Spatiotemporal Pattern Formation in
Biological and Active Matters
March 2nd (Sun), 2014

Program & Abstracts

Promoters
Center for Simulation Science, Ochanomizu University
&
MEXT Project "Synergy of Fluctuation and Structure:
Quest for Universal Laws in Non-equilibrium Systems"

Place
6th floor of Graduate School Building, Ochanomizu University
(人間文化棟6階)
**Program**

9:00 - 9:30  Registration

9:30 - 9:35  Opening remarks

9:35 - 10:25  Markus Bear
Modelling collective motion and pattern formation of gliding and swimming bacteria

10:25 - 10:45  Robert Grossmann
Collective dynamics of active particles: From microscopics to coarse-grained theories

11:00 - 11:40  Takuji Ishikawa
Pattern formation in a suspension of squirmers

11:40 - 12:00  Azusa Kage
Spontaneous pattern transition in bioconvection of Chlamydomonas reinhardtii

12:00 - 12:20  Hirofumi Wada
Forces and shapes in radish sprouts during phototropism

13:00 - 13:50  Poster Session

14:00 - 14:40  Akatsuki Kimura
Meiotic cytoplasmic streaming: a self-organized flow in the C. elegans embryo

14:40 - 15:10  Hiroyuki Ebata
Swimming droplets driven by surface wave

15:10 - 15:30  Shuji Ishihara
Morphodynamics of a migrating cell
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16:00 - 16:40  Sergio Alonso
   A poroelastic model for mechanochemical waves and pattern formation in Physarum polycephalum

16:40 - 17:00  So Kitsunezaki
   Dynamics of a growing elastic string

17:00 - 17:20  Hiroyuki Kitahata
   Elliptic particle motion driven by surface tension gradient

17:20 - 17:40  Hiroshi Kori
   Mechanism of Jetlag approached with a multi-oscillator model for the circadian master clock

18:00 - 21:00  Reception & Poster session

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1. Hironobu Noguchi
   Collective dynamics of active filament complexes

2. Takeshi Kano
   A Simple Model for Self-organization of Heterogeneous Elements
   Inspired by Friendship Formation

3. Sayaka Fujisawa
   Emergent wisdom in microorganisms with chemotaxis

4. Yusuke Maeda
   Opto-thermal approach for pattern formation of soft biological materials

5. Yuki Koyano
   Oscillatory Motion of a Self-driven Particle in a 1-D Finite Region

6. Kaori Sugimura
   Lifetime of spatiotemporal chaos

7. Miho Sako
   Propagation of excitable waves in heterogeneous excitable media
8. Chiyoko Kageyama
   A novel model for aggregating cellular slime molds

9. Yasuaki Kobayashi
   Re-entrant transition in noisy coupled oscillators

10. Megumi Tsubakida
    Simulation of vein formation based on optimization

11. Saho Chikugo
    Study of jet lag using a simple model for the circadian clock

12. Makoto Yomosa
    Analysis of coordinated behaviors in pigeon flocks

13. Yuki Izumida
    Coarse-graining oscillator networks

14. Sadato Yamanaka
    Non-equilibrium soliton-like dynamics of traveling bands in deformable self-propelled particles

15. Hideyuki Kato
    Two-population model for circadian master clock

16. Mami Shigedomi
    Simulation of microparticles in fluid

17. Daiki Nishiguchi
    Turbulent State of Janus Particles in a Crowded Situation

18. Martin Robert
    Metabolic synchronization and pattern formation in E. coli

19. Ken Nagai
    Experimental realization of swarming by short-range nematic interaction

20. Tomo Kurimura
    Autonomous oscillation of a micro object under DC voltage and the effect of noise

21. Shun Watanabe
    Translational motions of phase separated droplets near critical point with local heating.

22. Fumiko Ogushi
    Reliability of cell fate decision using a simple multi-cell model
Modelling collective motion and pattern formation of gliding and swimming bacteria
Markus Bear (Physikalisch-Technische Bundesanstalt)

Experimental studies of colonies of gliding bacteria on a substrate as well as of suspensions of swimming bacteria have revealed many complex patterns stemming from coordinated collective motion of the involved cells. Examples include “living clusters” [1,2] and rippling of myxobacteria [3] gliding on a substrate as well as turbulent vortex patterns of swimming Bacillus subtilis in two [4] and three dimensions [5].

In this talk, I will describe different model approaches for these phenomena. For gliding bacteria, an individual based model of self-propelled rods [6] and related kinetic descriptions [7] explain the transition to clustering above a critical surface density of the bacteria. For bacterial suspensions, a phenomenological continuum model is introduced [8] and shown to be in good agreement with experimental findings [3,4]. Finally, the relation between “microscopic” agent-based models and continuum descriptions will be briefly discussed.


Collective dynamics of active particles: From microscopics to coarse-grained theories
Robert Grossmann (Physikalisch-Technische Bundesanstalt)

In this talk we will derive a coarse-grained description of self-propelled particles with aligning interactions in 2D. Based on the formulation of a nonlinear Fokker–Planck equation, we derive a kinetic description of the system dynamics in terms of equations for the Fourier modes. This approach allows for the derivation of a hydrodynamic theory by performing a closure at the level of the second Fourier mode of the one-particle density function. We show that the general form of the equations is in agreement with the theory formulated by Toner and Tu. We analyze the stability of spatially homogeneous solutions and compare our analytical predictions with results of individual-based simulations. They show good agreement for sufficiently large densities.

Pattern formation in a suspension of squirmers
Takuji Ishikawa (Tohoku University)

Some recent research efforts have demonstrated the importance of biomechanics in understanding collective motions of microorganisms. Although various levels of modeling have been proposed so far, none
of them could solve both near- and far-field fluid dynamics precisely while keeping number of swimmers enough large. In this study, we solve both far- and near-field fluid dynamics precisely and investigated the collective motions of hydrodynamically interacting microorganisms in a mono-layer.

The model microorganism is assumed to be spherical or ellipsoidal and propels itself by generating tangential velocities on its surface, i.e. a squirmer. Three types of microorganisms were modeled by varying the surface velocity: a puller, a pusher, and a neutral swimmer. The flow field around a squirmer can be assumed as Stokes flow. We use a boundary element method based on the double-layer representation, which is suitable for parallel computing. We use a half-mesh by exploiting the symmetry of the problem and introduced a multipole expansion for far-field fluid dynamics. For the parallel computing, we apply full-GPU implementation. Our developed method achieved 590GFLOPS.

We analyzed interactions of 100 squirmers with various swimming mode and aspect ratio in a mono-layer. The results showed that the neutral swimmers tended to orient in one direction and formed ordered structures. In the suspension of pullers, the swimming velocity of squirmers in a cluster decreased as the aspect ratio was increased. In the suspension of pushers, on the other hand, vortex structure appeared more strongly as the aspect ratio was increased. We clarified that the difference in the collective swimming could be well explained by the near-field fluid dynamics. The knowledge obtained in this study should be useful to understand wide variety of collective motions generated by micro-swimmers in nature.

**Spontaneous pattern transition in bioconvection of Chlamydomonas reinhardtii**

Azusa Kage (Ochanomizu university)

Bioconvection is a collective motion occurring from the action of gravity and swimming behavior of microorganisms. A spatially periodic pattern of density spontaneously emerges in the suspension of motile microorganisms, the scale of which (mm or cm order) is about 100 times larger than that of the individual microorganisms (10-100 µm order). This pattern of density corresponds to vertical flows of the microorganisms: when viewed in vertical section, the microorganisms sink as blobs in the dense region and move negative-gravitactically upwards in the sparse region.

Although the onset of bioconvection pattern formation has been extensively investigated both theoretically and experimentally, little attention has been paid to the long-term behavior of bioconvection. A previous study found spontaneous phase transition in bioconvection of the unicellular, biflagellated green alga *Chlamydomonas reinhardtii*. This theoretically-unpredicted phase transition, termed specifically "pattern transition," is characterized as a sudden breakdown and subsequent re-formation of the pattern with a decreased wavelength. Focusing on the pattern transition, we have experimentally explored the long-term behavior of bioconvection of *C. reinhardtii*.

The newly developed two-axis view method revealed that when the pattern transition occurred, the population of *Chlamydomonas* moved downwards. This downward movement suggests the enhancement of gyrotaxis in the pattern transition. Gyrotaxis, specifically observed in some microalgae including *Chlamydomonas*, is the tendency for the organisms to be pulled into the center of the downward flow. Experiments with flagellar mutants revealed that bioconvection of the mutant *ida1* with impaired flagellar waveform showed rather different behavior from that of the wild type, while bioconvection of another mutant *oda2* with normal waveform and lower beat frequency did not. Individual swimming analysis showed that both of the mutants swam much more slowly than the wild type. These results imply that flagellar waveform, not swimming speed nor beat frequency, might dominate bioconvection behavior of *C. reinhardtii*.

**Forces and shapes of radish sprouts during phototropism**

Hirohumi Wada (Ritsumeikan University)

Phototropism, the directed bending of plants in response to unilateral light, is a typical example that demonstrates that plants move. It is well known that a detailed study on phototropic movement of plants by Charles Darwin eventually led to the discovery of the first plant hormone, auxin. In principle, phototropic curvature is understood to emerge due to differential growth between shaded and illuminated sides of seedlings. While the Cholodny-Wend model provides a dominant explanation on how the auxin regulates this differential growth pattern, other models are still challenging its validity. Here, from a
somewhat different perspective, we would like to ask the following questions: What is the exact shape of a plant during its phototropic bending, and how much force do they generate to realize such shape changes? To explore these, we have first observed phototropic movements of radish sprouts, and obtained the kinematic information about shapes of the sprouts during phototropism. We then developed an elastic rod theory based on the Kirchhoff rod equations by incorporating growth-induced active (physiological) stress generations. In order to describe the slow growth mechanics, the model is also assumed to possess morphoeelastic character that may express the underlying irreversible creeping of cell walls, similar to the classical Lockhart-Ortega model. By combining this theoretical model with our preliminary experimental results, we can roughly estimate the magnitude of the active stress that may enable the sprout to bend towards the light.

Meiotic cytoplasmic streaming: a self-organized flow in the C. elegans embryo

Akatsuki Kimura (Cell Architecture Laboratory, National Institute of Genetics)

Cytoplasmic streaming is a massive movement of intracellular materials observed in various cell types. In most cases, the direction of the flow is pre-determined due to the polarity of the cell. In contrast, the direction of a meiotic cytoplasmic streaming in the Caenorhabditis elegans embryo is unlikely pre-determined. It has been shown that the microtubule and its associated motor proteins drive the streaming. However, how the activities of individual motor protein are organized into the cell-wide collective streaming without an obvious cue for its direction remains mystery. We conducted live cell imaging combined with gene knockdown analyses and image processing to characterize the streaming quantitatively. Based on the experimental observations, we propose a model to explain the emergence of the collective streaming. We conducted a numerical simulation of our model and demonstrated that the simulation recapitulated important features of the streaming. I would like to propose that this cytoplasmic streaming offers a new example of spatiotemporal pattern formation in biological systems.

Swimming droplets driven by surface wave

Hiroyuki Ebata (Chiba University)

The problem "How to swim in the viscous fluid" has attracted attention for a long time. Because of large viscous force, micro-swimmers must keep non-reciprocal deformation for the migration, such as beating flagella and cilia. There are also those who use surface waves to migrate, e.g. Planarian and Opalina. In non-living systems, swimmers of liquid-crystal elastomer or artificial flagella migrate by means of traveling wave of deformation through the body.

When an oil droplet on viscous oil bath is vibrated vertically, the standing wave (Faraday wave) is excited only on the droplet-air interface, and the droplet is elongated [1]. We found that a water droplet on oil bath showed rich dynamics due to Faraday wave, such as spinning, rotation, straight motion, and squirming motion. The droplets swim by using the surface wave on liquid-liquid interface, and the strong coupling between deformation and migration was observed. The motion of the droplet is easily reproduced by controlling the frequency, acceleration, and viscosity. Thus, migrating droplet forced by the surface wave provide an easily-controlled experimental system of soft active objects.


Morphodynamics of a migrating cell

Shuji Ishihara (The University of Tokyo)

Cells show diversity of morphological dynamic such as polar, keratocyte-like, and complex amoeboid motions, depending on the cell types, environmental conditions, etc. Recently, it becomes well recognized that spatio-temporal pattern dynamics of some molecular systems, such as phosphoinositide lipids, occurs
in cell and are responsible for the regulation of active filaments that drive cell morphodynamics and migration. However, it is still unclear how the spatio-temporal patterns are organized by the underlying molecular interactions, and how the pattern regulates the morphological dynamics of cells. In the presentation, we will report the dynamics of phosphoinositide lipids in Dictyostelium [1]. Two-dimensional chemical wave is behind their amoeboid motion, where appearance and disappearance of phase singularity represent the transition among patterns. A mathematical model to connect molecular interactions with cell shape change dynamics is studied, in which some typical pattern in experimental observations are reproduced. We also give a simple model of cell morphodynamics for possible explanation of diversity of cell dynamics [2].


A poroelastic model for mechanochemical waves and pattern formation in Physarum polycephalum

Sergio Alonso (Physikalisch-Technische Bundesanstalt)

Mechanochemical waves control the reorganization on protoplasmic droplets of Physarum polycephalum, where the local deformations of the droplets are coupled to oscillations on Calcium concentrations. Similarly to other living cells, the cytoplasm on protoplasmic droplets is an active material with both viscoelastic and liquid properties. We incorporate the active stress into a two-phase model of the cytoplasm which accounts for the spatiotemporal dynamics of the cytoskeleton and the cytosol. The cytoskeleton is described as a solid matrix that together with the cytosol as interstitial fluid constitutes a poroelastic material. The mechanical model for the poroelastic material is coupled to a simple chemical oscillator giving rise to an active poroelastic model. The prediction from the stability analysis and numerical simulations of the resulting model are compared with the mechanochemical waves observed on protoplasmic droplets of Physarum polycephalum.

Dynamics of a growing elastic string

So Kitsunezaki (Nara Women's University)

Elastic strings, such as vines of plants and rod-shaped bacteria, change their shape with growth in length, and such elastic string-like behaviors are also observed in microscopic discrete systems such as polymer chains.

In this study, we investigated on an ideal growing chain of linear springs with restoring forces for bending [1]. This string was assumed to grow exponentially in balance with viscous drag forces on a 2-dimensional space.

We focus on the relations among three levels of description: the original discrete system, its continuous approximation, and the stiff limit for stretching. After we discuss the breaking condition for the continuous approximation, we apply the center-manifold reduction to the continuous equation. We obtain the equation of an elastic string with a length constraint, which is the same with that proposed by Goldstein et al.[2,3], as the reduced equation.

We also report a result of numerical simulations of the reduced equation. The size of a cluster of a growing string begins to oscillate spontaneously after the string grows sufficiently.

Elliptic particle motion driven by surface tension gradient

Hiroyuki Kitahata (Chiba University)

The coupling between deformation and motion in a self-propelled system has attracted broader interest [1], especially in the field of "active matter". In order to investigate the features of such interaction, the effect of the particle shape on the direction of motion is focused. We consider a model system in which surfactant molecules diffuse from the particle and reduces the surface tension around it. The symmetric concentration profile of the surfactant molecules can exhibit spontaneous symmetry breaking, which leads to a one-directional motion. In fact, a circular camphor particle floating at water surface can exhibit spontaneous motion while it diffuses surface-active camphor molecules to the water surface [2]. In the present study, thus, we adopt the camphor-water system. As for the particle shape, we focus on the most fundamental but nontrivial deformation from a circle, i.e., an elliptic shape. Therefore, we consider an elliptic camphor particle which diffuses camphor molecules for investigating the effect of the particle shape on spontaneous motion. We analytically calculated the force working on the camphor particle using the perturbation method. We concluded that the symmetric spatial distribution of camphor molecules at the water surface becomes unstable first in the direction of a short axis, which induces the camphor particle motion in the short direction. Experimental results also support the theoretical analysis. From the present analysis, we suggest that an elliptic particle supplying surfactant molecules to the water surface can exhibit translational motion only in the short-axis direction [3,4].


Mechanism of jet lag approached with a multi-oscillator model for the circadian master clock

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. It is 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. To uncover the mechanism of jet lag symptoms, we constructed a mathematical model consisting of three oscillators for the circadian master clock (the suprachiasmatic nucleus, SCN), in which each oscillator represents a functionally distinct region in the SCN. Our model uncovers the mystery that lack in neurotransmitter results in the quick response to jet lag.

** Abstracts (poster presentations) **

**Collective dynamics of active filament complexes**
Hironobu Noguchi, Shuji Ishihara (The University of Tokyo)

Collective dynamics of active matters have been well studied both theoretically and experimentally. In these model, however, the shape of each particles is too simplified compared to the real components in nature (e.g. mitotic spindles and microtubules connected to basal body of a cilia). So we take complex shapes into account in modeling and studied collective pattern formations of “active filament complexes”. We confirmed the new type of global order that indicates both ferromagnetic and density waves in the MD simulation.

**A Simple Model for Self-organization of Heterogeneous Elements Inspired by Friendship Formation**
Takeshi Kano (Tohoku University), Koichi Osuka (Osaka University), Toshihiro Kawakatsu (Tohoku University), Akio Ishiguro (Tohoku Univ./ JST CREST)

Self-organization of heterogeneous elements, in which dynamical order emerges from local interactions among elements having different characters, is widely observed in nature and social systems such as cellular networks [1], economic systems [2], and pedestrian flows [3]. It has attracted attention to researchers and has been extensively studied in various fields. However, their underlying “core” mechanism has not yet been clearly understood.

Our final goal of the study is to clarify the essential mechanism underlying self-organization of heterogeneous elements from a unified viewpoint. For this purpose, we here propose a minimal mathematical model of self-organization inspired by the process of friendship formation. In human society, people having different characters interact with each other by properly balancing their self-assertion and compromise: then, dynamical order emerges. Hence, friendship formation is an attractive phenomenon for investigating the essential mechanism for self-organization of heterogeneous elements.

For constructing the model, we drew inspiration from swarm oscillator model [4], in which dynamical order emerges from local interactions among motile elements that have internal states. In our model, characters of individuals are expressed by using “phase”, and the position and the phase of each individual are adjusted in response to the phase difference and distance between the other individuals. Simulation results showed that various dynamic patterns such as linear chain pattern, grid pattern, membrane pattern, and exocytosis-like pattern emerged via the change of a small number of parameters. Thus, our finding made a great step in understanding the essential mechanism for self-organization of heterogeneous elements.


**Emergent wisdom in microorganisms with chemotaxis**
Sayaka Fujisawa, Hiroshi Kori (Ochanomizu University)

There are many living organisms that carry out collective motion, such as fish, birds, and cellular slime mold. Animals and microorganisms may act in groups, cooperating each other for a certain purpose. Sardines and zebras move in groups to defend themselves, and wild geese and swans fly in groups to save energy. The aims of this study were to make a mathematical model of collective motion and to reveal the merit of collective motion. In this study we proposed a mathematical model to analyze the effect of...
collective motion when microorganisms try to find food. Many animals and microorganisms have chemotaxis, by which they migrate toward the increase in the concentration of a specific chemical substance to find food or other things. As a model of chemotaxis, we assume that each organism has four receptors, which receive a smell molecule from food. If a receptor receives a smell molecule, the organism turns toward the direction of the receptor. The model stochastically gets the information about the location of food. We performed simulations of our constructed model. When there is no interaction between organisms, it took a long time to find food. In contrast, in the presence of interaction, they arrived at food more rapidly. We found that there is a certain interaction strength that minimizes the time to arrive at food. All together we found that collective motion enhanced the efficacy for seeking food. With the mutual interaction, a population of organisms acts as a big unit, and this unit has more receptors than single organisms. Therefore the group can find food rapidly.

**Opto-thermal approach for pattern formation of soft biological materials**

Yusuke Maeda (Kyoto University, The Hakubi Center)

Atoms and molecules move along a gradient of temperature, which is called thermophoresis or the Soret effect. Thermophoresis depletes a polymer such as polyethylene glycol (PEG) from the hot region and builds a concentration gradient [1]. In such a solution, solutes of small concentration experience thermophoresis and the restoring force dependent on PEG gradient of large concentration [2]. Under focused laser heating, DNA and RNA as solutes localize as a ring-like structure which diameter monotonically decreases with their size following a behavior analogous to gel electrophoresis [3]. Moreover, I show that the motion of small RNA depends on its stem-loop structure [4]. Thus trapping and selection of molecules could be physically feasible in a simple way relying on temperature gradient. Furthermore, I have developed this experimental method to work in two dimensional spaces and time [5]. The steering of laser traps colloids, DNA, and living cells in designed two-dimensional patterns. I also show the opto-thermal approach helps controlling spatio-temporal pattern formation in a group of cells.


**Oscillatory Motion of a Self-driven Particle in a 1-D Finite Region**

Yuki Koyano, Hiroyuki Kitahata, Tatsunari Sakurai (Chiba University)

Self-driven motions have been paid more and more attention to in terms of “active matter”, where free energy is transformed into kinetic energy. A camphor grain at water surface is a famous example of the self-driven particle. If a camphor grain is floated on the water, camphor molecules spread at water surface and reduce the surface tension because they work as surfactants. If the concentration field has anisotropy around the camphor grain, then surface tension also has anisotropy. Thus, the camphor grain is driven in the direction with the largest surface tension. In the previous work, the self-driven particle in a 1-dimensional infinite region is investigated analytically and experimentally[1].

In this study, to clarify the effects of the field boundary, we have analytically investigated what motion can be exhibited when the self-driven particle is put in a 1-dimensional finite region. The field boundary can affect the camphor grain motion through the field. We found that oscillating motion appears as a final state in a finite region instead of uniform motion in an infinite region. This is because the field translational symmetry is broken in the finite system. We also found that the particle motion changes from rest at the system center into oscillation around it when a parameter such as the system size or viscosity is changed. In other words, the stability of the center position is depending on parameters. We regarded this change in particle motion as bifurcation and investigated its bifurcation structure by reducing the model equations around the center position of the system.

Lifetime of spatiotemporal chaos

Kaori Sugimura, Hiroshi Kori (Ochanomizu University)

An excitable medium is known to show spatiotemporal chaos where the cores of spiral waves spontaneously generate or annihilate. Depending on initial conditions and parameter values, such chaotic dynamics arise only as a transient process. In this case, the system eventually arrives at a steady quiescent state after a transient time, which we refer to as lifetime. A previous numerical study demonstrated that the lifetime increases exponentially with the system size [1], but its mechanism has not been fully understood.

To elucidate its mechanism, using the same model, we investigate the dependence of various dynamical properties of excitable media on the system size. For both periodic and free boundary conditions, cores of the spiral waves (namely, defects) continue to generate or annihilate, and the number of defects vanishes when the system falls into a steady state. We numerically found that the dependences of generation and annihilation rates are functions of the number of defects, and their functional forms vary with the system size. We analytically showed that the dependence of lifetime on the system size holds to be exponential under a mild condition for their functional forms.

This type of the spatiotemporal chaos is believed to occur in the heart in fibrillation, in which the electric waves cannot properly propagate across the heart well. As its clinical treatment, maze operation is often performed, in which the heart wall is cut into pieces. We will discuss the implication of our study to this clinical treatment.


Propagation of excitable waves in heterogeneous excitable media

Miho Sako, Hiroshi Kori (Ochanomizu University)

The atrial fibrillation occurs when electric waves persistently propagate independently of electric signals from the heart pacemaker. In this study, we aim to reproduce and analyze this phenomenon numerically. We considered various geometries for the media and found the condition for an excitable wave to loop. We will discuss the implication of our results on heart arrhythmia.

A novel model for aggregating cellular slime molds

Chiyoko Kageyama, Hiroshi Kori (Ochanomizu university)

When cellular slime molds starve, they begin to aggregate. In the course of aggregation, each cell periodically emits a certain chemical substance (cAMP) and moves along the gradient of the chemical substance. Conventionally, the aggregation process is described by Keller-Segel model, but in this model, the oscillation of the chemical substance is not considered. Therefore, we propose a mathematical model that takes into account the oscillation of the chemical substance and investigate the critical difference between Keller-Segel model and our model. In both models, depending on parameter values and initial conditions, the population may aggregate into one group or split into multiple groups. We found that the nonlinear term that exists only in our model facilitates the formation of big groups. Therefore, we conclude that oscillatory emission contributes to the aggregation process.

Re-entrant transition in noisy coupled oscillators

Yasuaki Kobayashi (Hokkaido University), Hiroshi Kori (Ochanomizu University)

Synchronization phenomena are abound in biological systems, and there are many practical cases where synchronization must be accomplished under noisy circumstances. In such cases, it is generally considered that strong coupling would overcome noise and thus give stable synchronization, but in this...
study we show that that is not always the case.

We introduce a system of two identical phase oscillators, where one oscillator is subjected to Gaussian white noise and is affected by another freely revolving oscillator with the same natural frequency. In order to consider strong-coupling cases, we adopt a Winfree-type phase model, where the coupling term consists of the response function and an interaction function, which are chosen such that the time-averaged system shows stable synchronization with sufficiently strong coupling.

In this system, we find that, although the two oscillators synchronize as increasing the coupling constant, they start to de-synchronize by undergoing phase slips as further increasing it, and that the rate of the phase slip increases as the coupling constant increases. We show that this can be understood in the picture of a particle in a time-periodic potential, where a sufficiently strong noise intensity is required for escaping the state from the synchronization solution. The threshold of the re-entrant transition is given semi-analytically. We also study a system of two Brusselators coupled in the same way to confirm that the same type of instability occurs in limit cycle oscillators. A generalization to a system of network-coupled noisy oscillators is also discussed.

Simulation of vein formation based on optimization
Megumi Tsubakida, Hiroshi Kori (Ochanomizu University)

Many biological organisms have beautiful patterns, such as animal coat patterns and spiral form of seashells. It is expected that such patterns have some merit for survival and are evolutionarily obtained. In this presentation, we propose a numerical optimization method to reproduce the pattern of leaf vein. We considered that a primal role of leaf vein is to carry water to the entire leave. By setting a cost function characterizing this role, we numerically optimized the form of leaf vein under a fixed vein length. We succeeded to produce both tree-like structures and loop structures. The similarity between the obtained patterns and real leave veins will be discussed.

Study of jet lag using a simple model for the circadian clock
Saho Chikugo, Hiroshi Kori (Ochanomizu University)

Our daily activity is controlled by the circadian clock. We suffer from jet lag because of this endogenous clock. In this study, we considered a simple mathematical model for the circadian clock and investigated the response to a abrupt phase shift of light-dark cycles. We mainly focus on the dependence on the natural period of the circadian clock.

Analysis of coordinated behaviors in pigeon flocks
Makoto Yomosa Tsuyoshi Mizuguchi (Osaka Pref Univ), Yoshinori Hayakawa (Tohoku Univ)

For a long time now, the problem of how homing pigeon flocks return to their loft from distant points has fascinated researchers. Apart from how each individual knows a route to its loft, it is interesting to note that individuals cooperate with each other to return to their nest. Some researchers equipped pigeons with GPS devices and analyzed the experimental data regarding group decision-making. Nagy et al. obtained three-dimensional position data of pigeon flocks using high-precision GPS devices. By calculating the directional correlation delay time, they characterized a leader-follower relationship between each flock member. They revealed the hierarchical structure of the leader-follower relationship and the relation between the hierarchical order and the averaged relative position in the flocks.

In this poster, we reanalyzed the same data used in Nature 464, 890 (2010) from the viewpoint of the spatio-temporal structure of the formation of flocks rather than the hierarchical order. Even if the personal relationship between each member is ignored, the internal structure of the flock is well characterized, i.e., each individual tends to maintain its relative position in a circling flight. We characterized this tendency statistically by focusing on the relative
position between pairs of individuals. Furthermore, we analyzed the relationship between the relative position and the leader-follower relation. The result not only is consistent with that of a previous study but also quantitatively clarifies the relation between the dynamical variables of the individuals. According to the analysis, the velocity of each individual is meaningful for determining the flock configuration.

**Coarse-graining oscillator networks**

Yuki Izumida, Hiroshi Kori (Ochanomizu University)

Natural phenomena emerge from complicated interactions between many variables in general. However, it is common that the essence of those phenomena can be deduced from the dynamics only of a few effective variables. A coarse-graining method is a powerful tool for elucidating such effective variables and deriving closed dynamical equations for them.

In this talk, we present a novel coarse-graining method applicable to phase equations that describe dynamics of general oscillator networks. To be more specific, our method enables us to reduce the number of equations by performing a nonlinear transformation of the phase variables based on the information of eigenvalue problem of a linearized system around a phase-locked solution. We demonstrate our method by applying it to (i) oscillators on a random graph that exhibit a saddle-node bifurcation in the absence/presence of external forcing, and (ii) multi-clustered oscillators that exhibit a Hopf bifurcation.

**Non-equilibrium soliton-like dynamics of traveling bands in deformable self-propelled particles**

Sadato Yamanaka (The University of Tokyo), Takao Ohta

Collective pattern formations have long been focused in the studies of non-equilibrium dynamics of self-propelled particles. Vicsek model, a seminal dynamical model of self-propelled particles, shows traveling bands emerging just below the transition point from ordered to disordered state [1]. Band-shaped cluster of concentrated ordered particles travel in the dilute disordered region. The direction of velocity of the band is normal to the interface between the ordered and the disordered region. This kind of traveling band was reported in several types of dynamical model. The mechanisms of the band formation have not, however, been resolved from a viewpoint of dynamics far from equilibrium.

In our numerical study, collective dynamics of deformable self-propelled particles are investigated, where the particles elongate depending on the migration velocity [2]. The aim of our study is to reveal whether or not traveling bands can be stable when we impose that the migration velocity is an increasing function of the local density.

As a result of detailed investigation, the local density dependence of migration velocity destabilizes the homogeneous ordered state, and the traveling bands having similar shape to that in Vicsek model emerge spontaneously. Furthermore, we found a counterintuitive phenomenon in which these bands are stable upon head-on collisions similarly to solitons in integrable systems. Recently, an experimental study revealed that non-chemotactic mutants of cellular slime mould D.discoideum show soliton-like behavior [3]. The similarities and the differences between the experiments and our results will also be discussed in our presentation [4].

**Two-population model for circadian master clock**

Hideyuki Kato, Hiroshi Kori (Ochanomizu University)

Circadian rhythm is controlled by oscillations of clock genes in the suprachiasmatic neuclus (SCN). Synchronous oscillations of the clock genes is robust but once the light/dark (LD) cycle is rapidly shifted, the orchestration of oscillatory clock genes is immediately broken up, which might be the origin of the jet lag symptom. The previous experiments suggested that the disorder in the SCN derives from the different nature of two subdivisions of the SCN. In the experiments, one of them (subdivision A) can adopt new schedules of the LD cycle more rapidly than the other (subdivision B). However, it is still unclear what happens in the subdivision B. In order to clarify the low adoptability of the subdivision B, we construct a SCN model, which includes two populations in the subdivision B, with Kuramoto phase oscillators whose frequencies are heterogeneous and analyze its response to the jet lag. For better modeling of the SCN, we also analyze the response of the one-population model to compare the two-population one. As a result, only the two-population model can reproduce the jet lag symptom as observed in the experiments of rats and mice in which the 8-hour LD cycle shifting induces the strong jet lag symptom. Our results suggest that the heterogeneity of the intrinsic frequency of the clock gene oscillations leads to grouping of two populations in the subdivision B of the SCN.

**Simulation of microparticles in fluid**

Mami Shigedomi, Yusaku Nagata, Hiroshi Kori (Ochanomizu University)

It is known that swimming microorganisms show various collective motion and patterns. Hydrodynamical interaction between microorganisms is responsible for such complex dynamics. When modeling such microorganisms, we may employ the Stokes approximation because inertia can be neglected. In this study, using the stokeslet for the calculation of flow, we first simulated the dynamics of dropping particles in a fluid. Our numerical results are in a reasonable agreement with known experimental results. Then, using the stresslet, we simulated a group of micro swimmers and investigated the collective motion of the swimmers.

**Turbulent State of Janus Particles in a Crowded Situation**

Daiki Nishiguchi, Masaki Sano (The University of Tokyo)

Recently, some experiments have been conducted to investigate the universal behavior of active suspensions showing turbulent structures[1][2][3]. In the former study[1], the power spectrum of the velocity filed of dense bacterial suspension has been measured. In this power spectrum, the power law behavior was found and this state is referred to as “active turbulence”. These kinds of experiments have been done only using bacteria.

In order to figure out whether this power law in the spectrum is a universal feature of active turbulence or not, we conducted experiments using non-biological self-propelled Janus particles. Our Janus particles are asymmetrical colloidal particles made by coating hemisphere of polystyrene beads with metal, which exhibit self-propelling motion under AC electric field.

In a very crowded situation, Janus particles collide frequently and reorient themselves. Because Janus particles are propelling by making flows around themselves, hydrodynamic interactions are remarkable when they pass by each other. These interactions lead to the emergence of a turbulent state.

Here we present the power law behavior seen in the power spectrum of dense suspension of Janus particles. We explain the origin of this spectrum by analyzing what kinds of structures Janus particles are forming. Some of their behaviors can be understood by hydrodynamic interactions obtained by solving Stokes equation analytically.

Metabolic synchronization and pattern formation in E. coli

Martin Robert (Tohoku University)

The bacterium Escherichia coli (E. coli) is an excellent model to study fundamental cellular processes. While it is often considered as a unicellular organism, E. coli is known to form biofilms and other structured cellular aggregates. Previously, the amino acids valine and aspartate have been connected with biofilm and some types of pattern formation in E. coli. Although not yet clearly demonstrated, metabolic interactions between cells might therefore provide a mechanism for the formation of complex spatiotemporal patterns. We, and others have previously shown that in well-mixed continuous cultures, respiratory oscillations can spontaneously emerge, suggesting that population-wide synchronized temporal activity is possible. Using capillary electrophoresis mass spectrometry (CE-MS) we analyzed the dynamics of several extracellular metabolites during these oscillations. The dynamics of multiple secreted metabolites and respiratory activity suggest temporal sorting of metabolic activities. Here we also discuss the possible relevance of these findings to spatiotemporal pattern formation in E. coli. While additional experiments are required to confirm these links, spatiotemporal pattern formation and collective behavior in E. coli and other bacteria are likely connected to dynamical changes in metabolic activity and extracellular metabolites may act as important mediators of this process.

Experimental realization of swarming by short-range nematic interaction

Ken Nagai (The University of Tokyo), Yutaka Sumino (Aichi University of Education), Hugues Chaté (CEA Saclay), Kazuhiro Oiwa (NICT)

It is expected that there is universality in collective behaviors of active matters such as swarming of fish or birds. To investigate the universal features of swarming, Vicsek, et al. described swarming using the symmetry of the system. Although only the short-range orientational interaction was considered in their mathematical model, the swarming phase with the global order of the direction of motion emerged in two dimensional space.

We experimentally tried to realize the swarming by short-range orientational interaction using the self-propelled microtubules driven by the dyneins grafted on a glass plate. Two running microtubules were nematically aligned when they collided. In other words, there was the short-range nematic interaction between the microtubules. When the density of the microtubules was larger than the critical value, the swarming of the microtubules were observed. In one of swarming phases, the microtubules formed the hexagonal lattice of vortices. The swarming phase with global nematic orientational order was also observed.

We measured the trajectory of an isolated microtubule and found that the correlation time of curvature was long. Focusing this characteristics, we analyzed the swarming of the microtubules using the agent-based model with a finite correlation time of the change rate of the moving direction. To clarify the effect of the correlation time, we considered only the symmetry of the motion in the mathematical model as Vicsek, et al. did. As a result of the numerical simulations, we found that the hexagonal lattice of vortices was formed when the correlation time was long enough and the global nematic order emerged with short correlation time (Y. Sumino, et al. (2012)). We compared the experimental results with the numerical results, concluding that the correlation time is a significant parameter in the swarming of the microtubules.
Autonomous oscillation of a micro object under DC voltage and the effect of noise

Tomo Kurimura, Masatoshi Ichikawa (Kyoto Univ), Masahiro Takinoue (Tokyo Tech Univ), Kenichi Yoshikawa (Doshisha Univ)

Recently, it was reported that an aqueous droplet in an oil phase exhibited rhythmic back-and-forth motion under stationary dc voltage on the order of 100 V. Here, we demonstrate that the threshold voltage for inducing such oscillation is successfully decreased to the order of 10 V through downsizing of the experimental system. Notably, the threshold electric field tends to decrease with a nonlinear scaling relationship accompanied by the downsizing. We derive a simple theoretical model to interpret the system size dependence of the threshold voltage. This model equation suggests the unique effect of additional noise, which is qualitatively characterized as a coherent resonance by an actual experiment as a kind of coherent resonance. Our result would provide insight into the construction of micrometer-sized self-commutating motors and actuators in microfluidic and micromechanical devices.

Translational motions of phase separated droplets near critical point with local heating.

Shun Watanabe, Kentaro Oshima, Kenichi Yoshikawa (Doshisha University)

We inserted focused laser into a liquid-liquid phase separated solution near the critical point. The results is phase separated droplets comes into the local heating point of which temperature is higher than critical temperature. The velocity of the translational motion of a droplet does not related with the composite of the droplet. The velocity depends on the radius of the droplet. We also found that the droplet showed Marangoni convection inside of the droplet. Thus, we concluded that the translation motion of the droplet was caused by the Marangoni convection due to the difference of interface tension on the droplet between near side and far side from the local heating point.

The difference of the interface tension increases with the difference of temperature. Especially, near the critical point, the difference becomes maximized, because the interface tension becomes 0 at the critical temperature. Basically, Marangoni convection is hard to be observed smaller than sub millimeter scale. This system enhances the Marangoni effect by using such characteristic of the critical point and effectively converts thermal energy into translational force to drag a object.

Reliability of cell fate decision using a simple multi-cell model

Fumiko Ogushi, Hiroshi Kori (Ochanomizu University/ JST CREST)

Cell differentiation is one of the most fundamental ability of a biological cell and it is considered to be controlled by the expression level of certain genes. Recent experimental studies indicate that cell-cell interaction plays an important role in the cell differentiation process.

To understand the basic mechanisms of cell differentiation, we introduced a simple multi-cell model with inhibitory cell-cell interaction. Each cell $i$ differentiates in a deterministic way with a dynamical equation $du_i/dt = -4(u_i^3 - u_i) - k(\langle u \rangle - u_i)$ where $u_i$ ($i = 1, \ldots, n$) and $k$ denote the state variable and the intensity of cell-cell interaction, respectively. $\langle u \rangle (= \sum u_i / n)$ denotes the averaged state of all the cells. Let us consider a cell population in an undifferentiated state in initial condition, the system reaches equilibrium state and all the cells differentiate into two states. In this model, the symmetric double-well potential is skewed by the averaged state of all other cells with coupling constant $k$. Cell $i$ feels different potential depth depending on its surroundings and the initial condition of $u$ decides the fate of the entire system (proportion $R$ of the number of cells in one state to the total number of cells in equilibrium). On another front, the range of $R$ is bounded by the reciprocal of the intensity $k$ of cell-cell interaction.

To discuss reliability of fate of the entire system differentiating into two states, we introduced an interaction range and we found that there is an optimal length (number) in this context. In this presentation, we will discuss about more details and a case with "reset" operation for our model.