アクティブマター研究会2019

日時：
2019年1月11日（金）、12日（土）
於：
明治大学 中野キャンパス

Active Matter Workshop 2019

VENUE:
Meiji University (Nakano Campus)

DATE:
11 - 12 January, 2019

主催 | Organiser

共同利用・共同研究拠点　明治大学
先端数理科学インスティテュート（MIMS）現象数理学拠点

MEXT Joint Usage/Research Center Meiji University
"Center for Mathematical Modeling and Applications" (CMMA)

世話人 | Organisation committee

江端　宏之（九州大学） Hiroyuki Ebata (Kyushu Univ.)
北畑　裕之（千葉大学） Hiroyuki Kitahata (Chiba Univ.)
末松 J. 信彦（明治大学） Nobuhiko J. Suematsu (Meiji Univ.)
多羅間充輔（京都大学） Mitsusuke Tarama (Kyoto Univ.)
山口　智彦（明治大学） Tomohiko Yamaguchi (Meiji Univ.)

問い合わせ | Contact

email: active2019@googlegroups.com

Program

2019/1/11 Fri.

10:00 - 10:20	Registration
10:20 - 10:30	Opening
10:30 - 11:10	**FL** Masahiro Takinoue (Tokyo Institute of Technology) "Phase-separated DNA microdroplets controlled by base sequence information"
11:10 - 11:50	**FL** Yasuhiro Ikezoe (Nippon Institute of Technology) "Study of motion of the object caused by various energy conversion processes in materials"
11:50 - 13:10	Lunch
13:10 - 14:55	**ST1**
14:55 - 15:20	Break
15:20 - 16:00	**PL** Ryoichi Yamamoto (Kyoto Univ.) "Active matter modeling: swimming microorganisms / crawling and proliferating cells on substrate"
16:00 - 16:40	**FL** Akihisa Shioi (Doshisha Univ.) "Design of chemical systems with semblance of life"
19:00 -	Banquet

* Special lecture entitled "How do we describe the dynamic performance of materials - A case study for cracking problems -" is given by Prof. Yasumasa Nishiura (Tohoku Univ.) from 17:10 to 18:50, after the first day of the workshop.

2019/1/12 Sat.

9:30 - 10:10	**FL** Ben Nanzai (Shizuoka Institute of Science and Technology) "*Physicochemical approach for reaction in spontaneous running droplet on glass substrate*"
10:10 - 10:30	Break
10:30 - 11:30	**ST3**
11:30 - 13:00	Lunch
13:00 - 14:30	**ST4**
14:30 - 14:50	Break
14:50 - 15:30	**FL** Yoshiyuki Kageyama (Hokkaido Univ.) "Light-driven limit-cycle self-oscillation and autonomous swimming of azobenzene-assembly under photostationary state"
15:30 - 16:10	**FL** Yusuke Hara (AIST) "Development of self-oscillating gel actuators for application to microfluidic devices and soft robots"
16:10 - 16:20	Closing

==========

Presentation time

PL: Plenary lectures [40 min each, including discussions]
FL: Focused lectures [40 min each, including discussions]
ST: Short talks [10 min presentation + 5 min discussions for each]

基調講演

Plenary Lectures

1月11日（金）10:00 – 11:00

Ryoichi Yamamoto

(Kyoto Univ.)

Active matter modeling: swimming microorganisms / crawling and proliferating cells on substrate

企画講演
Focused Lectures on "Active matter in chemistry”

1月11日（金） 10：30 – 11：10
Masahiro Takinoue (Tokyo Institute of Technology)
“Phase-separated DNA microdroplets
controlled by base sequence information”

1月11日（金） 11：10 – 11：50
Yasuhiro Ikezoe (Nippon Institute of Technology)
“Study of motion of the object caused by
various energy conversion processes in materials”

1月11日（土） 16：00 – 16：40
Akihisa Shioi (Doshisha Univ.)
“Design of chemical systems with semblance of life”

1月12日（土） 9：30 – 10：10
Ben Nanzai (Shizuoka Institute of Science and Technology)
“Physicochemical approach for reaction
in spontaneous running droplet on glass substrate”

1月12日（土） 14：50 – 15：30
Yoshiyuki Kageyama (Hokkaido Univ.)
“Light-driven limit-cycle self-oscillation and autonomous swimming
of azobenzene-assembly under photostationary state”

1月12日（土） 15：30 – 16：10
Yusuke Hara (AIST)
“Development of self-oscillating gel actuators
for application to microfluidic devices and soft robots”

Light-driven limit-cycle self-oscillation and autonomous swimming of azobenzene-assembly under photostationary state

Yoshiyuki KAGEYAMA
Condensed Matter Chemistry Laboratory,
Department of Chemistry Faculty of Science, Hokkaido Unmiversity

Due to the development in polymer science in light-responsive azobenzene polymer, especially AzoLCE (azobenzene liquid crystalline elastomer) in which the self-align properties of azobenzene motif play a key role for macroscopic motion, it became possible to make materials showing designed light-triggered movements. Small assembled-machines equipped with such azobenzene polymer for a light-driven actuator have been processed, and showed wonderful locomoting dynamics under light-control. However, perhaps the participants in the active matter symposium cannot be satisfied by such tiny and clever machines, because (a) we usually use more useful assembled-machines, such as vehicle, train, and airplane, (b) the requirement of intermittent light is not so autonomous, and (c) the motion, which always follows the owner's control, is not active but passive.

Unfortunately, the author has not understand the meaning of "active"-matter until now. However, the author knows the active-matter require energy for their motion, and it can works against potential gradient with consumption of the received energy. Here, the thermodynamics is a keyword. Unfortunately again, the thermodynamics of such open-system including information is quite difficult to understand for the author, and therefore it is difficult to distinguish that a motion is active or not. However, materials, which can continuously move directionally in plane potential surface against resistance with conversion of acquired energy, but without under direction of external information, are active materials. It means that active materials should have ability of self-sustained, self-directed, and self-regulated energy conversion to mechanical energy. We know such materials and their motions have been reported, for instance, self-propelling Janus-particle, and self-walking BZ-hydrogel. Especially when we aim to create such materials using multi-molecular system, it seems synchronization of involving molecules is required, and the requirement may be satisfied by the combination of nonlinear dynamics.

Following our study on a unique light-triggered cooperative dynamics of oleate-azobenzene mixed lyotropic liquid crystals,[1,2] we successfully found self-oscillatory flips of crystalline assembly under steady blue-light irradiation (**Figure 1**).[3] The self-continuous motion is the resultant of photoreaction velocity regulation due to the photoreaction-induced forward and backward phase transitions (**Figure 2**). Since (a) the photoreaction direction is considerable to be governed by the molecular alignment in the assembly, (b) there are critical isomer-ratios for the subcritical transitions (the fact also means the reversible phase transition shows hysteresis), and (c) the metaphases involving the dynamics are pseudo-stable, the periodic route is a limit-cycle. The time-profile of the motion of an assembly shown in **Figure 3** and its analyzed result shown in **Figure 4** indicate clearly that the assembly converts light energy for its periodic flipping motion. In other

ショートトーク
Short talks

Short Talks 1

2019年1月11日（金）
13:10 – 14:55

1. **Mitsusuke Tarama**
   “Mechanochemical modeling of crawling cells”
2. **Simon K. Schnyder**
   “Control of cell colony growth by contact inhibition”
3. **John Jairo Molina**
   “Modeling the mechanosensitivity of fast-crawling cells”
4. **Estelle Gauquelin**
   “Emergence of large scale propagative signals during epithelial cell migration”
5. **Hiroyuki Ebata**
   “Cell-type dependent durotaxis on micro-elastically heterogeneous gels”
6. **Alexandre Baccouche**
   “Seeing the shape of a molecular program”
7. **Anthony Genot**
   “Molecular programming with DNA”

Mechanochemical modeling of crawling cells

Mitsusuke Tarama[1], Kenji Mori[2], Ryoichi Yamamoto[2,3]

[1]Fukui Institute for Fundamental Chemistry, Kyoto University
[2]Department of Chemical Engineering, Kyoto University
[3]Institute of Industrial Science, The University of Tokyo

Despite the diversity of cell types, biological cells, which are the basic unit of living creatures, share common structures. They are composed of a number of proteins, lipids, and sugar, which form stable structures such as cellular membranes. At the same time, a living cell is at a far-from-equilibrium state. Complex chemical reactions take place inside a cell, the information of which is converted to mechanical forces by molecular motors. Consequently, a cell exhibits various dynamics spontaneously.

Spontaneous motion is a key property of active matter, which generates force in itself by consuming potential energy. Such force vanishes in total because of the law of action and reaction. To achieve a net directional motion under the force-free condition, symmetry breaking plays a fundamental role.

Typical mechanism of cell crawling is thought of as a cycle of four processes: 1) protrusion of the leading edge, 2) adhesion of the leading edge to the substrate, 3) deadhesion of the trailing edge from the substrate, and 4) contraction of the trailing edge. In our previous study [1], we clarified the importance of the order of these four basic processes by introducing a simple model crawling cell composed of two elements connected by a viscoelastic spring. The spring contains a linear actuator that elongates and shrinks in time, representing the protrusion and contraction. Since the force generated by the actuator acts on the two elements symmetrically, the force-free condition is satisfied. In addition, the substrate friction characteristics switches between the adhered stick state and the deadhered slip state, modelling the adhesion and deadhesion processes. The phase shift between the stick-slip transitions in the substrate friction of the two elements breaks the symmetry, which enables the cell to achieve a net migration.

In this presentation, we consider an extension of the model to two dimensions where the cell is modelled by many of such subcellular elements connected by viscoelastic springs. In order to control the actuator elongation and the stick-slip transition of the substrate friction of each subcellular element, we couple the mechanical model with reaction-diffusion equations that represent intracellular chemical reactions. By introducing mechanical and chemical dependence of the substrate friction, we show that the cell changes migration behaviour including the direction.

References

1. M. Tarama and R. Yamamoto, *J. Phys. Soc. Jpn.* **87**, 044803 (2018).

Control of cell colony growth by contact inhibition

S. K. Schnyder[1], J. J. Molina[2] and R. Yamamoto[2]

[1] *Fukui Institute for Fundamental Chemistry, Kyoto University, Kyoto, 606-8103, Japan*

[2] *Department of Chemical Engineering, Kyoto University, Kyoto 615-8510*

Contact inhibition is a cell property that limits the migration and proliferation of cells in crowded environments. However, its role in the emergence of the collective behaviors observed experimentally is not clear. Here we investigate the growth dynamics of a cell colony, see panel a), composed of migrating and proliferating cells on a substrate using a minimal model that incorporates the mechanisms of contact inhibition of locomotion and proliferation. We find two distinct regimes. At early times, when contact inhibition is weak, the colony grows exponentially in time, fully characterized by the proliferation rate, see panel b). At long times, the colony boundary moves at a constant speed, determined only by the migration speed of a single cell and independent of the proliferation rate, see panel c). Our model illuminates how simple local mechanical interactions give rise to contact inhibition, and from this, how cell colony growth is self-organized and controlled on a local level.

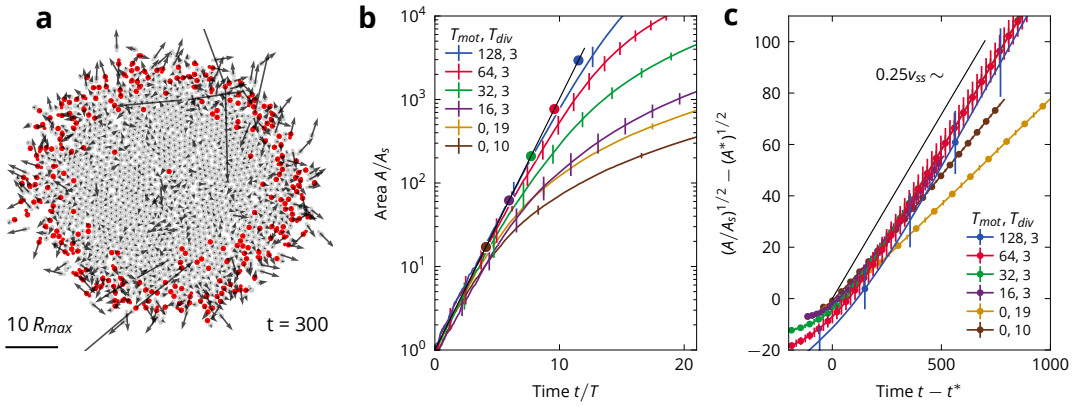


Figure: a) Snapshot of a cell colony. New cells are marked in red, and cell velocities given as arrows. b) Size of the colony versus time *t*. The exponential asymptote is marked by a black line. Both migrating cells and non-migrating cells follow the same growth law at early times. c) Scaling plot exposing the collapse of the growth dynamics at long times for the migrating cells.

Acknowledgements

We acknowledge support by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant No. 26610131, 16H00765, and 17H01083.

References

1. S.K. Schnyder, Y. Tanaka, J.J. Molina, and R. Yamamoto, “Collective motion of cells crawling on a substrate: Roles of cell shape and contact inhibition”, Scientific Reports 7, 5163 (2017).
2. S.K. Schnyder, J.J. Molina, and R. Yamamoto, “Control of cell colony growth by contact inhibition”, arXiv:1810.00546.

Modeling the mechanosensitivity of fast-crawling cells

John J. Molina[1], **Ryoichi Yamamoto**[1,2]
[1]Dept. of Chemical Engineering, Kyoto University
[2]Institute of Industrial Science, The University of Tokyo

The ability of cells to actively respond to signals received from their environment is crucial for all biological systems and can be exploited to design novel cell sorting assays, as well as bio-materials capable of controlling the proliferation and differentiation of stem cells.

In this work, we focus on the mechanosensitive response of fast-crawling cells (e.g., dictyostelium, HL-60, keratocytes) over cyclically stretched substrates. Experiments have shown that the cells reorient in a cell-specific manner[1]. While much is known regarding the response of slow-crawling cells, our understanding of how fast-crawling cells reorient is still limited. From experiments we know that they prefer a perpendicular orientation, but the mechanism behind this has yet to be fully determined[1].

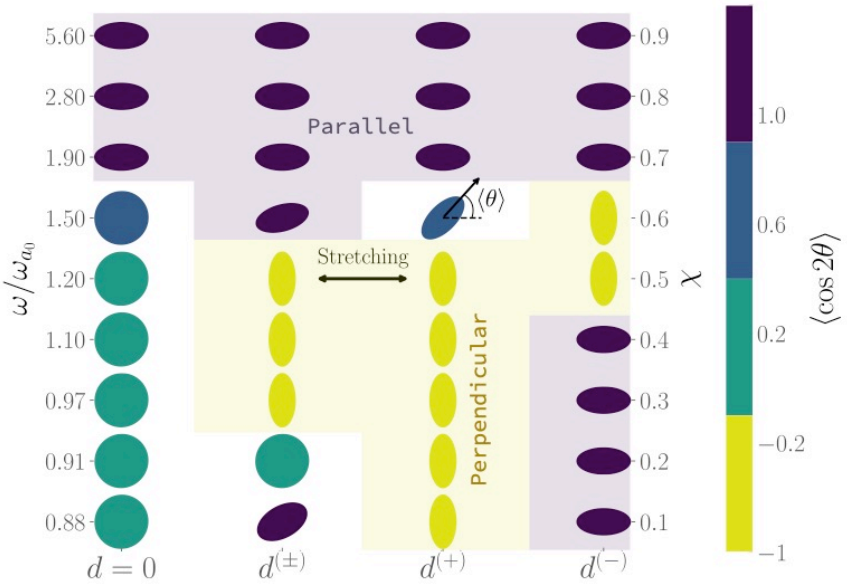


Fig. 1 Phase-diagram showing the steady-state orientation of cells over cyclically stretched substrates for different adhesion response functions d and stretching frequencies ω.

To address this problem, we have developed a computational model capable of relating the mechanosensitive response of such fast-crawling cells to their sub-cellular dynamics when placed on a cyclically stretched substrate[2]. We consider the dynamics of the cell membrane, the actin-cytoskeleton, and the focal adhesions. Depending on which process is being probed by the stretching, and the type of coupling with the substrate, we observe considerably different realignment dynamics. In particular, we show that an asymmetry in the stability of the adhesions during extension/compression can align the cells at specific orientations (Fig. 1), and can account for the realignment observed experimentally. Our results and proposed simulation method can be used to interpret current experiments and to propose new ones, in order to gain a better understanding of how cells react to mechanical cues from their environment.

Acknowledgements
We acknowledge fruitful discussion with N. Yoshinaga to determine the source of the instability, as well as useful feedback and suggestions during the preparation of this manuscript from K. Sadakane, K. Yoshikawa, M. Turner, T. Taniguchi, and S. Schnyder. This work was supported by the Japan Society for the Promotion of Science Wakate B (17K17825) and Kakenhi (17H01083) Grants, as well as the JSPS bilateral joint research project.

References

1. C. Okimura, K. Ueda, Y. Sakumura, Y. Iwadate: “Fast-crawling cell types migrate to avoid the direction of periodic substratum stretching”. *Cell Adh. Migr.* **10**, 331-341 (2016).
2. J.J. Molina and R. Yamamoto: “Modeling the mechanosensitivity of fast-crawling cells” *Soft Matter* (in press)

Emergence of large scale propagative signals during epithelial cell migration

Estelle Gauquelin[1], **Marc-Antoine Fardin**[1], **René-Marc Mège**[1], **Benoît Ladoux**[1,2]

[1]Institut Jacques Monod (IJM), Université Paris Diderot- Paris 7, CNRS UMR 7592, Paris
[2]Mechanobiology Institute, National University of Singapore, Singapore

Collective cell migration is a fundamental phenomenon in biology involved in processes such as morphogenesis and tissue repair. During collective cell migration, various mechanisms play a role in the regulation of tissue expansion including cell proliferation. It can indeed disturb the dynamic organization of cell monolayers. This project is thus focusing on the study of collective cell behaviors and their link with cell proliferation. We developed an *in vitro* assay using micro-fabrication techniques to compare the migrating behavior of cell monolayers with and without cell proliferation (Figure 1.a), and to measure the local effects of cell division on their environment in migrating and non-migrating tissues.

We first measured velocities within the monolayer on a global scale. In the case of migration without proliferation, patterns of high velocities appear in the monolayer, propagating from the front of migration toward the bulk (Figure 1.d) [1]. Those velocity waves can propagate on distances as long as few millimeters within the tissue. When there is proliferation, the waves are unable to propagate on long distances and are rapidly damped within the monolayer (Figure 1.c). Our study of local velocity fields surrounding division events during migration shows that there is a competition between velocities induced by division events and the global velocity of migration, suggesting that divisions create defects that prevent the propagation of the velocity waves towards the back of the migrating monolayer. Moreover the wave ability to propagate is dependent of the level of confinement of the tissue and of the initial cell density within the monolayer, and rely on the contractility of the cell actin cytoskeleton.

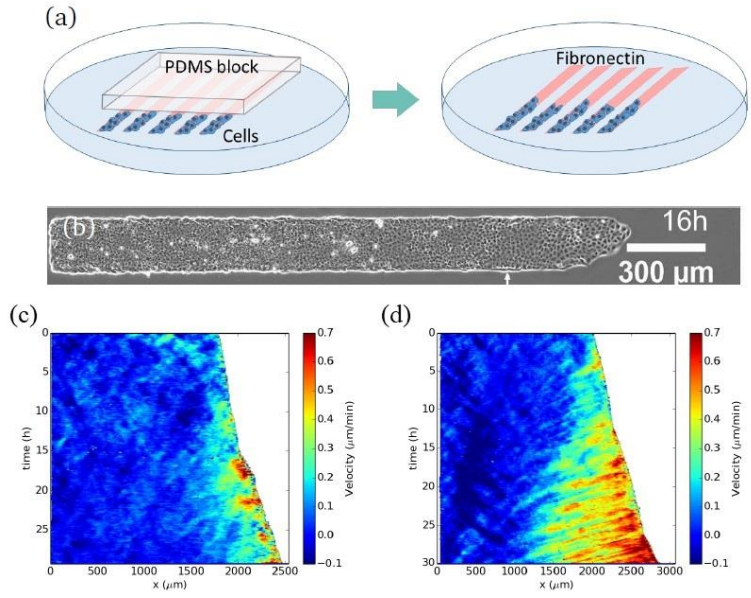


Figure 1. (a) Schematic representation of the protocol. Cells are first cultured overnight on a segment of the micropatterned lines restricted by a block of PDMS (left), and then the block is removed and the cells are free to invaded the fibronectin substrate. (b) Snapshot of a monolayer 16 hours after the start of the experiment. The white arrow indicates the location of the front at t = 0, that is when recording starts. (c) Spatiotemporal diagrams of the velocity with divisions. (d) Spatiotemporal diagrams of the velocity without divisions.

References

1. S. Tlili, E. Gauquelin, B. Li, O. Cardoso, B. Ladoux, H. Delanoë-Ayari and F. Graner: "Collective cell migration without proliferation: density determines cell velocity and wave velocity", *Royal Society Open Science* **5**, 172421 (2018).

Cell-type dependent durotaxis on micro-elastically heterogeneous gels

Hiroyuki Ebata, Kousuke Moriyama, Thasaneeya Kuboki, and Satoru Kidoaki
Institute for Materials Chemistry and Engineering, Kyushu University

In general, the mechanical properties of living body are heterogeneous. For examples, macroscopic elasticities of the organs vary from 10^2 to 10^9 Pa depending on the type of those, such as nerve, muscle, and bone. Even in the same organs, microscopic spatial distribution of the elasticity is also heterogeneous. It should be noted that the cells in our body lives in such a heterogeneous environment of mechanical property, and spontaneously migrate in microscopic spatial heterogeneity of the matrix elasticity. Therefore, to characterize, predict, and manipulate the cell migration in the living tissues, it is essential to reveal the migratory behavior on elastically heterogeneous environment.

When the soft and stiff substrates are joined, cells exhibit directional migration from soft to stiff region, which is called as durotaxis[1]. The elasticity gradient required to induce the durotaxis has positive dependence on the elasticity of the soft region[2]. For fibroblast cells and mesenchymal stem cells (MSCs), soft domain with the elasticity of 10 kPa requires 100 – 300 kPa for the hard domain to induce the durotaxis[2, 3]. On the other hand, many living tissue (~ 63 %) have the elasticity of more than 10 kPa on the average, while the local variation of elasticity is up to tens of kPa for most tissues. According to these observations, strong durotaxis seems not to be induced in the most of living tissues, and occurs only in the limited condition. Since the sizes of soft and hard domains in living tissue typically range from 10 to 1000 μm, cells should sense microscopically heterogeneous filed of elasticity[3, 4]. However, while migration on broad elasticity gradient or a single steep elasticity jump has been focused, the size effect of soft and stiff domain, i.e., microscopic heterogeneity, on the durotaxis has not been systemically investigated.

In this study, we aimed to get principle insight for the role of microscopic heterogeneous filed of elasticity on the durotaxis in a model system of living tissues. By systematically changing the domain sizes of micro-elastically stripe patterned gels that mimic the fibrous tissues, we examined the durotaxis of fibroblast cells and MSCs on heterogeneous substrates that have elasticity distribution of typical fibrous organs (10 ~ 70 kPa). We found that the different type of cells have a preferable domain size to induce strong durotaxis with the small elasticity gradient. Fibroblasts accumulated in wider hard stripes, while MSCs localized in narrower hard stripes. To explain the domain-size dependent durotaxis, we provided the cell migration model by incorporating the response of pseudopodia to the elasticity gradient into the shape-fluctuation based cell migration model[5]. The model well reproduced the domain-size and cell-species dependent durotaxis (Fig. 1). The model suggested that the dynamics of the pseudopodia on the elasticity boundary is a key to determine preferable domain size for durotaxis.

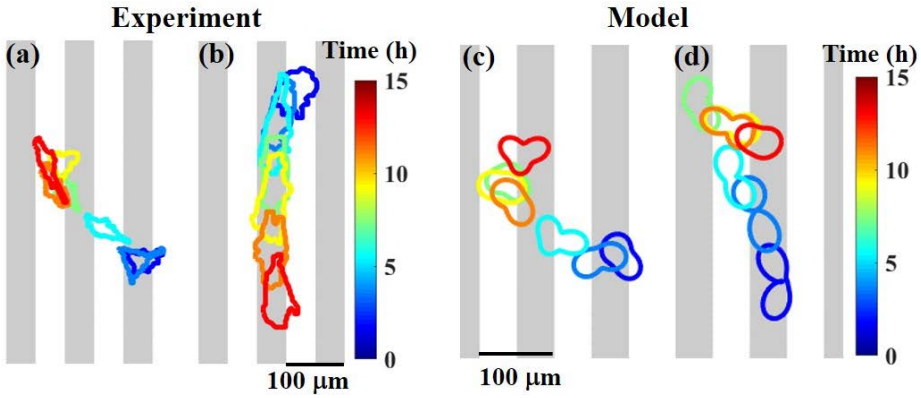


Figure 1. (a, b) Examples of the cell-shape dynamics of (a) a fibroblast and (b) a MSC on patterned gels with 100 μm period. Gary areas indicate hard domains. (c, d) cell-shape dynamics calculated from the model for (c) a fibroblast and (d) a MSC on patterned gels with 100 μm period.

References

1. C-M. Lo, H-B. Wang, M. Dembo, and Y-l. Wang, *Biophys. J.* 79, 144 (2000).
2. K. Moriyama and S. Kidoaki, *Langmuir* (2018).
3. T. Kawano and S. Kidoaki, Biomaterials 32, 2725- 33 (2011). Biomaterials 34, 7563-7564 (2013).
4. A. Ueki, and S. Kidoaki, Biomaterials 41, 45-52 (2015).
5. H. Ebata, et al. *Sci. Rep.* 8, 5153 (2018).

Seeing the shape of a molecular program

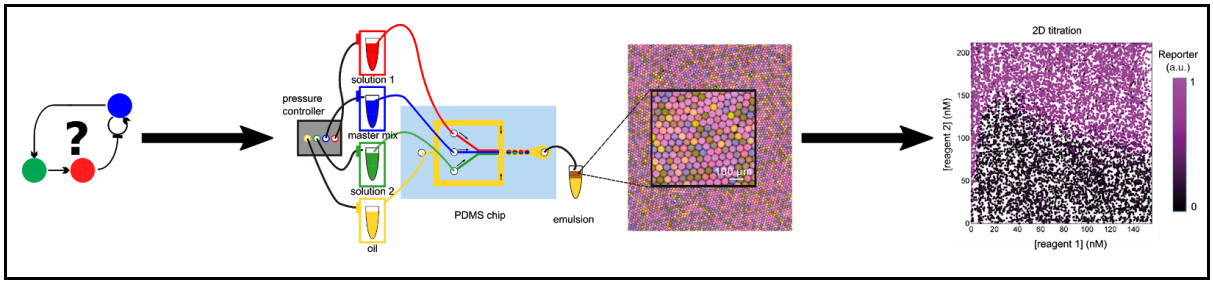
Alexandre Baccouche[1], Yannick Rondelez[2], Teruo Fujii[1], Anthony Genot[1]
1 LIMMS/CNRS-IIS, Institute of Industrial Science, The University of Tokyo, Japan
2 Laboratoire Gulliver, ESPCI, PSL Research University/CNRS, Paris, France

Unicellular organisms like bacterias are computing at the molecular level by processing sets of stimuli into an appropriate response through chemical reactions. For instance in chemotaxis, where a bacteria computes and travels along a spatial gradient of nutrients to find the best source of food. The emerging field of molecular programming aims at programming molecules in a similar way a bacteria would do, in order to control complex mechanisms and engineer new functions.

Our objective is to demonstrate innovative computational behaviors in micro-nano systems. To this end, we assemble short DNA molecules and enzymes into reaction networks using the PEN-DNA toolbox,[1,2] a set of 3 cascadables enzymatic reactions: activation, inhibition and degradation. The continuous anabolism and catabolism of the DNA strands is ruled by the topology of the network, and drive the system out of equilibrium, thus enabling dynamics such as oscillations[3] and bistability.[4]

In order to test molecular programs with high throughput, we developed a droplet microfluidic platform, which allows us to screen the parameter space with high resolution while reducing both reagent consumption and work-up time by 3 or 4 orders of magnitude.[5]

Here, I will present the first high-throughput mapping of a nonlinear biochemical system using droplet microfluidic. The large scale of the data sets (10^4 points) allowed us to discover subtle dynamics in two PEN-DNA toolbox circuits : a bistable switch and a predator-prey oscillator.[6] The maps grasped the bifurcation frontiers in parameter space, and confirmed experimentally prior theoretical predictions on how competition for the processing enzymes shapes the molecular program landscape.[7,8]



1. Montagne, K., Plasson, R., Sakai, Y., Fujii, T. & Rondelez, Y., *Mol. Syst. Biol.* **7**, 466–466 (2014).
2. Baccouche, A., Montagne, K., Padirac, A., Fujii, T. & Rondelez, Y., *Methods* **67**, 234–249 (2014).
3. Fujii, T. & Rondelez, Y., *ACS Nano* **7**, 27–34 (2013).
4. Padirac, A., Fujii, T. & Rondelez, Y, *Proc. Natl. Acad. Sci.* **109**, E3212–E3220 (2012).
5. Baccouche, A. *et al.*, *Nat. Protoc.* **12**, 1912–1932 (2017).
6. Genot, A. J. *et al.*, *Nat. Chem.* **8**, 760–767 (2016).
7. Rondelez, Y., *Phys. Rev. Lett.* **108**, (2012).
8. Genot, A. J., Fujii, T. & Rondelez, Y., *Phys. Rev. Lett.* **109**, (2012).

Generation, encapsulation and control of micrometric beads of DNA hydrogels

Anthony Genot[1,2]
[1]CNRS
[2]University of Tokyo

Hydrogels have recently attracted a lot of attention in fields like regenerative medecine or drug delivery due to their biocompatibility, their 3D scaffold and their mechanical properties. Hydrogels made of DNA are especially interesting because they can be programmed to respond to external stimuli, such as a change in temperature, pH or the presence of a target DNA strand. The encapsulation, culture and unloading of cells would bring numerous benefits, not only for tissue engineering, but also for single-cell analysis.

Our DNA gels are based on a design reported by the Murata group at Tohoku University. In this design 4 DNA strands mutually bind to each other to form a X motif, from which protude sticky ends that allow the X-motifs to reticulate into a large network. Starting from this design, we adapted to a microfluidic format - demonstrating the generation of DNA beads of ~50 micrometers in diameters. We also encapsulated antibodies in the beads, and demonstrated the control dissolution of the gel beads through the addition of complementary strands.

Short Talks 3

2019年1月12日（土）
10:30 – 11:30

1. **Hiroyuki Kitahata**
   “Spontaneous motion of a camphor particle depending on its shape”
2. **Makoto Yoneya**
   “Azo liquid-crystals as a molecular active matter: Molecular dynamics simulation study”
3. **Yoshino Hasegawa**
   “Traveling wave of graphite particles induced by photo-irradiation”
4. **Nicolas Lobato-Dauzier**
   “MEGABOTS: DNA nano-robots swarms for multiscale dynamic construction”

Spontaneous motion of a camphor particle depending on its shape

Hiroyuki Kitahata, **Yuki Koyano**
Department of Physics, Chiba University

In nonequilibrium systems, a particle or a droplet can spontaneously move by dissipating free energy. Such particles or droplets are called self-propelled particles. The fundamental theory on the relation between the motion and the shape of the self-propelled particles was proposed by Ohta and Ohkuma [1,2]. Based on the model, the characteristics of some experimental systems have been discussed [3]. A camphor particle on water is a good example of a self-propelled particle [4,5]. When a camphor particle is put on water, camphor molecules are released to the water surface from the particle. The camphor molecules reduce the surface tension of water. The imbalance of the surface tension around the camphor particle drives the camphor particle. If the position of the camphor particle changes, it rearranges the camphor molecule concentration at the water surface. By this procedure, the rest state of a camphor particle can be destabilized and it may start spontaneous motion. Since the camphor concentration profile at the water surface is affected by the shape of the camphor particle, the shape of the particle can affect the motion of the camphor particle.

In our previous study, we investigated the motion of the elliptic camphor particle [6,7]. Based on a theoretical model composed of a reaction-diffusion equation for the camphor surface concentration and a Newtonian equation for the camphor particle motion [8], we predicted that an elliptic camphor particle moves in its minor-axis direction. This prediction was confirmed with the numerical calculation and actual experiments [6,7].

In the present study, we extended our previous study for the case with other shapes. Especially, we consider the camphor particle with the third-mode deformation. We theoretically discuss the coupling between translational and rotational motion of the camphor particle by considering the force and torque [9]. In the presentation, we will show the results of the analysis together with the results of the preliminary experiments.

References

1. T. Ohta and T. Ohkuma: “Deformable self-propelled particles”, *Phys. Rev. Lett.* **102**, 154101 (2009).
2. T. Ohta: “Dynamics of deformable active particles”, *J. Phys. Soc. Jpn.* **86**, 072001 (2017).
3. H. Ebata and M. Sano: “Swimming droplets driven by a surface wave”, *Sci. Rep.* **5**, 8546 (2015).
4. S. Nakata, Y. Iguchi, S. Ose, M. Kuboyama, T. Ishii, and K. Yoshikawa: “Self-rotation of a camphor scraping on water: new insight into the old problem”, *Langmuir* **13**, 4454 (1997).
5. S. Nakata, M. Nagayama, H. Kitahata, N. J. Suematsu, and T. Hasegawa: “Physicochemical design and analysis of self-propelled objects that are characteristically sensitive to environments”, *Phys. Chem. Chem. Phys.* **17**, 10326 (2015).
6. H. Kitahata, K. Iida, and M. Nagayama: “Spontaneous motion of an elliptic camphor particle”, *Phys. Rev. E* **87**, 010901 (2013).
7. K. Iida, H. Kitahata, and M. Nagayama: “Theoretical study on the translation and rotation of an elliptic camphor particle”, *Physica D* **272**, 39 (2014).
8. M. Nagayama, S. Nakata, Y. Doi, and Y. Hayashima: “A theoretical and experimental study on the unidirectional motion of a camphor disk”, *Physica D* **194**, 151 (2004).
9. H. Kitahata, Y. Koyano, K. Iida, and M. Nagayama: “Mathematical model and analyses on spontaneous motion of camphor particle”, in “Self-organized motion: Physicochemical design based on nonlinear dynamics” (eds.) S. Nakata, V. Pimienta, I. Lagzi, H. Kitahata, and N. J. Suematsu (Royal Soc. Chem., 2018).

Azo liquid-crystals as a molecular active matter: Molecular dynamics simulation study

Makoto Yoneya and Yasuo Norikane

National Institute of Advanced Industrial Science and Technology (AIST)

Azo-dyes are known to show mass-transportation upon irradiation of (UV and/or visible) light [1-3]. Photoisomerization of azobenzene chromophore is considered to be the origin of this mass-transportation as schematically shown in Fig. 1 [3]. Although, the picture shown in Fig. 1 is totally uncertain, this figure inspired us that the azo-dyes could be a candidate of light-driven molecular active matter.

Last year, we reported results of molecular dynamics (MD) simulations of azo-dye 4-(dimethylamino) azobenzene (DMAAB) shown in Fig. 1 under periodic irradiation of UV and visible (VIZ) lights that enforced periodic photoisomerization between trans- and cis-form (Fig. 1). Our simulation results showed enhanced diffusion of DMAAB molecules under the irradiation.

In this study, we have done the corresponding MD simulations with an azo liquid crystal (LC) molecule 4-pentyl-4'-metoxy azobenzene (PMAB) [4] shown in Fig. 2. If the picture shown in Fig. 1 is somehow correct, we can expect enhanced anisotropy of diffusion along molecular long-axis. Our simulation results showed enhancement of molecular diffusion of azo LC but reduction of diffusion anisotropy upon irradiation.

References

1. Uchida E. *et al.*: "Light-induced crawling of crystals on a glass surface", *Nat. Commun.* **6**, 7310 (2015).
2. Nakano H. and Tanino T.: "Surface relief grating formation on a single crystal of 4-(dimethylamino) azobenzene", *Appl. Phys. Lett.* **87**, 061910 (2005).
3. Fiorini C. *et al.*: "Molecular migration mechanism for laser induced surface relief grating formation", *Synth. Met.* **115** 121 (2000).
4. Steistrasser and Pohl: "Niedrigschmelzende *p*-alkyl-*p'*-alkoxy- und *p*-alkyl-*p'*-acyloxy-azobenzole", Z. Naturforsch B, **25b**, 577 (1971)

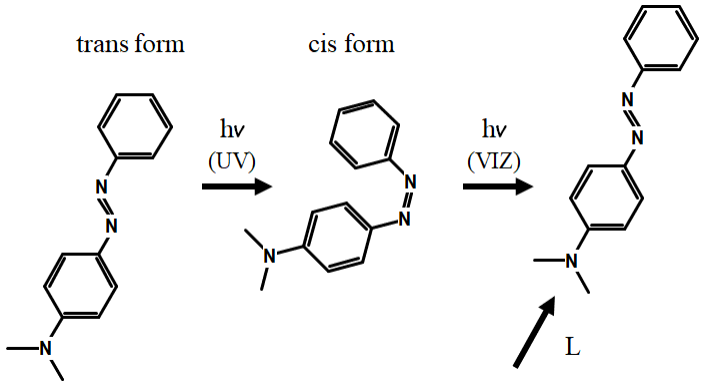


Fig. 1 : Photoinduced caterpillar-like DMAAB molecule motion upon light irradiation (after Ref. 3)

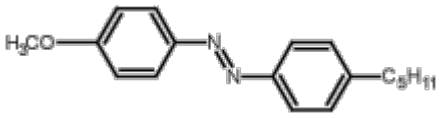


Fig. 2: Azo liquid-crystal molecule PMAB (Cry. 39℃ Nem. 65℃ Iso.) [4]

Traveling wave of graphite particles induced by photo-irradiation

Yoshino Hasegawa, Tomoko Tanaka, Satoshi Takatori,
Koichiro Sadakane, Takahiro Kenmotsu, Kenichi Yoshikawa
Faculty of Life and Medical Sciences, Doshisha Univ.

The temporal and spatial patterns appear almost everywhere in the nature, especially under non-equilibrium open system; BZ reaction, the stripe on the skin of a zebra and so on. These complicated self-organized patterns emerged by some simple physics stimulate our curiosity. Besides this social and scientific interest, we previously reported the collective motion of micro particles and centimeter-sized droplets in open and multiparticle nonequilibrium systems by photo-irradiation[1-3]. In these former works, the movements of targets in gas and in liquid switch forward and backward via photo-thermal effect.

In this presentation, we newly reported how micro particles behave in alcohol solution by steady photo-irradiation(λ=532 nm)(Fig. 1). Here, an experimental setup is described briefly, where the CW laser is induced horizontally to ethanol solution that graphite particles scattered in. We discovered that the compressional pattern of micro particles is emerged in gas-liquid interface of alcohol solution by laser. In Fig. 2, we found that long wavelength of compressional wave already exists and flows forward, then right after photo-irradiation, the wavelength of compressional wave became shorter. The shape and the velocity of the wave are significantly different between the cases the upper side of the container is open and close with the lid; it shows how important high volatility of ethanol is. For example, where the gas-liquid interface is the open state, translational compressional waves is emerged constantly. The wavelength is about 1 to 3 mm. Whereas, where the gas-liquid interface is the closed state, the compressional waves become remarkably instable. The wavelength is about 12 mm and 4mm. Also, the velocity in open state is 2.5 mm/sec, and it is 5 to 40% faster than that in the closed state. This result suggested that the volatility of ethanol in the gas-liquid interface is largely involved in the formation of compressional waves. Also, by changing relevant parameters, we find a similar tendency of graphite particle's compressional wave by solving adventive diffusion equation numerically. In our presentation, we discuss the mechanism of this self-organizing phenomenon of graphite particles by photo-induced effects, such as Marangoni instability and radiometric force.

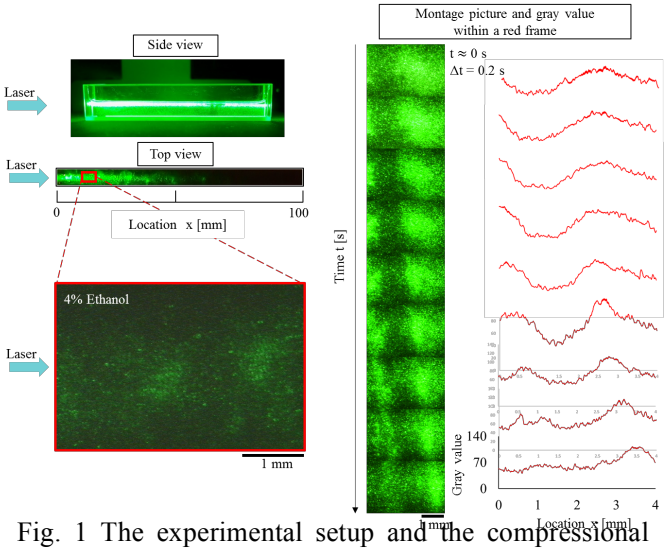


Fig. 1 The experimental setup and the compressional waves of graphite particles by photo-irradiation.

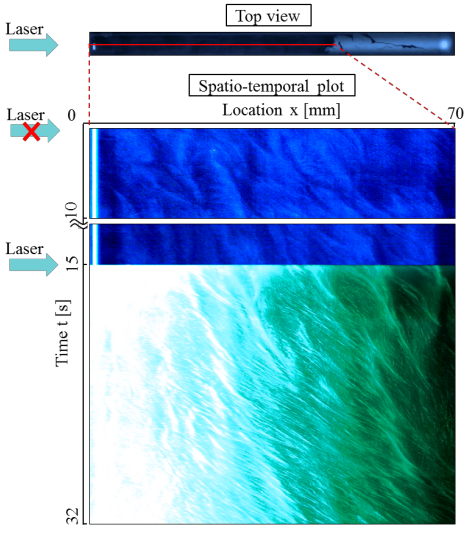


Fig. 2 The spatio-temporal plot of the gas-liquid interface of solution.

References

1. S. Watanabe, et al., "Negative photophoresis of smoke particles observed under microgravity", Chem. Phys. Lett., 511, 447-451 (2011).
2. M. Ichikawa, K. Yoshikawa, et al., "Controlling negative and positive photothermal migration of centimeter-sized droplets", Phys. Rev. E, 88, 12403/1-8 (2013).
3. S. Rybalko, N. Magome, and K. Yoshikawa, "Forward and backward laser-guided motion of an oil droplet", Phys. Rev. E, 70, 046301/1-4(2004).

MEGABOTS:
DNA nano-robots swarms for multiscale dynamic construction

N. Lobato-Dauzier[1], **G. Gines**[2], **Y. Rondelez**[2], **T. Fujii**[1], **A.J. Genot**[1]
[1] LIMMS, CNRS-Institute of Industrial Science, UMI 2820, The University of Tokyo, Tokyo, Japan
[2] UMR Gulliver 7083 CNRS, ESPCI ParisTech, PSL Research University, Paris, France

The environment, healthcare or energy need radically new techniques to orchestrate matter at a multi-scale level, from meters (human scale) to nanometers (molecular scale). For instance, tissue engineering to create in-vitro organs requires to arrange in space and time a network of blood microvasculature. In photovoltaics, periodically organizing single nanocrystals (quantum dots) could dramatically improve the performance of solar panels. DNA nanosystems, because of their nanometric size, their inherent compatibility with biological systems and their programmability could offer a new dimension to tackle such challenges. Imagining swarms of DNA nano-robots becoming the architects, engineers and workers in our future constructions can seem pure science-fiction as the possibilities it opens are beyond our understanding. However, recent breakthrough in DNA nanotechnology [1], show we are not that far from our goal: designing and programing swarms of millions of DNA nano-robots (Figure 1) to self-assemble from nanometers to centimeters in a massively parallel and reprogrammable way.

In this talk I will present how the PEN-DNA Toolbox allows to create microscopic agents that can compute and communicate [1]. I will then introduce how such a framework can allow to shape matter dynamically by showing experimental results of conditional aggregation of micro sized robots. Finally, I will show the work done using DNA coated gold nanoparticles and how using the Transmission Electron Microscope liquid cell and the high-throughput droplet platform [2] will allow a better understanding of the thermodynamics involved.

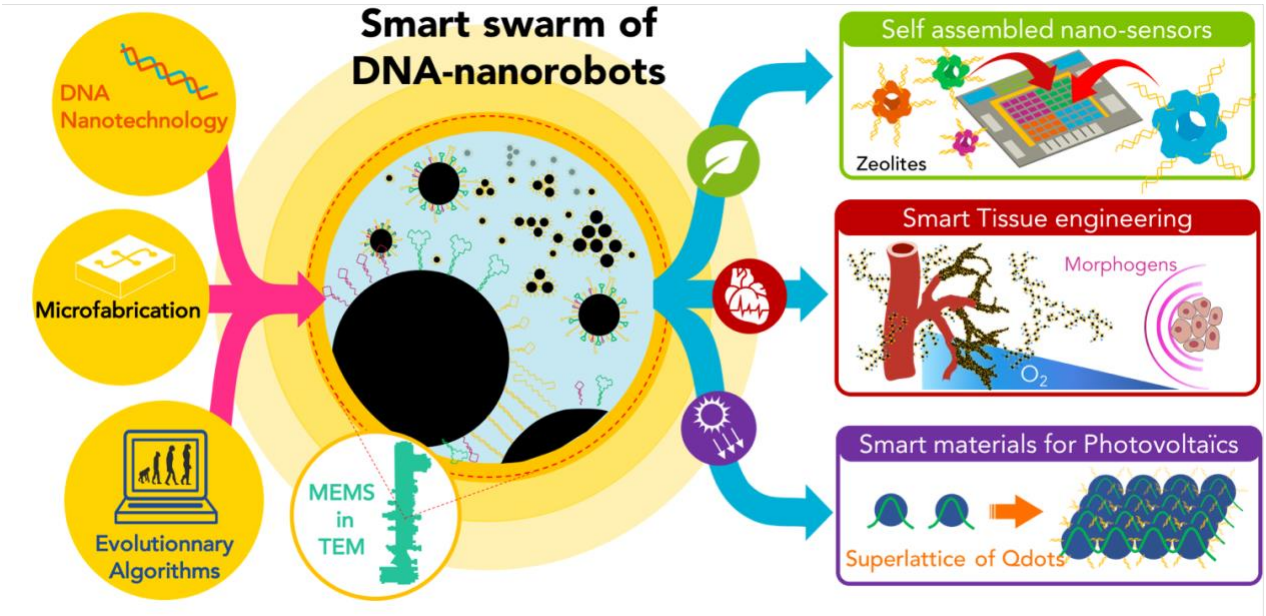


Figure 1- Smart swarms of millions of DNA nano-robots that self-assemble could enable ultra-sensitive sensor to monitor air pollution, help the growth of artificial organs or enhance quantic properties of solar panels to improve their efficiency.

References

1. G. Gines, et al.: *"Microscopic agents programmed by DNA circuits"*. *Nature nanotechnology* **12**.4 351. (2017)
2. A. J. Genot et al.: "High-resolution mapping of bifurcations in nonlinear biochemical circuits". *Nature Chemistry* **8**, 760–767 (2016)

Short Talks 4

2019年1月12日（土）
13:00 – 14:30

1. **Kei Kikuchi**
   “Characteristics of the collective motion of barnacle larvae”
2. **Shiho Sato**
   “Self-running droplets: Mode bifurcation and synchronization”
3. **Saori Suda**
   “Coupling between the internal convention and the self-propelled motion in a water-in-oil droplet system"
4. **Masahide Okada**
   “Self-split of oil droplets on surfactant aqueous solution”
5. **Masahiro Makuta**
   “Anomalous diffusion of a microparticle encapsulated in a cell-sized active gel droplet composed of actomyosin”
6. **Ryota Takenaka**
   “experiment of development of reconstruction system to find out the mechanism of cytokinesis”

Characteristics of collective motion of barnacle larvae

Kei Kikuchi[1], **Yukitaka Ishimoto**[1], **Keiju Okano**[1], **Stephanie Nix**[1]
[1]Akita Prefectural University

1. Background

Barnacles are a type of crustacean with two distinct larval stages, the nauplius and cypris stages. Cyprids are on a mission to find a good surface to settle and cement themselves on. Many features of cyprid motion have been revealed, including that they are attracted to adult pheromones. However, the mechanism of group formation on an adult-free surface, analysis of cypris swimming modes, and mechanical details have not been clarified.

In order to elucidate the barnacle cypris navigation system, we tracked barnacle larvae swimming and analyzed characteristics of their collective motion.

2. Method

Figure 1 shows an overview of the experiment devices used in this study. Barnacle cypris larvae of genus *Rhizocephala* were placed in a chamber consisting of acrylic and rubber. A laser sheet (KANOMAX, CW532-5W) was shone from above the chamber, and barnacle larvae swimming was recorded for 10 sec at a frame rate of 250 fps with a high-speed camera (Photron,SA5). The captured video was analyzed partially by using ImageJ.

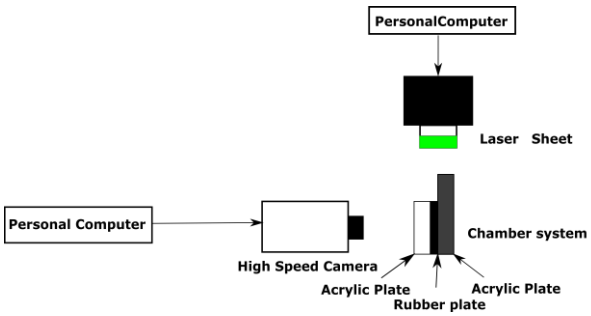


Fig. 1: Experimental setup.

3. Results and Discussion

Figure 2 extracted some trajectories of barnacle cyprids. We confirmed three swimming patterns: (a) swimming, (b) sinking, and (c) swimming and sinking. These swimming patterns were also observed in [1, 2]. In addition, the overall average swimming speed was 17 mm/s.

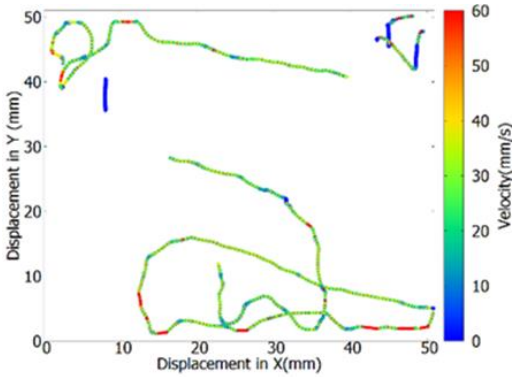


Fig. 2: Example trajectories in x-y plane.

The MSD (mean squared displacement) of two characteristic patterns are shown in Figure 3. Circular points show MSD of active cyprids travelling for relatively further distance. Trianglar points show MSD of static cyprids who seem relatively disfavour travelling. The 'active' MSD increases steadily up to 4 s, thenit becomes nearly constant from 4 to 8 sec. This may be well accounted by a fact that cyprids mostly do not swim straight. They swim a certain distance, then change their angles of motion. On the other hand, the 'static' MSD increases monotonically. It may be because some of such larvae which rarely swim would move while falling/sedimenting.

From the speed autocorrelation, we found that they swim with a period of about 0.024 sec.

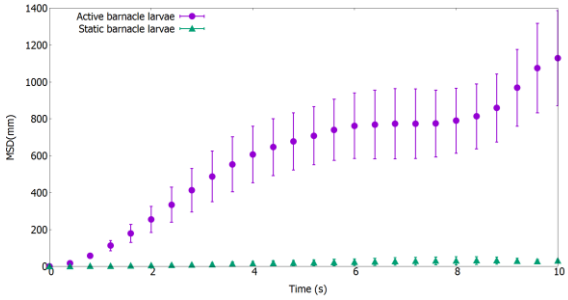


Fig. 3: Mean squared displacement of barnacle cyprids.

References

1. S. Maleschlijski, Journal of the Royal Society Interface, **12**, 1-9 (2015)
2. A. I. Larsson, PLoS ONE **11**, 1-17 (2016)

Self-running droplets: Mode bifurcation and synchronization

Shiho Sato, **Hiroki Sakuta**, **Koichiro Sadakane**, **Kenichi Yoshikawa**
Faculty of Life and Medical Sciences, Doshisha University, Kyoto 610-0394, Japan

We report characteristic behavior of self-running droplets driven by chemical nonequilibricity under isothermal condition. We discuss the mechanism of mode switching on the motion and synchronous motion in terms of nonlinear dynamics under interfacial instability.

1. Mode Bifurcation of motion by drop position

It will be shown that unique behavior of self-propelled droplets of nitrobenzene floating on an aqueous solution. Fig.1(a) exemplify the traces of oil droplets, representing difference on the modes of self-motion. It was found that, even under the same experimental conditions, different modes are generated depending on the initial positioning of the droplet, either on the center of near the wall; reciprocating back-and-go motion and revolution motion. Self-propelled modes of the droplet are summarized as a phase diagram in Fig. 1(b).

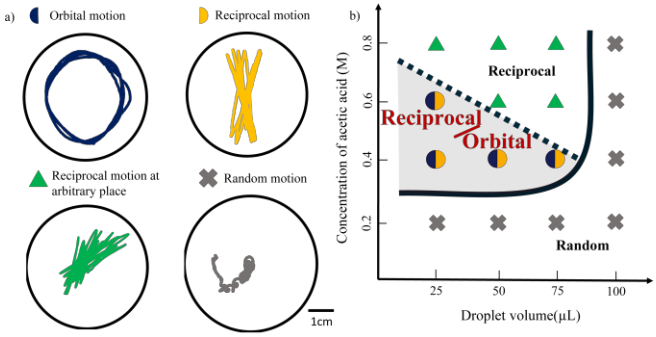


Fig.1 Mode bifurcation of the droplet motion. (a) Schematic representation on motional trajectory, (b) pase diagram with the variable of droplet volume and acetic acid concentration.

2. Synchronous motion

When droplets are dropped onto the water surface, they move synchronously. A Pasteur pipette is inserted in the center of a glass container with a diameter of 14 cm and a width of 1 cm. The aqueous phase is acetic acid aqueous solution (0.3M, 10mL). Nitrobenzene droplets are dropped on the left and right sides of the container and start moving immediately. In a little, the two droplets show a swinging motion. This is a synchronous phenomenon that occurs due to the interaction of droplets at the center. Mathematical model is also created from the experiment result and the essence of synchronous motion is reproduced.

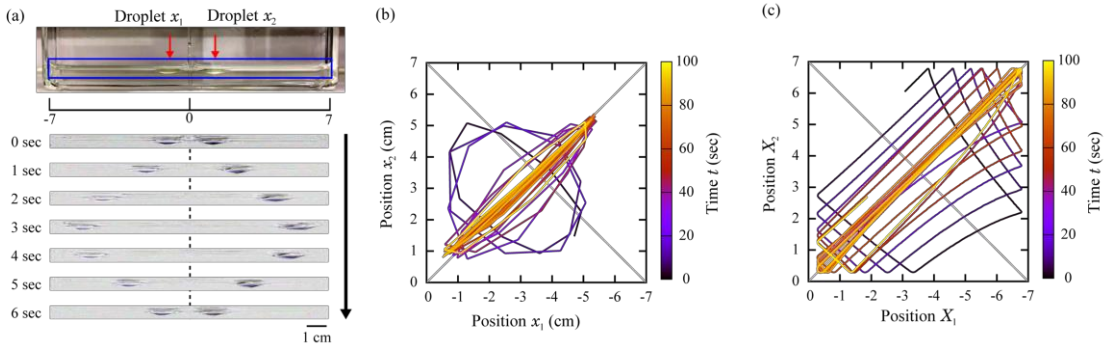


Fig.2 Synchronous motion. (a) Snapshot of droplets every 1 sec. (b) Correlation on the motions of the couple of droplets. The both droplets are 100μL and the concentration of acetic acid in the aqueous phase is 0.3M.(c) Result of mathematical model.

References

1. Y. Sumino and K.Yoshikawa: " Self-Running Droplet: Emergence of Regular Motion from Nonequilibrium Noise ", Phys. Rev. Lett., 94, 068301/1-4 (2005).
2. Y. Chen, K. Sadakane, et al: "Spontaneous Oscillations and Synchronization of Active Droplets on a Water Surface via Marangoni Convection", *Langmuir*, **33**, 12362-12368 (2017)
3. Y. Chen, Y. Nagamine and K. Yoshikawa: "Self-Propelled Motion of a Droplet Induced by Marangoni-Driven", *Physical Review* **E, 80**, 16303-7 (2009)
4. H. Sakuta, N. Magome, et al: "Negative/Positive Chemotaxis of a Droplet: Dynamic Response to a Stimulant Gas", *Appl. Phys. Lett*. **108**, 203703(2016).
5. Y. Sumino, et al: “Emergence of vortices of microtubules”, *Nature*, 483, 448-452 (2012)

Coupling between the internal convention and the self-propelled motion in a water-in-oil droplet system

Saori Suda[1], **Takuya Ohmura**[1], **Tomoharu Suda**[2] **and Masatoshi Ichikawa**[1]
[1]Grad. Sch. of Sci. Kyoto Univ.
[2]Grad. Sch. of Human & Environ. Studies Kyoto Univ.

A self-propelling swimming droplet is one of simple systems of active matters, with potential applications such as micro and nano machinery. In this study, we investigate the Marangoni effect driven droplet of water introduced into the oil including surfactant [1].

By controlling the size of droplets, we found a transition behavior of the mode of motion. The smaller droplets move straight ahead, whereas larger ones wander in a curved fashion. We measured the internal convection via Particle Imaging Velocimetry (PIV), and then decomposed it into spherical harmonics components [2]. Through comparison between the components and the motion of the droplet, we discuss the possible mechanism of the transition of motion.

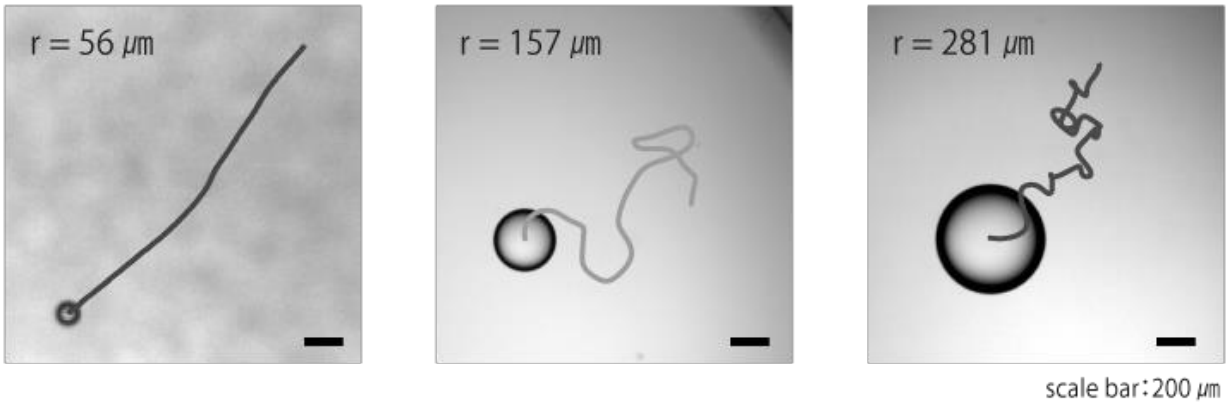


Fig. 1 ：Characteristic motions of water-in-oil droplet as a function of droplet size.
The lines are the trails of the center-of-mass of the droplets.

References
1. Z. Izri, M. N. van der Linden, S. Michelin, and O. Dauchot, Phys. Rev. Lett. **113**, 248302 (2014).
2. M. Schmitt and H. Stark, Phys. of Fluids **28**, 012106 (2016).

Self-split of oil droplets on surfactant aqueous solution

Masahide Okada[1], **Hiroyuki Kitahata**[2]
[1] Graduate School of Science and Engineering, Chiba university
[2] Graduate School of Science, Chiba university

Split of oil droplets which deform themselves on the surface of an aqueous phase has been reported[1-3]. In these studies, the droplet composed of tetradecane containing anionic surfactant (palmitic acid, PA) was put on the cationic surfactant (stearyltrimrthylammonium chloride, STAC) solution. At the boundary between the oil and aqueous phases, the aggregates are formed from PA and STAC. Then, the aggregates are stacked at the boundary and expand the droplets. Some time after, the aggregates are removed from the boundary and the droplets shrink. As the result of the deformation (expansion and shrink, named "blebbing"), droplets sometimes split by themselves[2].

In previous studies, blebbing of the droplets was often focused. For example, a simple equation to describe the mechanism of blebbing was proposed[1-2]. However, self-splitting has been less concerned.

In the present study, we focused on the split of droplets like Fig. 1. Figure 2 shows the size-dependency of split frequency (STAC:1 mM/ PA:20 mM). We fitted the experimental results to a sigmoid function $f(A_0)$. From these results, we found that the larger droplets split themselves more frequently than the smaller droplets. In this presentation, we will discuss the process of the droplet split based on the split frequency (Fig. 2), the droplet are before and after split and so on.

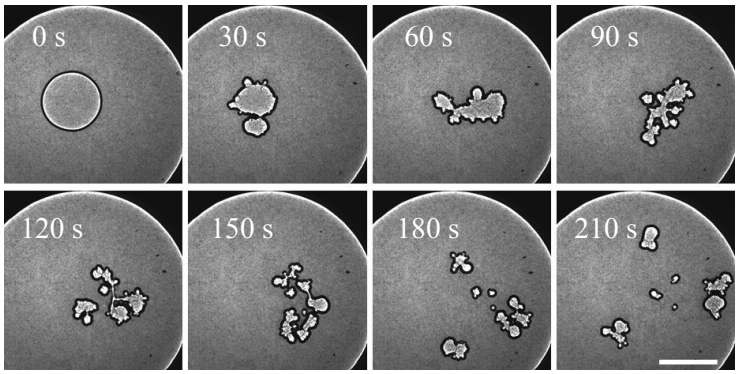


Figure 1: Snapshot of the splitting droplets (STAC:1 mM/ PA:20 mM). Scale bar shows 10 mm.

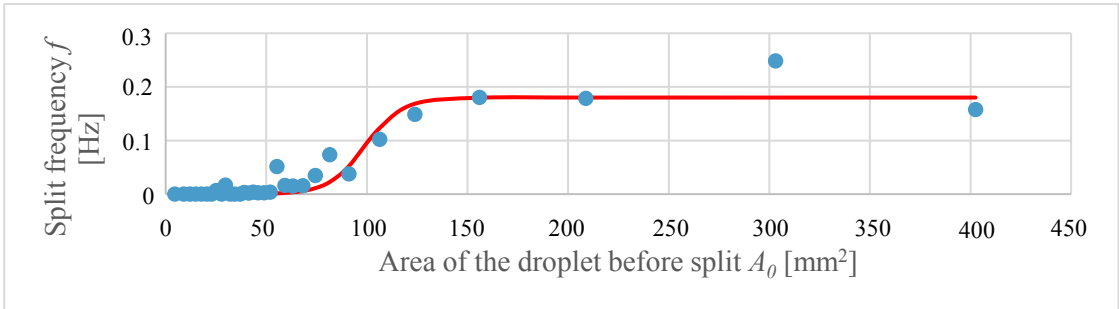


Figure 2: Size-dependency of split frequency f (STAC:1 mM/ PA:20 mM). Experimental results are fit by a sigmoidal function $f(A_0) = \frac{\alpha}{1+\exp(-{}^{(A_0-\beta)}/_{\gamma})}$, the result of which is shown with a red curve. By the fitting, we obtained $\alpha = 0.1816$ Hz, $\beta = 99.5962$ mm^2 and $\gamma = 9.1735$ mm^2.

References

1. Y. Sumino et al.: "Blebbing dynamics in an oil-water-surfactant system through the generation and destruction of a gel-like structure", *Phys. Rev. E*, **76**, 055201 (2007).
2. Y. Sumino et al.: "Dynamical blebbing at a droplet interface driven by instability in elastic stress: a novel self-motile system", *Soft Matter*, **7**, 3204 (2011).
3. Y. Sumino et al.: "Formation of a multiscale aggregate structure through spontaneous blebbing of an interface", *Langmuir*, **28**, 3378 (2012).

Anomalous diffusion of a microparticle encapsulated in a cell-sized active gel droplet composed of actomyosin

Masahiro MAKUTA[1], **Yukinori NISHIGAMI**[2] and **Masatoshi ICHIKAWA**[1]

[1]Dept. of Phys., Kyoto Univ.
[2]RIES, Hokkaido Univ.

Living cells actively regulate the generation of force during various biological processes. Cytoskeletons and its associated proteins mainly perform such force generations. Actin filament, which is one of the cytoskeletons plays a major role in force generation of living cells. For example, muscle actin generates contraction force in cooperation with the motor protein myosin. Actomyosin, which is a composite material of actin and myosin also works in deformation and maintenance of the cell shapes. We have performed in vitro experiments by using artificial cells to clarify the primitive mechanism of the deformation induced by actomyosin extracted from *A. proteus* [1,2]. These works figured out the dynamic interface deformation and analyzed their statistical features. However, it has not yet examined internal dynamics inside the artificial cells correlated with the interfacial deformations. We here studied active fluctuation induced by actomyosin through the motion of probe beads encapsulated in the droplet of actomyosin purified from rabbit skeletal muscle [3].

The basic behaviors of the interface were consistent with the results of previous studies, i.e., induction, nonperiodic oscillation, and winkling phases were emerged in order. Through the experiments, fluctuation of microbeads accompanied with motion transition of the interface exhibited correlations as shown in Figs. 1. (a) and (b). In induction phase (0 - 300 s), microbeads fluctuated around the initial position, and the motion became larger in the nonperiodic oscillation phase (400 – 500 s). In the early winkling phase (600 – 700 s), the microbead was fallen into the interface where the actomyosin cortex formed. In the former phases, anisotropic fluctuation was observed, e.g., diffusion coefficient in the tangential direction was different from radial direction. The result suggests anisotropic formation of actomyosin bundles and their force network due to the small spherical boundary condition.

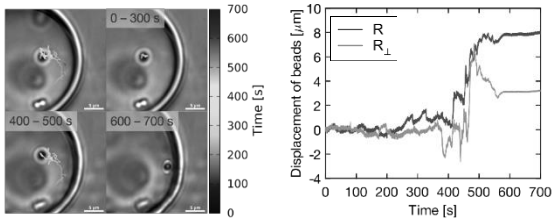


Fig. 1. (a)Trajectory of microsphere in actomyosin droplet.
(b)Displacement of microsphere from initial position.

References
1. H. Ito, Y. Nishigami, S. Sonobe, M. Ichikawa, *Phys. Rev. E* 92, 062711 (2015).
2. Y. Nishigami, H. Ito, S. Sonobe, M. Ichikawa, *Sci. Rep.* 6, 18964 (2016).
3. H. Ito, M. Makuta, Y. Nishigami, M. Ichikawa, *J. Phys. Soc. Jpn* 86 (2017).

Experiment of development of reconstruction system to find out the mechanism of cytokinesis

Ryota Takenaka[1], **Yukinori Nishigami**[2], **Masatoshi Ichikawa**[1]
[1]Kyoto University
[2]Hokkaido University

The cytokinesis occurs in the final process of the cell division. In this process, multiple proteins are localized on the cleavage furrow. For specifying proteins essential for the cytokinesis, we put actin, HMM (Heavy Meromyosin), and proteins related to the cytokinesis in water-in-oil droplets as a simple boundary condition and observed them. The results showed that some of them formed constrictions or showed actin rings in several conditions.

Acknowledgements
We would like to thank Makito Miyazaki and Tetsuya Takeda for providing reagents advice on experimental design.

References

1. Miyazaki, M., Chiba, M., Eguchi, H., Ohki, T., & Ishiwata, S.: "Cell-sized spherical confinement induces the spontaneous formation of contractile actomyosin rings in vitro", *Nature Cell Biology* **17**, 480–489 (2015).
2. Takeda, T., Robinson, I. M., Savoian, M. M., Griffiths, J. R., Whetton, A. D., McMahon, H. T., & Glover, D. M.: "Drosophila F-BAR protein Syndapin contributes to coupling the plasma membrane and contractile ring in cytokinesis", *Open Biology* **3**, 130081–130081 (2013).
3. Kessels, M. M., & Qualmann, B.: "Syndapin oligomers interconnect the machineries for endocytic vesicle formation and actin polymerization", *Journal of Biological Chemistry* **281**, 13285–13299 (2006)