Introduction

The East Asia Joint Seminars in Statistical Physics (EAJSSP) 2015 is the third of the series of international meetings in the field of statistical physics with the joint efforts of working scientists from East Asia.

Topics include

nonequilibrium statistical mechanics, complex system, soft matter physics, and more....

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Jaegon Um (KIAS)

Program Schedule

Day 1 – October 14 (Wed)

09:00-09:30	Opening at 09:25 Sandwich	
09:30-10:00	H. Nishimori	Quantum annealing and quantum phase transitions
10:00-10:30	H. Kim	Generalized Microcanonical Ensemble: from Quantum to Classical
10:30-11:00	break	
11:00-11:30	B. Zheng	How Volatilities Nonlocal in Time Control the Price Dynamic in Complex Financial Systems
11:30-12:00	C.-H. Chang	Contraction of stochasticity on hierarchical kinetic networks
12:00-12:30	H.-J. Zhou	None-Equilibrium Steady Flow in Human Rock-Paper-Scissors Game: Experiment and Theory
12:30-14:00	Lunch	
14:00-14:15	S. Wang	Energy dissipation in an adaptive molecular circuit
14:15-14:30	H. K. Lee	Fluctuation-dissipation theorem and detailed-balance in the presence of velocity-dependent force
14:30-15:00	Y.-F. Chen	Fluctuations of entropy production in partially masked electric circuits
15:00-15:30	M.-C. Wu	Developing adaptive data analysis approaches for protein research
15:30-16:00	break	
16:00-16:30	J. Yeo	Detailed Balance Breaking and Housekeeping Entropy Production in Continuous Stochastic Dynamics
16:30-17:00	H.-R. Jiang	Active soft matter under gradients
17:00-17:30	J. Um	Total cost of operating an information engine
17:30-18:00	L.-H. Tang	Sequential pattern formation as a front instability problem
18:00-20:00	Poster (Pizza & Beer)	

Day 2 –October 15 (Thur)

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10:00-10:30	D. Mizuno	Rheology and fluctuations in active systems
10:30-11:00	break	
11:00-11:30	H. Kori	Mathematical approach to jet lag
11:30-12:00	H. Hong	Traveling wave state induced by correlated disorder
12:00-12:30	Y. Lan	Physics of finite-size scaling in the Kuramoto oscillator model
12:30-14:00	Lunch	
14:00-14:15	H.-Y. Chen	Hydrodynamic model of epithelial tissues
14:15-14:30	S. H. Lee	Finding Lagrangian coherent structures using community detection
14:30-15:00	B. J. Kim	Network of likes and dislikes; Conflict and membership
15:00-15:30	T. Aoki	A model of adaptive temporal networks
15:30-16:00	break	
16:00-16:30	C. Tang	Cell fate determination
16:30-17:00	A. Ikeda	Thermodynamic glass transition of a randomly pinned glass-former
17:00-17:30	H. Wada	Shapes of a looped elastic ribbon under tension
17:30-18:00		
18:00-20:00	Banquet	

Day 3 –October 16 (Fri)

09:00-09:30	Sandwich	
09:30-10:00	S.-I. Sasa	Replica symmtery breaking in trajectories of a driven Brownian particle
10:00-10:30	C. Tian	The kicked rotor: from KAM to integer quantum Hall effect
10:30-11:00	break	
11:00-11:30	H. Hayakawa	Divergence of viscosity in jammed granular materials: a theoretical approach
11:30-12:00	J.-H. Jeon	Geometry-controlled fluctuation in obstructed diffusion
12:00-12:30	L. Xu	Structural origin of fractional Stokes-Einstein relation in glass-forming liquids
12:30-14:00	Photo & Lunch	
14:00-14:15		
14:15-14:30		
14:30-15:00		
15:00-15:30	Excursion (Fortress Wall of Seoul)	
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Day 4 – October 17 (Sat)

09:00-09:30	Sandwich	
09:30-10:00	C.-K. Chan	Positive Feedback and Synchronized Bursts in Neuronal Culture
10:00-10:30	X. Xu	Tracer dynamics in E-coli suspensions
10:30-11:00	break	
11:00-11:30	P.-Y. Lai	Non-equilibrium steady-states in a tilted periodic potential
11:30-12:00	J. D. Noh	On the efficiency of a Brownian heat engine
12:00-12:30	Y. Deng	Potts Antiferromagnetism in Two and Three Dimensions
12:30-14:00	Closing	

Quantum annealing and quantum phase transitions

Hidetoshi Nishimori, Tokyo Institute of Technology

Quantum annealing is a quantum-mechanical paradigm to solve combinatorial optimization problems, represented by an Ising model, and is a quantum alternative to simulated annealing. The success of quantum annealing is strongly related with the existence or absence of a quantum phase transition. I will review these facts briefly and present new results on the control of the order of quantum phase transitions.

Generalized Microcanonical Ensemble: from Quantum to Classical

Hyungwon Kim, Rutgers University

We start with arguing that construction of microcanonical ensemble for quantum integrable system is a nontrivial task. In classical quantum integrable system, however, construction of generalized microcanonical ensemble is clear. We propose an operational construction of generalized microcanonical ensemble guided by classical counterpart and motivated by generalized Gibss ensemble. It is simply in the form of multivariable Gaussian ensemble determined by first and second moments of conserved quantities. We go over advantages of our construction and apply the ensemble to simple systems and a quantum many-body systems.

How Volatilities Nonlocal in Time Control the Price Dynamics in Complex Financial Systems

Bo Zheng, Zhejiang University

We briefly review our progress in financial dynamics, and then focus on the recent results on the volatility-return correlation. What is the dominating mechanism of the price dynamics in financial systems is of great interest to scientists. The problem whether and how volatilities affect the price movement draws much attention. Although many efforts have been made, it remains challenging. The usual volatility-return correlation function, which is local in time, typically fluctuates around zero. Here we construct dynamic observables nonlocal in time to explore the volatility-return correlation, based on the empirical data of hundreds of individual stocks and 25 stock market indices in different countries. Strikingly, the correlation is discovered to be non-zero, with an amplitude of a few percent and a duration of over two weeks. This result provides compelling evidence that past volatilities nonlocal in time affect future returns. Further, we introduce an agent-based model with a novel mechanism, that is, the asymmetric trading preference in volatile and stable markets, to understand the microscopic origin of the volatility-return correlation nonlocal in time.

Keywords: statistical physics, econophysics, complex systems

References

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Contraction of stochasticity on hierarchical kinetic networks

Cheng-Hung Chang, National Chao Tung University

Kinetic networks are widely used for studying complex systems. Since the selection of network for a real system is often not unique, a concern is raised whether and under which conditions hierarchical networks will give the same experimentally measured fluctuating behaviors and identical fluctuation related properties. To clarify these questions, we introduce stochasticity into the traditional lumping analysis, generalize it from rate equations to chemical master equations and stochastic differential equations, and extract the fluctuation relations between kinetically and thermodynamically equivalent networks under intrinsic and extrinsic noises. The results provide a theoretical basis for the legitimate use of low-dimensional models in the studies of macromolecular fluctuations and, more generally, for exploring stochastic features in different levels of contracted networks in chemical and biological kinetic systems. As examples, the theory is applied to account for the behaviors of ion channels under intrinsic noises and biological receptors subject to extrinsic noises.

None-Equilibrium Steady Flow in Human Rock-Paper-Scissors Game: Experiment and Theory

Hai-Jun Zhou, Institute of Theoretical Physics

How humans make decisions in non-cooperative strategic interactions is a big question. For the fundamental Rock-Paper-Scissors game system, classic Nash equilibrium theory predicts that players randomize completely their action choices to avoid being exploited, while evolutionary game theory of bounded rationality in general predicts persistent cyclic motions, especially in finite populations. We performed a laboratory experiment on the RPS game involving six human subjects. We observed population-level persistent cyclic motions for five different payoff parameters. This collective behavior was quantitatively explained, without any adjustable parameter, by a microscopic model of win-lose-tie conditional response. Our work demonstrates the feasibility of understanding human competition behaviors from the angle of non-equilibrium statistical physics.

[C1] Energy dissipation in an adaptive molecular circuit

Shouwen Wang, Beijing Computational Research Center

The ability to monitor nutrient and other environmental conditions with high sensitivity is crucial for cell growth and survival. Sensory adaptation allows a cell to recover its sensitivity after a transient response to a shift in the strength of extracellular stimulus. The working principles of adaptation have been established previously based on rate equations which do not consider fluctuations in a thermal environment. Recently, Lan et al (2012 Nat. Phys. 8 422–8) performed a detailed analysis of a stochastic model for the Escherichia coli sensory network. They showed that accurate adaptation is possible only when the system operates in a nonequilibrium steady-state (NESS). They further proposed an energy-speed-accuracy (ESA) trade-off relation. We present here analytic results on the NESS of the model through a mapping to a one- dimensional birth-death process. An exact expression for the entropy production rate is also derived. Based on these results, we are able to discuss the ESA relation in a more general setting. Our study suggests that the adaptation error can be reduced exponentially as the methylation range increases. Finally, we show that a nonequilibrium phase transition exists in the infinite methylation range limit, despite the fact that the model contains only two discrete variables.

[C2] Fluctuation-dissipation theorem and detailed-balance in the presence of velocity-dependent force

Hyun Keun Lee, Seoul National University

We study the fluctuation-dissipation theorem and detailed-balance in Langevin system with velocity-dependent force. It is discussed that the well-known implication of such conditions could not be valid as a velocity-dependent force is involved.

Fluctuations of entropy production in partially masked electric circuits

Yung-Fu Chen, National Central University

We experimentally investigate fluctuations of entropy production in two capacitively coupled RC circuits driven by constant currents. We focus on analyzing entropy production by merely utilizing partial information of the system with two different reduced descriptions, and give two main statements based on the experimental and theoretical agreements. First, the apparent entropy production derived from a naive reduced description of the circuit follows the Fluctuation Theorem (FT) in the long time limit compared with the intrinsic RC time constants in the circuit. On the other hand, the coarse-grained entropy production follows FT in the short time limit. Moreover, our results imply in general FT can be observed in a system where its environmental couplings to all slow degrees of freedom are weak.

Developing adaptive data analysis approaches for protein research

Ming-Chya Wu, National Central University & Academia Sinica

The biological activities and functional specificities of proteins depend on their native three-dimensional structures, which are defined by the corresponding chemical compositions or sequences. Statistics on the structures suggests that, there are universal geometric factors as constraints on native conformations, while the combinations of properties of amino acids in sequences lead to diversity of functions. In this seminar, I will introduce our recent works on structure, stability, and dynamics of biomolecules based on adaptive data analysis approaches which are developed to reconcile two concepts. Application of the idea to the analysis of intrinsically disordered proteins will also be discussed.

Detailed Balance Breaking and Housekeeping Entropy Production in Continuous Stochastic Dynamics

Joonhyun Yeo, Konkuk University

We revisit the detailed balance (DB) condition and its breakage in the continuous stochastic dynamics in the presence of the odd-parity variable such as momentum. In this case, the housekeeping entropy production (EP) does not satisfy the fluctuation theorem (FT). We investigate how to construct a component of housekeeping EP, which represents the breakage of DB and satisfies the FT. We find that this can be achieved in an infinitely many ways characterized by a single parameter σ. For an arbitrary value of σ, one of the two parts contributing to the housekeeping EP satisfies the FT.

We show that for a range of σ values these EPs can be associated with the breakage of the detailed balance in the steady state, and can be regarded as continuous versions of the corresponding EP that has been obtained for discrete state variables. The other part of the housekeeping entropy does not satisfy the FT and is related to the parity asymmetry of the stationary state distribution. We discuss our results in connection with differences between continuous and discrete variable cases especially in the conditions for the detailed balance and the parity symmetry of the stationary state distribution.

Active soft matter under gradients

Hong-Ren Jiang, National Taiwan University

Soft matter is known for its sensitivity to external gradients. In this presentation, we report two special cases of soft matters under gradients, one is time-dependent thermal gradient in a polymer solution and the other is self-generated unknown gradient around a Janus particles. In the polymer solution, we discover a flow without normal moment transfer in a time-dependent thermal gradient. And in the Janus particle system, we observe a surface dependent motion under chemical reactions. In both cases, we find that active process relating to energy dissipation instead of external force seems to be the key to understand these processes.

Total cost of operating an information engine

Jaegon Um, KIAS

We study a two-level system controlled in a discrete feedback loop, modeling both the system and the controller in terms of stochastic Markov processes. We find that the extracted work, which is known to be bounded from above by the mutual information acquired during measurement, has to be compensated by an additional energy supply during the measurement process itself, which is bounded by the same mutual information from below. Our results confirm that the total cost of operating an information engine is in full agreement with the conventional second law of thermodynamics. We also consider the efficiency of the information engine as a function of the cycle time and discuss the operating condition for maximal power generation. Moreover, we find that the entropy production of our information engine is maximal for maximal efficiency, in sharp contrast to conventional reversible heat engines.

Sequential pattern formation as a front instability problem

Lei-Han Tang, Beijing Computational Science Research Center & HKBU

Pattern formation is a fundamental process in embryogenesis and development. In his seminal paper half a century ago, Turing proposed a mechanism for spontaneous pattern formation in biological systems that involve the diffusion of two types of morphogens ("activator" and "inhibitor") whose interaction stimulates their own synthesis. Starting from random initial perturbations, the Turing model typically generates patterns via the development of finite-wavelength dynamical instabilities in confined geometries. Recently, a collaboration led by Terry Hwa at UCSD and Jiandong Huang at HKU conducted experiments of pattern formation in open geometry through control of the synthetic chemotactic circuit of bacteria[1]. A key feature of the system is a concentration-dependent diffusivity of the active species which can be tuned in the experiment through control of gene expression. Theoretical analysis of the traveling wave solution reveals key parameters that span the phase diagram of the system[2]. Very recently, we carried out linear stability analysis of the traveling wave which yields a localized mode. Depending on the sharpness of the motility variation in space, either a Hopf bifurcation or a first order transition to a pulsating front solution can be observed[3]. The autonomous diffusion control together with the open, expanding geometries offered by growing biological systems, give rise to novel strategies to generate well-defined patterns in space and time.

References

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Hybrid percolation transitions

Byungnam Kahng, Seoul National University

Recently hybrid phase transitions including natures of both continuous and discontinuous phase transitions simultaneously have been obtained in diverse complex systems, for example, k-core percolation, cascading failures in interdependent networks, synchronization, etc. However, it is not manifest yet if the critical behavior of hybrid phase transition can be understood within the conventional framework of second-order phase transition. Here, we investigate the critical behaviors of hybrid percolation transitions in the cascading failure model in inter-dependent networks and the restricted Erdos-Renyi model. We find that the critical behaviors of the hybrid percolation transitions contain some unconventional features that cannot be described by the conventional theory of second-order percolation transitions.

Rheology and fluctuations in active systems

Daisuke Mizuno, Kyushu University,

Seen as a material, the interior of biological cells is a very unique kind of active system, driven away from equilibrium by the internal energy-dissipating and force-generating machinery. Understanding out-of-equilibrium machinery in cells or other active systems is challenging. Cellular compounds are typically soft and highly nonlinearly responding so that their mechanics is profoundly affected by self-generated forces. It is therefore essential to develop experimental and theoretical methodologies to quantify both of these (force and mechanics) in active systems. This would be possible, as long as we know, with “microrheology” operated in two different modes that observe fluctuation (passive mode) and response (active mode) of embedded probe particles.

Here we performed both active and passive microrheology simultaneously in cultured eukaryotic cells using high-bandwidth laser interferometry and optical trap technology implemented with a smooth 3-dimensional feedback of a piezo-mechanical sample stage. This technique allows us to stably track a probe particle in cells, over several hours, within the laser focus regardless of vigorous spontaneous flows and fluctuations naturally existing in active systems. Our experiments demonstrate the breaking of the fluctuation-dissipation theorem as an excessive (non-thermal) fluctuation in the low frequency domain, where the out-of-equilibrium activity should critically affect the mechanics of active polymeric materials in cells. We also developed a theoretical methodology to relate the observed non-thermal fluctuations to internal force generations and confirmed it in a reconstituted cell model, consisting of cross-linked filamentous actin driven by myosin motor proteins, that have been shown to usefully resemble nonequilibrium situations in cells. In prior studies, the second moment of the non-thermal fluctuations has been investigated following the standard procedure established for the microrehology in homogeneous continuum in equilibrium where Gaussian fluctuations are expected. Actually, however, the non-thermal fluctuations observed in active cytoskeletons was found to follow highly non-Gaussian distribution. We investigate the origin of non-Gauss and heavy-tailed probability distribution of fluctuations. Considering the action and dynamics of the force generators randomly-distributed in a homogeneous media, we provide analytical expression for the observed distribution which we call truncated Lévy. The model includes both Gauss and complete Lévy as the limiting cases of the experimentally controllable parameters and quantitatively describes the intermediate behaviors in physically attainable situations.

Acknowledgements: This work is supported by a Grant-in-Aid for Scientific Research on Innovative Areas "Fluctuation & Structure" (No. 25103011) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

Mathematical approach to jet lag

Hiroshi Kori, Ochanomizu University

Jet-lag symptoms arise from temporal mismatch between the internal circadian clock and external solar time. We know by experience that it takes about one week to recover from jet lag (i.e., reentrainment) after a long-distance trip. We recently reported in [1] that, in mice lacking the receptors of a certain neurotransmitter (KO mice), circadian rhythms of behavior and clock gene expression rhythms immediately reentrained to phase-shifted light-dark (LD) cycles. Experiments indicate that oscillation of clock gene expression in wild type mice significantly weakens after a large phase shift, whereas that in KO mice is robust. To uncover the mechanism underlying jet lag symptoms, we constructed a mathematical model consisting of multiple oscillators. In this presentation, after giving an overview of the experimental study, I will explain how our model uncovers the mystery that lack in neurotransmitter results in the quick response to jet lag.

Reference

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Traveling wave state induced by correlated disorder

Hyunsuk Hong, Chonbuk National University

In this talk, I will talk about the collective properties shown in a model of coupled phase oscillators with correlated disorder. Each oscillator in the model has a site-dependent coupling parameter in addition to the natural frequency, where the coupling parameter plays a role as a disorder. According to the previous studies, when the disorder distribution is symmetric with zero mean, no coherence has been found to emerge, but if a sort of correlation comes into the system, the coherence can emerge. Moreover, the coherence is characterized as the traveling wave (TW) state, which is induced by the interplay between the natural frequency and coupling disorder. The mechanism of the TW state in this model will be discussed briefly.

Physics of finite-size scaling in the Kuramoto oscillator model

Yueheng Lan, Tsinghua University

The mean-field theory describes well the synchronization of the Kuramoto oscillator model but is hard to accommodate fluctuations of the finite-sized system. We applied a special form of the RG theory recently developed for the differential dynamical systems to the finite size scaling observed numerically in the Kuramoto model and obtained interesting insights.

[C3] Hydrodynamic model of epithelial tissues

Hsuan-Yi Chen, National Central University

Recently, as a part of the advance in the research of active soft matters, generalized hydrodynamic theory has been applied to biological tissues with much success. Stratified epithelium is a special example of biological tissues due to the layered distribution of proliferative cells and differentiated cells. The slow dynamics of stratified epithelium therefore should reflect such spatial inhomogeneity. In talk I will show that the tissue dynamics predicted by a theoretical model with tissue viscosity that reflects such stratified structure indeed is quite different from a simpler model that assumes a constant tissue viscosity. In particular, when the proliferative cells occupy a thin region close to the basal membrane, the relaxation towards a tissue steady state is enhanced by cell division and cell apoptosis. On the other hand, when the region where proliferative cells reside becomes sufficiently thick, a flow induced by cell apoptosis close to the apical surface could enhance small perturbations. This destabilizing mechanism is general for continuous self-renewal multi-layered tissues, it could be related to the origin of certain tissue morphology and developing pattern.

[C4] Finding Lagrangian coherent structures using community detection

Sang Hoon Lee, KIAS

Lagrangian coherent structures (LCSs) are the most influential invariant sets in the extended phase space of nonautonomous dynamical systems, forming the backbone of mixing and transport. The available methods for detecting LCSs require a dense set of trajectory data. In many cases, e.g., data-driven oceanography, such dense information is unavailable from direct measurements. Here, we use network theory to detect LCSs from a sparse set of trajectories. The fluid elements whose trajectories are known form the nodes of the network. We define the network edges as the relative dispersion between fluid elements. We then apply the method of modularity maximization from network analysis to identify LCSs at multiple scales. To obtain a detailed spatiotemporal description of LCSs, we also consider a multilayer version of modularity maximization on a multilayer representation of a temporal network constructed from numerical and observational data. Being based on relative dispersion, our method can be performed on a sparse set of trajectory data. We illustrate this on drifter data measured by an ocean drifter data set.

Network of likes and dislikes: Conflict and membership

Beom Jun Kim, Sungkyunkwan University

We all have friends and foes. In the study of complex networks, such a pairwise interaction is described by a directed link since the relation is not necessarily symmetric. We study a real network constructed from a survey in which each individual chooses five members (s)he wants to work with, and other five (s)he does not like to work together. Although everyone's outdegrees for such like and dislike links are fixed to five, respectively, it is found that indegree sequence for each type of links exhibits very different behaviors. We also pursue to answer the question of proper divisions of the organization based on the concept of happiness defined for each directed relation. For example, two individuals connected by like (dislike) links in both directions are happy if they belong to the same (different) group(s). We then adopt the framework of the q-state Potts model with long-ranged ferromagnetic and antiferromagnetic interactions and discuss the group structure in the organization that minimizes a suitably defined unhappiness.

A model of adaptive temporal networks

Takaaki Aoki, Kagawa University

We study a model of adaptive temporal networks that are regulated by human activity and vice versa. Thereby we seek to develop a unifying understanding of the mechanisms governing human social dynamics. We analyze the model using a master equation approach and show that the temporal and structural heterogeneities seen in real-world networks can emerge spontaneously from completely homogenous initial conditions. This theoretically tractable model will promote further studies to understand how our society is organized by the interplay between social relations and human activity.

Cell fate determination

Chao Tang, Peking University

Cells have to make various fate choices/decisions in response to the external and/or internal signals and cues. Examples range from stress response, development, to stem cell differentiation and reprogramming. I will discuss several cases in the effort of elucidating the strategies and design principles in these systems.

Thermodynamic glass transition of a randomly pinned glass-former

Atsushi Ikeda, Kyoto University

Confirming by experiments or simulations whether or not an ideal glass transition really exists is a daunting task, because at this point the equilibration time becomes astronomically large. Recently it has been proposed that this difficulty can be bypassed by pinning a fraction of the particles in the glass-forming system. Here we study numerically a liquid with such random pinned particles and identify the ideal glass transition point TK at which the configurational entropy vanishes, thus realizing for the first time, to our knowledge, a glass with zero entropy.

Shapes of a looped elastic ribbon under tension

Hirofumi Wada, Ritsumeikan University

In three dimensional space, a thin elastic ribbon behaves like a developable surface, where its smooth deformation is mostly derived from out-of-plane bending deflections. A geometrically constrained ribbon may respond quite differently when subjected to external loadings. A simple experimentation of such processes is given by a paper strip that is looped and pulled. One finds that the loop either pops out (unfolds) or folds in on itself when it gets sufficiently tight. Here we study this seemingly very simple phenomenon in detail by combing experimental and theoretical approaches. We measure shape dynamics of this frustrated ribbon, and report various morphologies depending on relevant geometric parameters. We present an experimentally integrated phase diagram, which are physically interpreted using our numerical simulations based on a geometrically reduced ribbon model. We point out an essential role of the anisotropy of the bending elasticity that is inherent to thin strips and ribbons.

Replica symmetry breaking in trajectories of a driven Brownian particle

Shin-ichi Sasa, Kyoto University

We study a Brownian particle passively driven by a field obeying the noisy Burgers equation. We demonstrate that the system exhibits replica symmetry breaking in the path ensemble with the initial position of the particle being fixed. The key step of the proof is that the path ensemble with a modified boundary condition can be exactly mapped to the canonical ensemble of directed polymers.

This work was done in collaboration with M. Ueda. See Phys. Rev. Lett. 115, 080605 (2015) for the detail.

The kicked rotor: from KAM to integer quantum Hall effect

Chushun Tian, IAS & Tsinghua University

The discovery of integer quantum Hall effect (IQHE), a transport quantization phenomenon, heralded a revolution in condensed matter physics. This notwithstanding, IQHE is commonly conceived as being unrelated to chaos ubiquitous in Nature. Indeed, the salient characteristic of chaos – the sensitivity of system’s behavior to disturbances – is conceptually incompatible with the robustness of transport quantization in IQHE. Moreover, while chaos occurs even in simple one-body systems, IQHE is known to be a ground-state property of many-electron systems. Surprisingly, we discover in a canonical chaotic one-body system a Planck's quantum-driven phenomenon bearing a firm analogy to IQHE but of chaotic origin. Our finding indicates that rich topological quantum phenomena can emerge from chaos.

Reference

1. Y. Chen and C. Tian, Physical Review Letters 113 (Editors’ Suggestion), 216802 (2014).

Divergence of viscosity in jammed granular materials: a theoretical approach

Hisao Hayakawa, Kyoto University

A theory for jammed granular materials is developed with the aid of a nonequilibrium steady-state distribution function. The approximate nonequilibrium steady-state distribution function is explicitly given in the weak dissipation regime by means of the relaxation time. The theory quantitatively agrees with the results of the molecular dynamics simulation on the critical behavior of the viscosity below the jamming point without introducing any fitting parameter.
I will also talk on what is the real time scale near the jamming to discuss the validity of the theoretical analysis through the numerical simulation. This talk is mainly based on the following paper[1].

Reference

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Geometry-controlled fluctuation in obstructed diffusion

Jae-Hyung Jeon, KIAS

Recent advance of the single-particle tracking technique has enabled one to access real-time trajectories of single molecules in various crowded fluids including the living cells. It has been shown that at such crowded circumstances usually the diffusion of particles not only becomes anomalous but also exhibits significant trajectory-to-trajectory fluctuation. It is a fundamental issue to quantify and to understand these fluctuation, in particular, for the purpose of establishing theoretical framework for the analysis of experimental data obtained from the single-particle tracking. In this talk, within this single-trajectory scheme, we deal with two distinct anomalous diffusion processes occurring in obstacle-crowded space. In the first part the diffusion on percolation clusters is discussed based on Monte Carlo simulation results. We show that the population of finite clusters gives rise to geometry-specific non-vanishing fluctuation in the time-averaged mean squared displacement (TA MSD) of individual trajectories and that the fractality of the accessible space at a percolation threshold renders the slow convergence to ergodicity for TA MSD. In the second part the lateral molecular diffusion in protein-crowded lipid membranes is studied based on molecular dynamics simulation results. We find that the membrane proteins completely change the stochastic character of lateral diffusion. Thus the correlated gaussian processes of the fractional Langevin equation model, identified as the stochastic mechanism behind lateral motion in protein-free membranes, no longer adequately describe the lateral diffusion in protein-crowded membranes. It is shown that individual lateral motion attains strong non-gaussianity as well as the significant spatiotemporal fluctuation due to the geometrical effect of the membrane proteins.

Structural origin of fractional Stokes-Einstein relation in glass-forming liquids

Limei Xu, Peking University

In many glass-forming liquids, Fractional Stokes-Einstein relation (SER) is observed after the breakdown of SER above glass transition. As of yet, the origin of such phenomenon remains inclusive. Using molecular dynamics simulations, we investigate the breakdown of SER and the onset of fractional SER in a model of metallic glass-forming liquid. We find that SER breaks down when the size of the largest cluster consisting of trapped atoms starts to increase sharply at which the largest cluster spans half of the simulations box along one direction, and the fractional SER starts to follows when the largest cluster percolates the entire system and forms stable 3-dimentional network structures. Further analysis based on the percolation theory also confirms that percolation occurs at the onset of the fractional SER. Our results directly link the breakdown of the SER with structure inhomogeneity and onset of the fraction SER with percolation of largest clusters, thus provide a possible picture for the breakdown of SER and onset of fractional SER in glass-forming liquids, which is important for the understanding of dynamic properties in glass-forming liquids.

Keywords: Fractional Stokes-Einstein relation, dynamic heterogeneity, structural heterogeneity, metallic glasses

References

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Positive Feedback and Synchronized Bursts in Neuronal Culture

Chi-Keung Chan, Academia Sinica

Synchronized bursts (SBs) are common in neuronal cultures. Although the origin of SBs is still unclear, they have been studied for their information processing capabilities. Here, we investigate the properties of these SBs in a culture on multi-electrode array system. We find that characteristics of these SBs can be used to represent the different developmental stages of the cultures. A mean-field model based on short term synaptic plasticity and recurrent connections has been developed to understand these characteristics. A phase diagram obtained from this model shows that networks exhibiting SBs are in an oscillatory state due to large enough positive feedback provided by synaptic facilitation and recurrent connections. Our finding suggests that networks with SBs have too many recurrent connections and might have very little information processing capabilities.

Tracer dynamics in E-coli suspensions

Xinliang Xu, Beijing Computational Science Research Center

Active matter systems are driven out of equilibrium as each individual propels itself, as each fish swims in a school. At high concentration, active matter systems display collective dynamical behavior commonly known as 'flocking', as all individuals move in coordination. At phenomenological level, traditional theories assume an alignment interaction between individuals at a characteristic separation, predicting collective dynamics at concentrations relevant to the characteristic separation. However, the microscopic mechanism underlying this alignment is not well understood. Through close collaboration between experimental and theoretical studies of the motion of a passive ellipsoidal tracer suspended in an E-coli bath, here we try to unveil the interaction between bacteria in details.

Non-equilibrium steady-states in a tilted periodic potential

Pik-Yin Lai, National Central University

We report our recent experimental and theoretical studies on the non-equilibrium steady-state (NESS) dynamics of the diffusing colloids over a tilted periodic potential, in which detailed balance is broken due to the presence of a steady particle flux. A tilted two-layer colloidal system is constructed for this study. The periodic potential is provided by the bottom layer colloidal spheres forming a fixed crystalline pattern on a glass substrate[1]. The corrugated surface of the bottom colloidal crystal provides a gravitational potential field for the top layer diffusing particles. The measured mean drift velocity v(F,Eb) and diffusion coefficient D(F,Eb) of the particles as a function of F and energy barrier height Eb agree well with the exact solution of the one-dimensional Langevin equation[2]. From the exact results we show analytically and verify experimentally that there exists a scaling region, in which v(F,Eb) and D(F,Eb) both scale as ν'(F)exp[-Eb*(F)/kT], where the Arrhenius pre-factor ν'(F) and effective barrier height Eb*(F) are both modified by F. The Stoke-Einstein relation is shown to be violated to a different extend, depending on the driving or how far away from equilibrium[2]. Furthermore, the NESS probability distribution Pss is obtained exactly for the 1D case and compared well with the experimental results[3]. From the obtained exact solution of the 1D Smoluchowski equation, we develop an analytical method to accurately extract the 1D potential from the measured Pss(x). The experimental results are compared with the exact solution of the one-dimensional (1D) Smoluchowski equation and the numerical results of the 2D Smoluchowski equation.

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On the efficiency of a Brownian heat engine

Jae Dong Noh, University of Seoul

A heat engine extracts a work operating between two heat baths at different temperatures T_H and $T_C(< T_H)$. The efficiency η of a heat engine is measured by the ratio of the extracted work to the absorbed heat from a hotter heat bath. According to the thermodynamic second law, it is bounded from above by the Carnot efficiency $\eta_C = 1 - T_C/T_H$ that can be achieved only by the reversible heat engines. There are two general statements concerning the efficiency of nonequilibrium heat engines: (i) The efficiency of a heat engine operating at the maximum power could be universal and given by $\eta_{EMP} = 1 - \sqrt{1 - \eta_C}$. This result is derived in so-called endoreversible heat engines. (ii) The prabability density for the efficiency of a heat engine with a time-symmetric protocol is minimum at $\eta = \eta_C$, that is to say, the Carnot efficiency is least probable. This result is derived for systems with bounded energy. In this talk, we introduce an exactly solvable model for a Brownian heat engine. When one varies model parameters, the model acts as a heat engine or a heat pump. We find that the efficiency at maximum power is given by the universal form $\eta_{EMP} = 1 - \sqrt{1 - \eta_C}$ even though the engine is not endoreversible. This result indicates that the proposed form of η_{EMP} is more universal than expected. Relying on the solvability, we can calculate the large deviation function for the efficiency. The analytic solution shows that the Carnot efficiency is not least probable. This exemplifies the importance of the energy fluctuations in nonequilbrium systems.

Potts Antiferromagnetism in Two and Three Dimensions

Youjin Deng, University of Science and Technology of China

The Potts model-a simple statistical-mechanical system-plays an important role in the theory of critical phenomena and finds various application in condensed-matter physics and beyond. The ferromagnetic Potts model is now well understood, thanks to universality. In this talk, I shall report two recent studies of the q-state Potts antiferromagnet. I shall present argument as well as numerical evidence that the Potts antiferromagnet with arbitrarily large values of q can have a finite-temperature phase transition on some families of two-dimensional lattices. I will also demonstrate that the emergent continuous symmetry can occur in a series of three-dimensional Potts model.

[P1] Fluctuation of entropy productions under reduced description in coupled electric circuits

Kuan-Hsun Chiang, National Central University

We experimentally study the fluctuations of entropy production in two capacitively coupled RC circuits. Under the scenario when one of them is unrecognized, two reduced descriptions are proposed to map the dynamic of the accessible observable into single RC circuit. FT is violated under both descriptions.

[P2] Resolving the Gibbs paradox in small thermodynamic systems

Yuto Murashita, University of Tokyo

The Gibbs paradox originates from gas mixing, and is closely related to the foundation of statistical mechanics. Although the Gibbs paradox is often erroneously believed to be resolved by the quantum statistical mechanics, it is in fact resolved based on the assumption of extensivity in macroscopic thermodynamic systems. However, this resolution cannot apply to small thermodynamic systems because extensivity breaks down. We offer a resolution applicable to small thermodynamic systems based on our fluctuation theorem.

[P3] Statistical Mechanics of Undirected Unlabeled Connected Graphs

Daniel Kim, KAIST

We generate all of the connected undirected unlabeled graphs up to N≤12. We calculate the sum of non-negative eigenvalues of each graph. We consider this sum as the energy of a given graph and may correspond to Hueckel molecular orbital theory. We study the thermodynamic properties of the graphs within microcanonical ensemble figuratively.

[P4] Two-dimensional Bose-Einstein condensate under pressure

Wonyoung Cho, Sogang University

Evading the Mermin-Wagner-Hohenberg no-go theorem and revisiting with rigor the ideal Bose gas confined in a square box, we explore a discrete phase transition in two spatial dimensions. Through both analytic and numerical methods, we verify that thermodynamic instability emerges if the number of particles is sufficiently yet finitely large: specifically, $N \geq 35131$. The instability implies that the isobar of the gas zigzags on the temperature-volume plane, featuring supercooling and superheating phenomena. The Bose-Einstein condensation can then persist from absolute zero to the superheating temperature. Without necessarily taking the large N limit, under a constant pressure condition, the condensation takes place discretely both in the momentum and in the position spaces. Our result is applicable to a harmonic trap. We assert that experimentally observed Bose-Einstein condensations of harmonically trapped atomic gases are a first-order phase transition that involves a discrete change of the density at the center of the trap.

[P5] Time Irreversibility at Nonequilibrium Phase Transition

Pyoung-Seop Shim, University of Seoul

We investigate the emergence of macroscopic time irreversibility out of microscopic dynamics with broken detailed balance. We focus on a nonequilibrium system consisting of interacting Brownian particles in two dimensions. Particles in a thermal bath are acted on by a nonequilibrium velocity-aligning force that favors a collective motion. We find that the total entropy production is subextensive in the disordered phase without the collective motion. The entropy production becomes extensive in the ordered phase as the collective motion emerges. The scaling relations are derived between the critical exponents describing the entropy production rate density and those describing the order parameter.

[P6] Efficiency fluctuation in a linear heat engine model

Jong-Min Park, University of Seoul

The efficiency of a microscopic heat engine is stochastic as well as other thermodynamic quantities. Its long time behavior is described by a large deviation function (LDF) for its probability distribution. Recently, Verley et al. found a universal property of the LDF that the ideal Carnot efficiency is least probable [Nat. Commun. 5, 5721 (2014)]. This result was derived for systems with a bounded energy function and believed to be also valid for systems with an unbounded energy function. In order to investigate whether the universal property is valid in general systems, we introduce a heat engine model consisting of two particles which are coupled by a linear force. In this model, we calculate the LDF for the engine efficiency analytically. Our results show that the Carnot efficiency is not least probable any more.

[P7] Efficiency at Maximum Power of a Brownian Heat Engine without Endoreversible Condition

Hyun-Myung Chun, University of Seoul

We consider a coupled two-particle Langevin system as a heat engine. Each particle is respectively in contact with a heat bath at different temperatures and they are acted on by external driving forces. By tuning the external forces, the system can absorb heat from the hotter heat bath and work against the external force, hence the system can be regarded as an autonomous heat engine in steady state. For the case of the linear force, the exact form of the power and the efficiency in steady state are obtained analytically. Under a suitable condition, the efficiency at maximum power of this model is given by $1-\sqrt{T_2/T_1}$, which is called Curzon-Ahlborn efficiency. It has been understood that the Curzon-Ahlborn efficiency requires endoreversible condition. Our study shows that the Curzon-Ahlborn efficiency at maximum power can be reproduced without the endoreversible condition.

[P8] Opinion dynamics with time delay

Mina Kim, University of Seoul

To understand time-delayed properties observed in some social interactions of the opinion dynamics, we introduce a time-delayed voter model in a one-dimensional lattice and study its coarsening dynamics. In this model, a voter at each lattice site *i* has one of two opinions ($s_i = \pm$). At each time step, a voter on a randomly chosen site i copies opinion of one of its two nearest-neighbors at a time τ in the past ($s_i(t+\tau) \rightarrow s_j(t)$). Without delay, the voter model is dual to the coagulating random walks. We show that the time-delayed voter model is dual to coagulating sleeping random walks. Due to this duality, we can introduce a sleeping random walks (τ-SRWs). Using the duality, we find that the density of active bonds $\rho(t) \equiv \langle(1 - s_i(t)s_{i+1}(t))/2\rangle$ satisfies the scaling $\rho(t;\tau) = \rho_0(t/\tau^3)$ for $\tau > 1$, where $\rho_0(x \ll 1){\sim}1$ and $\rho_0(x \gg 1){\sim}x^{-1/2}$.

[P9] Impact of enzymatic gene coexpression of cellular networks on disease comorbidity

Gyeong-Gyun Ha, Inha University

The diverse interactions of numerous cellular ingredients in cellular networks have proved to be essential for understanding disease prevalence patterns. For instance, we have previously shown that the metabolites controlled by genetically-correlated enzymes are robust; the prevalence of their associated diseases is low. Yet, it remains elusive how the intricate connectivity pattern of cellular networks affects the relationship - a positive or negative correlation - between distinct diseases. Here we consider the distance between two metabolites at different layers of cellular networks - gene coexpression, protein interaction, and metabolism - and how much they can explain the correlation of distinct disease modules quantified by their comorbidity.

[P10] Analyses of dissipative dynamics in Langevin equation

Kyungsik Kim, Pukyong National University

[P11] Work fluctuations for a colloidal particle in a time-varying optical trap in analogy with gas in expansion and compression

Hyuk Kyu Park, UNIST

The fluctuation theorem provides a rigorous statistical rule for thermally fluctuating quantities such as work, heat, and entropy production in nonequilibrium thermodynamic processes. However, testing the theorem needs small systems where the fluctuations are more observable. Therefore, there are great difficulties in the experimental measurements. In this work, we investigate the motion of a colloidal particle trapped in a harmonic potential with time-varying stiffness. Here, we estimate the work done on the particle during compression and expansion by measuring its particle position in the first time. The resultant probability distributions of the work in both processes satisfy very well the Jarzynski equality and the Crooks fluctuation theorem. Because this isothermal expansion and compression process in a soft wall qualitatively mimics that in a rigid wall, it offers valuable tool for extracting work from micromechanical heat engines.

[P12] Percolation transitions under the Achlioptas processes in growing networks

Soomin Oh, Seoul National University

We study an explosive percolation transition under the so-called Achlioptas processes in growing networks. Every time step, a node is added to the system one by one, whereas in the static network, the number of nodes in the system remains constant during the evolution of the network. At each time step, a link is added between the two nodes that is optimally chosen to suppress the growth of a giant cluster among m candidate nodes randomly selected. It is known that the model with $m = 2$ undergoes an infinite-order phase transition. We find that when $m \geq 3$, the transition becomes second-order. Because small clusters are relatively rare at early stage of link-adding processes in the growing network compared with that in the static network, the suppression effect becomes relatively weaker. As a result, we find that the critical exponent β associated with the order parameter decreases with m algebraically in growing networks, whereas it does exponentially in static networks. We obtain other features of the explosive percolation transitions in growing networks as a function of m.

[P13] Molecular dynamics study on a nonequilibrium motion of a colloidal particle driven by an external torque

Donghwan Yoo, Myongji University

We investigate the motion of a colloidal particle driven out of equilibrium by an external torque. We use the molecular dynamics simulation that is alternative to the simulation based on the Langevin equation and is expected to mimic an experiment more realistically. We choose a heat bath composed of about a thousand particles interacting to each other through the Lennard-Jones potential and impose the Langevin thermostat to maintain it in equilibrium. We prepare a colloidal particle to interact with the particles of the heat bath also by the Lenard-Jones potential while any dissipative force and noise are not employed explicitly. We study the stochastic properties of the nonequilibrium fluctuation for work and heat produced incessantly in the steady state. We accurately confirm the fluctuation theorem for the work production. We also investigate the motion beyond the overdamped limit by varying the mass of the particle. We compare our result with a previous theoretical result in the overdamped limit based on the Langevin equation.

[P14] Efficient dynamic algorithm for mutually connected components

Deokjae Lee, Seoul National University

Mutually connected components (MCCs) play an important role as a measure of resilience in the study of interdependent networks. Despite their importance, an efficient algorithm to obtain the statistics of all MCCs during the removals of links has thus far been absent. Here, using a well-known fully dynamic algorithm for graph connectivity, we propose an efficient algorithm to accomplish this task. We show that the time complexity of this algorithm is approximately $O(N^{1.2})$ for random graphs, which is more efficient than $O(N^2)$ of the brute-force algorithm. We confirm the correctness of our algorithm by comparing the behavior of the order parameter as links are removed with existing results for three types of double-layer multiplex networks: (i) ER random graphs, and (ii) scale-free random graphs, in which degree of a node in one layer is stochastically the same as the one of the corresponding node in the other layer, and (iii) two-dimensional regular lattices. We anticipate that this algorithm will be used for simulations of large-size systems that have been previously inaccessible.

[P15] Biconnectivity of the cellular metabolism: A cross-species study and its implication for human diseases

Purin Kim, Seoul National University

The maintenance of stability during perturbations is essential for living organisms, and cellular networks organize multiple pathways to enable elements to remain connected and communicate, even when some pathways are broken. Here, we evaluated the biconnectivity of the metabolic networks of 506 species in terms of the clustering coefficients and the largest biconnected components (LBCs), wherein a biconnected component (BC) indicates a set of nodes in which every pair is connected by more than one path. Via comparison with the rewired networks, we illustrated how biconnectivity in cellular metabolism is achieved on small and large scales. Defining the biconnectivity of individual metabolic compounds by counting the number of species in which the compound belonged to the LBC, we demonstrated that biconnectivity is significantly correlated with the evolutionary age and functional importance of a compound. The prevalence of diseases associated with each metabolic compound quantifies the compounds vulnerability, i.e., the likelihood that it will cause a metabolic disorder. Moreover, the vulnerability depends on both the biconnectivity and the lethality of the compound. This fact can be used in drug discovery and medical treatments.

[P16] The origin of the criticality in meme popularity distribution on complex networks

Seok-Jong Park, Kyung Hee University

We study the origin of the criticality in meme popularity distribution of competition induced criticality model. From the direct Mote Carlo simulations of the models, we find that the meme popularity distribution, $P(n)$ satisfies a power-law, $P(n) \sim \alpha^n$ with $\alpha \sim 3/2$ if there is an innovation process. This power-law behavior of $P(n)$ is quite robust. On the other hand, if there is no innovation, then we find that $P(n)$ is bounded and highly skewed for early transient time periods, while $P(n) \sim \alpha^n$ with $\alpha \neq 3/2$ for intermediate time periods. For the systematic approach of the meme evolution, we exactly map the models into the position dependent biased random walk. Through this exact mapping, we find that the balance between the creation of new memes by the innovation process and the extinction of old memes is the key factor for the criticality with $\alpha = 3/2$. We show that the balance for the criticality sustains for relatively small innovation rate. Therefore, the innovation processes with significantly influential memes should be the simple and fundamental processes which cause the critical distribution of the meme popularity in real social networks.

[P17] Searching algorithm using true self avoiding walks

Seok-Jong Park, Kyung Hee University

To find optimal algorithm for information search on various networks, we study the algorithms based on true self avoiding walk (TSAW) and biased random walk (BRW). BRW based algorithm has been known to be optimal one among the algorithms using diffusion process. From the numerical simulations, we find that the mean first passage time τ for BRW algorithms depends on degree distribution and degree-degree correlation. The minimum value of τ, $\tau_{\min}$ satisfies the inequality $\tau_{\min} > 1$ for BRW algorithm. On the other hand we find that $\tau_{\min} > 0.5$ for TSAW algorithm. From the comparison between BRW algorithm and TSAW algorithm we find that τ/N for TSAW is always smaller than $\tau_{\min}/N$ for BRW and show that TSAW is more optimal algorithm than BRW in information search.

[P18] Statistical analysis of Rental of library books

Nam Jung, Inha University

We analyzed the data of the book rental of the Inha University's library, to obtain the features of the book rental and relationship between with user of library. This data is 2,816,624 of the book rental of the 10 years of data from 2004 to 2015. First, to determine the distribution of rental number and rental period based on the books and users to confirm its characteristics. And obtain an interval of distribution of the rental period to see how often Rental book and how often users use the library. Most of the distribution looks the exponential decrease, but they did not follow the power law. However, some of the distribution is follow the power law.

[P19] Percolation and cluster properties in spatial evolutionary prisoner's dilemma game on two-dimensional lattices

Woosik Choi, Kyung Hee University

We investigate percolation and cluster properties of cooperator (C) and defector (D) in spatial evolutionary prisoner's dilemma game (SEPDG) on two-dimensional lattices. Percolation properties depend on both the lattice structure and the temptation factor b. On the hexagonal lattices, C (D) clusters undergo the percolation transition when $1<b<3/2$, whereas a D cluster always percolates regardless of the initial C density piC. On the square lattices, when $1<b<4/3$ and $3/2<b<2$, percolation transitions occur. When $4/3<b<3/2$, a D cluster always percolates. On the triangular lattices, C clusters always percolate regardless of piC when $1<b<5/4$. When $5/4<b<3/2$, the percolation transitions occur. D clusters always percolate when $3/2<b<2$. By finite size scaling analyses the universality classes of all the percolation transitions belong to that of the random (ordinary) percolation regardless of the lattice structure. We also explain how the specific percolation properties arise from the evolution mechanism of SEPDG on a given lattice.

[P20] Reciprocity in spatial evolutionary public goods game on double-layered network

Jinho Kim, Kyung Hee University

We study spatial evolutionary public goods game (SEPGG) on double-layered random networks (DRNs) in which each node has one or zero interlink. In these networks imitation and interaction between individuals of opposite layers is established through interlinks. We use a biased imitation process: an agent update his strategy from the neighbor in the opposite layer with probability p. With probability $1 - p$, an agent update his strategy from the neighbor in the same layer. Based on the previous study of SEPGG on single layer [1], we construct 3 types of DRNs for $r_0 < 1$ depending on the average intradegree. When $r_0 > 1$, we find only one type of DRN can be defined. First, we consider SEPGG on the DRN with the same size. From numerical analyses, we find optimal point that has maximum cooperator density on each DRN. The effect of interlink on the DRN are also studied by changing the total number of interlinks. We also studied DRN with different sizes.

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[P21] Statistical Mechanics of Time-series Analysis for Meteorological Data via the Ising Model under Random Field

Yohei Saika, National Institute of Technology, Gunma College

Based on Bayesian inference using the expected a posterior (EAP) estimation regarded as statistical mechanics of the Ising model under random field [1], we forecast time evolution of meteorological variables, such as temperature, at a target point by making use of a set of time-series of meteorological variables which are similar to that of the target point selected due to the metric multi-dimensional scaling (metric-MDS) [2]. Using numerical simulation for a set of temperatures at 23 sampling points in Japan from 1st July to 31th July, 2011, we find that the present method succeeds in predicting time-series of temperature at the target point (Maebashi) by using the time-series of temperatures both at the target point and 5 sampling points (Kanuma, Kiryu, Isezaki, Kamisatomi) appropriately selected due to the metric-MDS, if we control fluctuations around the MAP solution appropriately tuning hyper-parameters corresponding to the coupling constant and the external field of the Ising model. Also, we find that the time-series of temperature can be predicted accurately by utilizing those 5 time-series of temperatures selected above, even if we do not use information on the target data.
In addition, similar results are obtained by the replica theory using the infinite-range model. Then, we apply this strategy for power demand prediction in the National Institute of Technology, Gunma College as a typical small-scale organization [3].

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[P22] Numerical Study of CDMA Multiuser Modulation and Demodulation Robust to the Correlation between Data13

Hirao Masahiro, Okayama University