converging views in the past few years towards the glass transition in supercooled liquids.

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[P1]

Observation of quantum work: An access to negative probability

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In the quantum mechanical framework used to obtain the Jarzynski relation, work is defined as the difference between the energy eigenvalues of the Hamiltonians at the start and end of a work protocol. To determine the two eigenvalues for the work protocol, two projective measurements are required. These projective measurements are unsatisfactory in that they do not allow the assessment of work values that are untouched by measurements when the initial quantum ensemble possesses coherence. Recently, the authors of [Phys. Rev. Lett. 118, 070601 (2017)] prove that a measurement operator, involving a copy of an initial ensemble, can fulfill the two requirements: (i) the measurement operator recovers the Jarzynski equality in the case of the canonical initial state and, (ii) at the same time, yields the average of the untouched work value. However, at the price of getting this untouched work average, the elements of the measurement operator can generally be negative. We discover that the linear combination of probability of work measured in three different projective measurement protocols leads to the same measurement operator element related to the untouched work output. It shows us the experimental background for observing the untouched work value, even if the probability of observing such a work output is negative.

[P2]

Boltzmann Sampling by Diabatic Quantum Annealing

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According to the quantum adiabatic theorem, quantum annealing (QA) arises as a mechanism of operating a larger number of qubits and used primarily for solving optimization problems. However, its use only for ground state searches makes it less attractive to quantum algorithm researchers.

In this study, we analytically demonstrate that performing diabatic quantum annealing (DQA), specifically by turning off the transverse field with a finite speed, effectively achieves Boltzmann sampling at a finite temperature. Based on this result, we verify how closely the distribution obtained via DQA matches the actual Boltzmann distribution at the corresponding temperature across various spin systems using multiple measures.

We particularly discuss how this methodology can be effectively utilized for calculating the expectation values of nodes, which is essential for performing gradient descent in the training process of energy-based machine learning models such as Restricted Boltzmann Machines (RBMs).

[P3]

Nonadiabatic Otto engine: frictional effects on performance bounds and operational modes

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We present a detailed study of a nonadiabatically driven quantum Otto cycle with a time-dependent harmonic oscillator as its working medium. Particularly, in the sudden-switch regime, we discuss the implications of the nonadiabatic driving on the performance of the thermal machine under consideration, and obtain analytic expressions for the maximum achievable efficiency and coefficient of performance of the harmonic Otto thermal machine. Further, we show that due to frictional effects, the quantum harmonic Otto cycle driven by sudden-switch protocol cannot work as a heat engine or refrigerator in the low-temperature limit. Finally, we show that in the high-temperature limit, the frictional effects give rise to a richer structure of the phase diagram of the harmonic Otto cycle. We identify the parametric regime for the operation of the Otto cycle as a heat engine, refrigerator, accelerator, and heater.

[P4]

A Unified Hierarchical Framework for Thermodynamic Inequalities: Extending the Thermodynamic Uncertainty Relation

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In recent years, significant advancements have been made in the field of thermodynamic inequalities, including the thermodynamic uncertainty relation (TUR) and the entropic bound (EB), which provide lower bounds for entropy production (EP) based on nonequilibrium currents. Additionally, the classical speed limit (CSL) establishes a lower bound on EP using the geometry of probability distributions, while the power-efficiency (PE) tradeoff defines the maximum achievable power of a heat engine given its thermal efficiency. This work introduces a unified hierarchical framework that integrates these various bounds. Central to this framework is a novel extension of the TUR, termed XTUR, which encompasses the broadest range of current-like and state-dependent observables. By selecting more specific observables, we demonstrate the emergence of TUR and EB from XTUR, followed by the derivation of CSL and the PE tradeoff from EB. Our derivations apply to both Langevin and Markov jump systems, including the first proof of EB for Markov jump systems and a generalized form of CSL. We validate our findings through three examples. First, we provide numerical validation of XTUR using a Brownian particle manipulated by an optical tweezer, showing that XTUR offers a significantly tighter estimate of EP compared to the original TUR. Additionally, we present examples that demonstrate the EB for Markov jump systems and the CSL for Langevin systems in an inhomogeneous temperature field.

[P5]

Thermodynamic uncertainty relation for systems with active Ornstein-Uhlenbeck particles

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Thermodynamic uncertainty relations (TURs) quantify trade-offs between thermodynamic cost and observable fluctuations in nonequilibrium thermal systems. We find TURs for systems consisting of active Ornstein-Uhlenbeck particles (AOUPs), deriving an explicit analytic expression incorporating a modification to the thermodynamic cost term. This modified cost term encompasses both the conventional entropy production and active noise-induced energy consumption. We apply our TUR theory to estimate anomalous diffusion in systems driven by a constant force under the active noise. By introducing a contracted probability density function, we derive a steady-state TUR specific to this system. Moreover, we optimize the TUR bound using a novel scaling parameter. Our findings indicate that the active noise impedes accurate estimation of anomalous diffusion extent. This study provides a framework for investigating fluctuations in biological systems operating in active environments.

[P6]

Local Faceting and Dynamic Crossover Scaling

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We investigate the interplay between roughening and phase ordering in a system where Ising spins are coupled to (1+1)-dimensional Kardar-Parisi-Zhang (KPZ) growth. The model investigates how surfaces become rougher (roughening) and how ordered domains emerge (phase ordering) due to the coupling. Two key phenomena are observed: local faceting and quasi-long-range Ising order. The Ising spins in the model move with the evolving surface, and the Ising domain walls have a preference to move in certain directions, reflecting surface reconstruction processes. The KPZ growth continues beyond the characteristic length and time scales of the facets, but with significantly altered spatial and temporal scales. Interestingly, the Ising spins maintain a quasi-long-range order within the facets, exhibiting a dynamic crossover scaling behavior. Our study also explores the connection between the model and the question of whether the wave function of a particle moving through a random medium can develop a specific type of order, known as sign-order. Our findings imply that only a quasi-long-range sign-order is possible, and not a dynamic phase transition in the thermodynamic limit.

[P7]

Random target search for a reactive target by multiple diffusive searchers

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We study random target search for a reactive target by multiple diffusive searchers in d-dimensional confined domain. Searching time τ is estimated analytically by solving Fokker-Planck equation and the results are also confirmed by Langevin dynamics simulations. We show that τ can be approximately expressed as power law with the number of searchers N, $\tau \sim N^{-\alpha}$, when uniform initial distribution of searchers is assumed. Different from perfectly absorbing target, another time scale called absorption time appears on reactive target model and show that absorption time makes the Mean First Passage Time (MFPT) to have different types of N-dependence. We divide the range of reactivity of the target, and show how the MFPT types changes explicitly.

[P8]

First passage time in compartmentalized medium

Xavier Durang, Jae-Hyung Jeon
POSTECH

Diffusion in heterogeneous media partitioned by permeable membranes has many applications in physical and life sciences. In this work, we consider a model of single particle diffusion in 1D multi-compartmentalized medium. The compartmentalization of the media is achieved by introducing barriers between areas with different diffusion coefficients. Then, we construct a renewal equation for multi-compartmentalized Brownian motion that relates the full probability density to the probability densities in each compartment. Then, using transfer matrices, we can solve the Laplace transformed renewal equation. We illustrate the results by analyzing the first passage time (FPT) problem for reaching the outer boundaries of the domain. We identify and discuss the appearance of a new intermediate time scale that characterize the heterogeneity of the system.

[P9]

Metastable states and hysteresis of congestion spreading dynamics in urban road networks

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University of Seoul

In urban road networks, congestion on one road can spread through the networks to neighboring roads. How does congestion spread in these networks? Furthermore, how do roads recover from their congestion? To address these questions, we analyzed the high-resolution velocity data of urban roads and found that congestion spreads like an infectious disease in the road networks but the recovery rate of roads from congestion decreases exponentially with the number of their congested downstream roads, which is quite different from an infectious disease. To investigate the role of these observed microscopic dynamical features in the macroscopic congestion dynamics, we developed a contagion-like model, called the recovery-hindered SIS model, in which the recovery process can be interrupted by the nearest neighbor interaction. Through the numerical simulation of the model, we observed metastable states and hysteresis, the characteristics of the discontinuous phase transitions, in the macroscopic congestion dynamics. These metastable states are well described by a mean-field theory. Our findings shed light on why it is more difficult for a road to return to a free-flow state once it has become congested, and suggest that not only contagion but also recovery mechanisms are essential to understanding macroscopic spreading phenomena.

[P10]

Contagion dynamics on hypergraphs with nested hyperedges

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Group-wise collective interactions, i.e., higher-order interactions, are a fundamental characteristic of many complex systems. These ubiquitous functional units can be encoded as hyperedges by using the hypergraph as a theoretical tool. In recent studies on dynamics featuring higher-order interactions on hypergraphs, a hyperedge plays a role as a venue where nonlinear mechanisms operate, and it has been reported that the correlation between hyperedges (i.e., higher-order correlation) can significantly change the dynamics on hypergraphs. One frequent but less explored higher-order correlation is nestedness: Some hyperedges can be entirely contained (that is, nested) within another larger hyperedge, and it can also occur in a hierarchical manner. However, most existing analytical methods hitherto do not capture the effects of nested structure faithfully. To fill this gap, here we propose an analytical framework that we name the facet approximation (FA), aiming to capture the correlation between local dynamics within the facet and its nested hyperedges in a mean-field way. Furthermore, to formulate the FA and to investigate the impacts of hyperedge nestedness on the higher-order susceptible-infected-susceptible dynamics on hypergraphs, we introduce a hypergraph model (named the random nested-hypergraph model) with a tunable level of nestedness. Our results reveal that the hyperedge nestedness makes notable shifts in phase diagram and outbreak size, emphasizing the importance of systematic research of dynamics on hypergraphs with nested hyperedges.

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[P11]

The community in your real-world network cannot be simply hierarchical

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The community structure in networks [1], detected at different resolutions [2], has been widely perceived to be hierarchical. However, we demonstrate that it is not a strictly hierarchical structure, but it rather undergoes reconstruction processes in general due to the nontrivial organization harbored in real networks. By examining the modularity function, we show analytically that multiple communities are naturally reconstructed as the resolution parameter increases. In other words, large communities are not simply fragmented into smaller ones in the case of modularity-maximization-based community identification. Consequently, the number of communities non-monotonically fluctuates as the resolution parameter increases. Such a behavior contradicts the traditional notion of hierarchical fragmentation and suggests a more subtle relationship among communities at different scales. Based on the Louvain algorithm [3], our extensive numerical analysis of real-world networks, including social, biological, and technological networks, reveals that this reconstruction process is ubiquitous in large-scale networks. Furthermore, we model these characteristics using a stochastic block model [4], which successfully replicates the up-and-down fluctuations in the number of communities as a function of resolution, further validating our theoretical predictions. For instance, in the case study of an airline network characterized by its complex connectivity patterns with geopolitical constraints, the community reconstruction process cannot be described by hierarchical or nested encapsulation. Our findings have significant implications to study of real networks, suggesting that community detection algorithms and models must account for the possibility of reconstruction and dynamic inter-scale community relations. Our work opens new avenues for exploring mesoscale structures of networks by sharpening both theoretical and practical aspects of community detection methods.

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[P12]

Mutual percolation on one-dimensional multiplex networks with long-range connections

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We numerically study the phase transitions of mutual percolation in one-dimensional multiplex networks with long-range connections. The connection probability follows $\sim 1/r^{1+\sigma}$ where r is the distance between two nodes and σ controls the extent of long-range connections. It has been argued that the necessary condition for continuous transitions is $0 < \sigma < 1$, with $\sigma = 0$ indicating the point where clustering, i.e., the abundance of triangles, vanishes. Our results suggest that the lower bound of σ for continuous transitions can vary from approximately 0 to $1/3$, depending on specific problem settings involving edge overlaps. Given that σ is related to the spectral dimension, we discuss our findings and related works from this perspective.

[P13]

Function and structure of the higher-order components in hypergraphs

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Hypergraphs are suitable for representing high-order interactions, in which multiple elements interact simultaneously, prevalent in real-world complex systems. Unlike networks, in hypergraphs, there are higher-order components composed of hyperedges with two or more shared common nodes between hyperedges. As the giant component is crucial for network functionality, we investigated the role of the hypergraphs' giant higher-order components, frequently observed in the real world, particularly on higher-order contagion dynamics.

We proposed a higher-order-connected hypergraph model to systematically analyze the function of the giant higher-order components. In this model, the probability that entire nodes belonging to a subgroup enter the hyperedge together during the hypergraph formation process is used as a model parameter p, and by adjusting p, the giant higher-order components can emerge. Our finding confirmed that the presence of the giant higher-order components is pivotal for spreading infection from a single hyperedge infection source in the empirical hypergraphs and higher-order-connected hypergraphs [1].

To understand the detailed structure of the higher-order-connected hypergraph, we investigated the emergence point of the giant higher-order components and behavior of this model's (k, q)-core [2], which is the largest subhypergraph with nodes' degree of at least k and hyperedges' size of at least q. Significantly, we confirmed that the behavior of the (k, q)-core differs from that of ordinary random hypergraphs. Lastly, to use this model as a null model for real-world hypergraphs, we generalized the model so that the degree and size distributions follow the power law [3].

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[P14]

Effects of structural properties of neural networks on machine-learning performance

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In recent times, neural-network-based machine learning techniques such as deep learning or graph neural networks have earned significant attention. One important recent study based on relational graph representation (defining neural networks as a message exchange function over graphs) called “graph2nn” [1] aims to understand the relationship between the graph structure of the neural network and its predictive performance, based on elementary types of model networks. In this work, we extend it to an even more general network structure, i.e, the static model [2] and study the effect on the predictive performance of a 5-layer multilayer perceptron (MLP). We found out that the network performance demonstrates a smooth U-shape correlation with degree exponent and increases proportionaly with edge number. Additionally, there exists a sweet spot of relational graphs, which leads to neural networks with significantly improved predictive performance.

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[P15]

Physically Consistent Neural Network for Large Deviation Estimation

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The large deviation function (LDF) quantifies the likelihood of atypical events, offering insights into system behavior under rare occurrences. Traditional Monte Carlo-based methods, such as the cloning algorithm and population dynamics with feedback controls, are often used to calculate the LDF. However, these methods demand extensive computational resources and suffer from critical slowing down near dynamical phase transitions. A recent study [1] proposed a machine learning approach to compute the LDF, showing a reduced computational cost and faster convergence compared to Monte Carlo-based methods. Yet, the conventional neural network design in this study required an exponential increase in parameters with system size. We implemented a permutation-equivariant neural network, *DeepSets* [2], to address this issue by leveraging the system's permutation symmetry. This physically consistent neural network design allows for efficient LDF computation, even for large system sizes. We tested this approach on an analytically solvable active matter model to estimate the LDF for active work. Our results indicate that the physically consistent neural network achieves comparable accuracy to conventional neural networks while using significantly fewer parameters for this system.

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[P16]

Skew scattering by triangular defects originates ratchet effect in photonic graphene

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The ratchet effect can be referred as appearance of steady unidirectional response to oscillating or stochastic driving excitation [1]. Present study is devoted to comprehensive theoretical study of the asymmetric (skew) scattering in photonic graphene similar to its conventional counterpart [2] with the main focus on its realization with semiconductor microcavity exciton-polaritons. As an important consequence of the skew scattering, we prove appearance of ratchet effect in that system. The triangular defects in the form of missing micropillars in regular honeycomb lattice are considered as ones that break the spatial inversion symmetry thus providing the possibility of ratchet effect [3]. By means of numerical solution of effective Schrodinger equation, we provide microscopical insight into the process of skew scattering and determine indicatrices, cross-sections, and asymmetry parameters. In the system with multiple coherently oriented triangular defects, macroscopic ratchet effect occurs as unidirectional flux upon the noise-like initial conditions. Our study broadens the concept of ratchet phenomena in field of photonics and optics of exciton-polaritons.

We acknowledge the financial support from the Institute for Basic Science (IBS) in the Republic of Korea through the projects IBS-R024-Y3 and IBS-R024-D1 (O.M.B.).

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[P17]

Single-spot nonequilibrium exciton-polariton condensation revisited

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Exciton-polariton condensates in planar microcavities have been the subject of extensive recent studies [1]. The interest in these "quantum fluids of light" is not only fundamental but is also stimulated by certain perspectives for practical applications, such as optical computing and photon packaging. For instance, polariton simulators we discussed in Ref. [2]. One way to create polariton condensate is incoherent pumping. Due to the laser radiation, polaritons populate the so-called reservoir, then relax to the low-energy state and condense if the gain overcomes losses (see, Ref. [1] and references therein). From the theoretical viewpoint, the physical processes can be modeled using two equations, one for the reservoir dynamics and another one (driven-dissipative Gross-Pitaevskii equation) for the condensate wave function [3]. The corresponding laser power at which the condensation occurs (pumping threshold) is a function of microcavity parameters as well as the pumping profile shape.

In the theoretical part of this study, we start with formulating an effective complex Ginzburg-Landau equation (cGLE) near the threshold based on the stationary reservoir assumption. Aiming for the description of the condensate wave function under the Gaussian pumping, we substitute it with the parabolic "pseudopotential." The latter allows for an analytical perturbative solution of the corresponding cGLE and provides an accurate description of the Gaussian profile problem. As the primary outcome of our analytical approach, we determine the pumping threshold as a function of microcavity parameters and the width of the pumping spot. This function is characterized by a single length scale, which turns out to be only dependent on the polariton spectral line properties.

In the experimental part of the study, the threshold pumping intensity was measured for three different samples in the continuous pumping regime as a function of the spot size. The

corresponding data were fitted using the analytically predicted dependence, and a faithful agreement was observed. It implies that the developed approach can be used for creating condensates with required properties, e.g., size in real space.

O.I.U. acknowledges financial support from the Institute for Basic Science in the Republic of Korea through Project No. IBS-R024-D1. S.V.K. acknowledges financial support from the Institute for Basic Science Young Scientist Fellowship (IBS-R024-Y3). I.S.A. thanks the Institute for Basic Science at Daejeon for support during his stay.

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[P18]

Global Netflix Consumption Flow Analysis via Information Theory

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This study applies information theory to analyze the OTT content consumption relationships between 71 countries, using Netflix's top 10 show rankings data from July 1, 2020, to September 30, 2022. We compare several methods of information theory, including Shannon entropy, cross entropy, Kullback-Leibler divergence, and transfer entropy, to evaluate the consumption patterns and information flow between countries. Our analysis aims to identify the most effective method for understanding major content consumption flows and trends across different nations. Additionally, building on similar consumption groups identified in our previous study, we determine the leading country in content consumption within each group and identify the key country that connects these groups.

[P19]

Enhancing Cooperation from Reactive Strategies with Reputation Information

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Cooperation is a fundamental element for both social and biological evolutions. Traditionally, direct and indirect reciprocity have been viewed as distinct mechanisms for promoting cooperative behavior. This study investigates the evolution of these strategies within a closed community by analyzing repeated Prisoner's Dilemma games, incorporating both direct interaction histories and public reputation information. We find that the integration of direct and indirect reciprocity fosters robust cooperation, significantly surpassing the classic tit-for-tat approach, particularly in scenarios where mistakes are prevalent. These results highlight the efficacy of a hybrid approach in enhancing cooperation, offering novel insights that extend beyond traditional reciprocity frameworks.

[P20]

Nash Equilibria in Asymmetric Semifinalists' Dilemma

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We extend the previous symmetric semifinalists' dilemma game to asymmetric case and identify the Nash equilibrium. The semifinalists' dilemma involves a four-player tournament where each player's strategy entails allocating stamina between the first and second rounds. Using more stamina in the semifinals to outperform the opponent may reduce the chances of winning in the finals, a situation known as the semifinalists' dilemma. Previous research explored the Nash equilibrium with equal player stamina, while we investigate a case with asymmetric stamina, featuring two strong and two weak players. In a scenario without a third-place match, where the last two players receive the same reward, we find the Nash equilibrium for different second-place reward values. The Nash equilibrium varies depending on the types of matchups in the semifinals. In the first type, each semifinal game features players with the same stamina, but the stamina levels differ between the two games. Here, we find that the expected payoffs for both strong and weak players become equal, nullifying any stamina advantage. In the second type, where players with different stamina levels meet in the semifinals, we find that the Nash equilibrium varies with the second-place rewards. When the second-place reward is small, players conserve stamina for the finals. Conversely, when the second-place reward is substantial, they focus on winning the semifinals

[P21]

Evolution as optimization problem on competition for the resources between populations and individuals

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The entanglement of population dynamics, evolution, and adaptive radiation for species competing for resources is studied. For resource harvesting, we modify the model used in Tikhonov and Monasson (Phys. Rev. Lett. 118:048103, 2017) [1], and introduce new resource contest principles. We realistically implement the effects of beneficial and deleterious mutations on the coefficients in the equations governing the population dynamics and consider the emergence of reproductive isolation. The proposed model is shown [2] to be in agreement with the competitive exclusion principle and no vacant niche principle. We establish a mechanism that contributes to preventing the accumulation of irreversible deleterious mutations: competition between recently diverged species/subpopulations. The proposed model is applicable for descriptions of more complex systems. In case of many constants in time resources, one observes very rapid specialization being a manifestation of optimization. Finally, the selected results will be presented on simple model of nervous system evolution as optimization problem.

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[P22]

Bend-induced Hysteresis of Heterogeneous Ring Polymers

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[2]*Asia Pacific Center for Theoretical Physics*

Semi-flexible polymers like microtubules, actin filaments, and DNA frequently form ring structures and are essential in both biological and synthetic contexts. The bending stiffness along these bio-polymers can vary due to different factors, resulting in anisotropic shapes and mechanical instabilities. The variability in polymer stiffness along their length complicates the development of an analytical theory. In this research, we extend Euler-Kirchhoff's theory to include heterogeneous two-state polymers. We offer an exact solution for the configurations of ring polymers and a method to address boundary condition issues. By examining a two-state polymer model where the proportion of each state can change dynamically, we identify buckling and kinking transitions that lead to various phases, including phase coexistence and hysteresis. These theoretical predictions are confirmed by numerical simulations, and we show that our theory is applicable to a realistic polymer model, oxDNA. We anticipate that our theory will be useful for estimating the bending energy and configurations of heterogeneous stiff polymers.

[P23]

Fluctuations and complexity in intracellular Ca^{2+} dynamics

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Fluctuations-driven complex oscillations are experimentally observed in cardiac cells, hepatocytes, neuronal cells, etc. We investigate the interplay between intrinsic fluctuation and the complexity of intracellular calcium (Ca^{2+}) dynamics using complexity measures of permutation entropy (PE) and statistical complexity (SC). We find that PE and SC characterize the diverse states of cytosolic Ca^{2+} and their interactions with intrinsic fluctuation. We identify distinct cytosolic Ca^{2+} states at different positions of the complexity-entropy (CH) causality plane, indicating varying complexity and information content as intrinsic fluctuation varies. The SC exhibits peaks in an intermediate range of intrinsic fluctuation, indicating high-complexity states, which likely correspond to optimal Ca^{2+} dynamics with biological significance.

[1] Chanu, A. L., Singh, R. K. B., & Jeon, J.-H. (2024). Exploring the interplay of intrinsic fluctuation and complexity in intracellular calcium dynamics. *Chaos, Solitons & Fractals*, **185**, 115138.

[P24]

Tracking bacillus subtilis in 2D and analyzing its run-and-tumble motions

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System of motile bacteria can be considered as a living active matter because they act like energy consuming particles. Our rod-shaped bacterium, bacillus subtilis, uses its multiple flagella which are uniformly distributed over its body skin to swim through its environment. Its swimming motion is usually classified as two distinct phases, run and tumble, and the bacterium can actively change its motile phase which results in the exploitation and the exploration of the environment. The combination of these two phases makes the complex motion of the active particle which is applicable to the various dynamical phenomena like diffusion of the bacteria. In this work, we suggest comprehensive bacterial tracking framework which adopts a deep learning (DL) based instance segmentation method. We resolved the difficulty in preparing the training dataset by generating auto-labeled synthetic images. This framework can help handling big dataset of living bacterial trajectories produced in visually complex bacterial solutions. We also study the swimming motion of tumbling bacteria, by modeling simple Langevin equations of motion for the speed and the angle of two-dimensional trajectory. The inference of the model parameters enables quantitative analysis of the experimental bacterial suspensions. We analyze the changes in model parameters corresponding to the various environmental temperature of bacterial suspensions from 15°C to 60°C.

[P25]

Active hinge model: a simple model for the motile active particle cluster within a crowded channel

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A recent experiment [1] demonstrated that self-propelled particles within a circular confinement crowded by granular particles form a motile boundary cluster. The continuous movement of this cluster is driven by symmetry breaking, resulting from a positive feedback loop between the cluster's asymmetries and those of the granular medium. We propose and analyze an active hinge model to understand this symmetry breaking mechanism. This model comprises a pair of self-propelled rods connected by a hinge, placed among granular particles in a quasi-one-dimensional channel. Extensive numerical simulations reveal that the cluster's directional persistence varies non-monotonically with the packing fraction of the granular medium and the self-propulsion force. Additionally, we observe signs of a first-order phase transition in our system, consistent with the experimental results in the circular confinement.

[1] K. Son, Y. Choe, E. Kwon, L. G. Rigon, Y. Baek, and H.-Y. Kim, “Dynamics of self-propelled particles in vibrated dense granular media,” Soft Matter, vol. 20, no. 12, pp. 2777–2788, 2024

[P26]

Effects of chemokinesis on the motility-induced phase separation

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Active materials convert the stored or environmental energy to systematic motion in the level of their individual constituents. Their nonequilibrium nature results in various collective phenomena, such as motility-induced phase separation (MIPS) in scalar active matter.

In the case where their activity is originated from the consumption of chemical fuel, one of the simple but practically relevant effect which is usually overlooked is the local fuel depletion. Unless the fuel is supplied with the precise amount, the fuel will eventually run out. Furthermore, when the phase separation is occurred, the spatial profile of fuel consumption will be inhomogeneous even if the fuel is constantly supplied to the overall system. This will diversify the self-propulsion strength of the particles depending on the spatial region they are included, and this will affect back to the collective phenomena of the system.

First, in basal metabolic regime (BMR) where the particles consume fuel even if they are stuck somewhere and not experiencing actual displacement, fuel is largely depleted inside the particle clusters. Through the linear stability analysis, we show that the MIPS is enhanced in the BMR. This is corroborated by numerically simulating the coarse-grained hydrodynamics and particle-based models. In contrast, in the active metabolic regime (AMR) where the fuel consumption is proportional to the spatial velocity of particles, our theory predicts the suppression of MIPS, which is also cheked by simulations. Moreover, the presence of microphase separation and oscillatory phases (highly variable over time) is also predicted by the theory, and verified by a less noisy, hybrid particle-based model with coarse-grained force which can be interpreted as quorum sensing.

These natural effects of local fuel depletion can be considered as a *chemokinesis*, since only the magnitude, not the direction of the motion is dependent on the profile of chemicals. This shows a clear contrast with *chemotaxis*, which also introduces various intriguing patterns to MIPS but often requires sophisticated apparatus for signal transduction and actuation to move ‘uphill’ the chemical gradient. Our study highlights the substantial impact of resource consumption mechanisms on the collective behavior of active matter.

[1] E. Kwon, Y. Oh and Y. Baek, *work in progress*.

[P27]

Motility-Induced Pinning in Self-Propelled Particle Systems with Discrete Symmetry

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In this study, we explore the behavior of self-propelled particles within the active Ising model (AIM), focusing on the phenomenon of motility-induced pinning (MIP). This research utilizes extensive Monte Carlo simulations to investigate how AIM, traditionally known for a liquid-gas type phase transition, behaves under varying conditions of alignment interaction strength. We find that the system, as indicated in recent studies where the ordered state is metastable against counter-propagating droplets, forms steady states characterized by traveling droplets. Notably, as the interaction strength increases, we observe these droplets becoming pinned, creating immobile interfaces between domains. This pinning is driven by the resonant back-and-forth motion of particles at these interfaces. The system undergoes slow coarsening dynamics, eventually reaching a steady state with macroscopic pinned interfaces. We provide a numerical phase diagram illustrating the conditions for the MIP transition and offer analytic insights into the pinning mechanism and coarsening process.

Keywords: Active Matter, Self-Propelled Particles, Motility-Induced Pinning, Active Ising Model, Phase Transition, Monte Carlo Simulations

[1] C-.U. Woo, J.D. Noh, arXiv:2403.10106

[P28]

Efficient Monte Carlo methods for active particle dynamics with thermodynamic consistency

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Active particles are known to exhibit various nonequilibrium collective phenomena, such as motility-induced phase separation and current rectification. Recently, there has been a surge of interest in identifying the role of energy dissipation in maintaining such large-scale nonequilibrium structures. As an efficient numerical method for investigating this issue, we propose a lattice-based kinetic Monte Carlo method that preserves the energetics of the system. We analytically show that the error stemming from the discretization of space and time can be reduced by choosing a suitable velocity-dependent prefactor for the transition rates. The model correctly reproduces the original dynamics in the proper continuum limit, all the while allowing us to quantify how far from equilibrium the system is by calculating the energy dissipation.

[P29]

Crystallization in low-density chiral Active Brownian Particles

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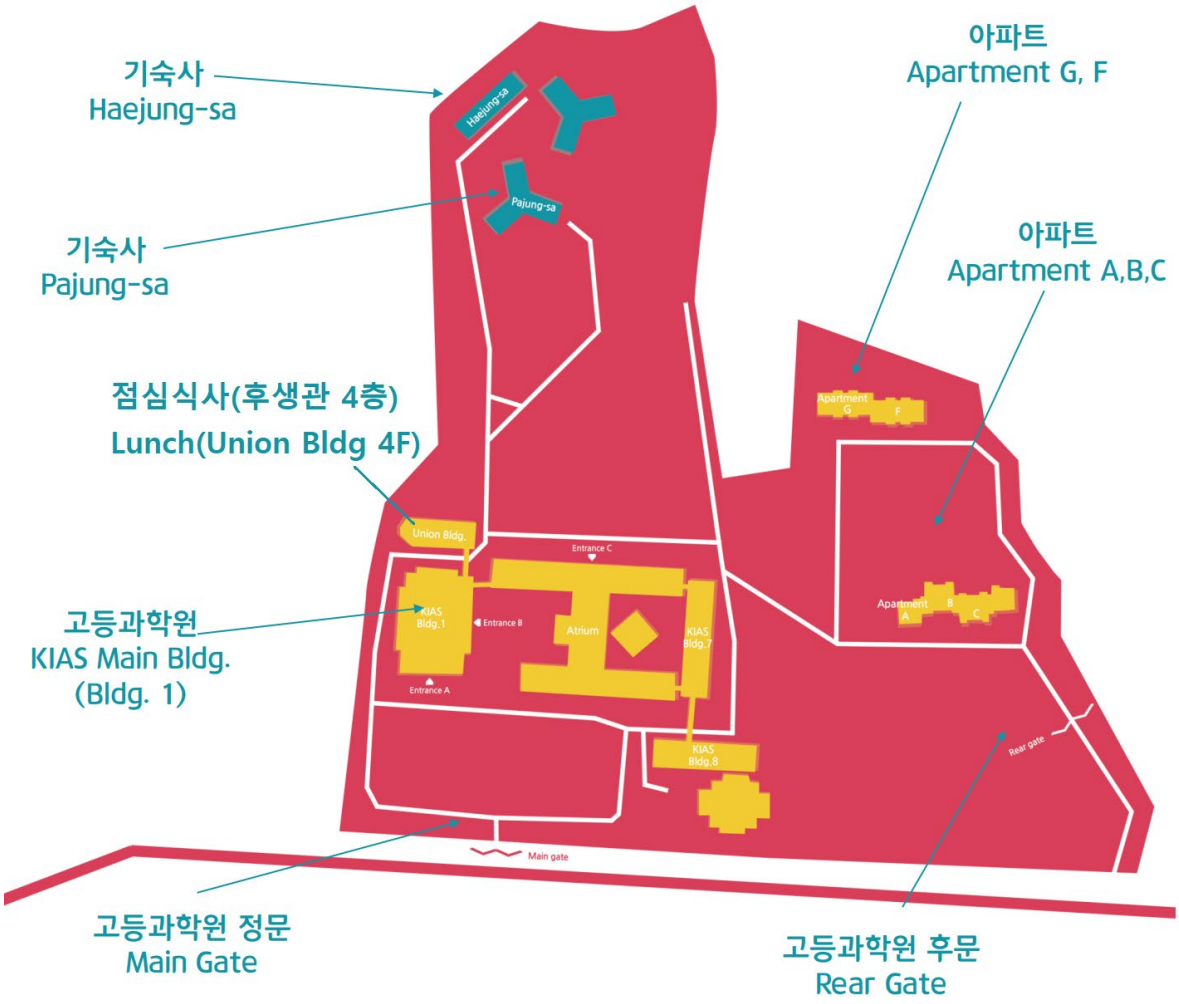
We conduct a numerical investigation of two-dimensional chiral active Brownian particles (cABPs) at low density. In this study, the cABP system can be effective particles by rotation characteristics for each particle. We measure the hexatic order parameter ψ_6 to analyze the formation of a hexatic phase in both the positions of cABPs and their effective particles, subsequently confirming crystallization within the system. Additionally, we construct a phase diagram of the crystallization and fluid in the plane defined by the Peclet number, Pe and rotation velocity, ω. Our results reveal that crystallization occurs within a narrow region of the phase diagram, indicating a highly sensitive non-equilibrium crystalline phase influenced by particle interactions and thermal noise.

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
고등과학원 후문
Rear Gate
아파트
Apartment G, F
아파트
Apartment A,B,C
Haejung-sa
Pajung-sa
Union Bldg.
Entrance C
KIAS Bldg.1
Entrance B
Atrium
KIAS Bldg.7
Entrance A
KIAS Bldg.8
Main gate
Rear gate
Apartment G F
Apartment A B C