BP 26: Focus Session: Bioinspired Systems

organized by Isabella Guido (MPI for Dynamics and Self-Organization, Göttingen) and Kerstin Göpfrich (MPI for Medical Research, Heidelberg)

Time: Thursday 15:00–17:30 Location: H15

Invited Talk BP 26.1 Thu 15:00 H15

Molecular robots working cooperatively in swarm — •Akira Kakugo — Hokkaido University, Sapporo, Japan

Cooperation is a strategy that has been adopted by groups of organisms to execute complex tasks more efficiently than single entities. Cooperation increases the robustness and flexibility of the working groups and permits sharing of the workload among individuals. Here, we demonstrate molecular transportation through the cooperative action of a large number of artificial molecular machines, photoresponsive DNA-conjugated microtubules driven by kinesin motor proteins. Mechanical communication via conjugated photoresponsive DNA enables these microtubules to organize into groups upon photoirradiation. The groups of transporters load and transport cargo, and cargo unloading is achieved by dissociating the groups into single microtubules. The group formation permits the loading and transport of cargoes with larger sizes and in larger numbers over long distances compared with single transporters. We also demonstrate that cargo can be collected at user-determined locations defined by ultraviolet light exposure.

BP 26.2 Thu 15:30 H15

Self-organization of microtubule filaments in energy dissipative evaporating droplet — •Vahid Nasirimarekani, Olinka Ramirez-soto, Stefan Karpitschka, and Isabella Guido — Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen, Germany

Cytoskeletal assemblies such as microtubule networks and motor proteins of the kinesin family drive vital cellular processes that, together with cargo delivery and cell division, also include providing mechanical stability when cells are exposed to external stresses. How these self-organising structures can orchestrate such response is not yet well understood. In this study, we develop a bioinspired system resembling intracellular cytoskeletal networks and characterise its activity under the influence of external stress. For this purpose, we confine an active network of microtubules and kinesin motors in an evaporating aqueous droplet. This setup serves as a bioreactor that enables to apply forces to the active system. Namely, the flow field generated by the Marangoni and capillary flow couples with the active stress of the microtubule-motor protein network. We observe that this coupling influences the spatio-temporal distribution of the driving forces and the emergent behaviour of the system, which shows contracting and relaxing behaviour. By analysing such non-equilibrium systems, our study can contribute to understand the response of biological structures to cues from the external environment.

BP 26.3 Thu 15:45 H15

Amphiphile-stabilized microemulsions formed from synthetic DNA-nanomotifs — Xenia Tschurikow[1], Mai Tran[2], Rakesh Chatterjee[3,4], Vasily Zaburdaev[3,4], Kerstin Göpfrich[2], and •Lennart Hilbert[1] — [1]Karlsruhe Institute of Technology — [2]Max Planck Institute for Medical Research — [3]Friedrich-Alexander-Universität Erlangen — [4]Max-Planck-Zentrum für Physik und Medizin

DNA in the nuclei of pluripotent cells exhibits a unique, finely dispersed microdomain pattern. This pattern is formed from DNA and RNA, which behave as two separating phases, and is stabilized in a microemulsified configuration by amphiphiles forming at sites where DNA is transcribed into RNA. Here, we synthetically reproduce such an amphiphile-stabilised microemulsion using DNA oligo-based nanomotifs. Specifically, we implemented a droplet phase in the form of DNA-nanomotifs with three self-affine "sticky ends", to which we add amphiphile particles that additionally harbour negative charges that are repelled from DNA-dense droplets. We confirmed behaviors expected upon amphiphile addition in titration experiments, time-lapse microscopy, and by mapping the amphiphile distribution within droplets. We are currently carrying out lattice simulations with multi-ended particles, which explicitly capture the interaction rules that are encoded via the different DNA-nanomotif ends. Our work provides an avenue towards the model-guided design of more complex multi-phase systems, to reproduce, for instance, the multitude of nuclear bodies observed in biological cells.

15 min. break

BP 26.4 Thu 16:15 H15

Bottom-up assembly of synthetic cells with bio-inspired DNA-based cytoskeletons — •Kevin Jahnke[1], Pengfei Zhan[2], Maja Illig[1], Na Liu[2], and Kerstin Göpfrich[1] — [1]Max Planck Institute for Medical Research — [2]Stuttgart University

The bottom-up assembly of synthetic cells with a functional cytoskeleton sets a major milestone to understand cell mechanics and to develop man-made cellular machines. However, the combination of multiple elements and functions remained elusive, which stimulates endeavors to explore entirely synthetic bio-inspired and rationally designed solutions towards engineering life. To this end, DNA nanotechnology represents one of the most promising routes. Here, we demonstrate functional DNA-based cytoskeletons operating in microfluidic cell-sized compartments and lipid vesicles. The synthetic cytoskeletons consist of DNA tiles self-assembled into filament networks (Zhan*, Jahnke* et al., in press at Nat. Chem. 2022; Jahnke et al., ACS Nano 2022). These synthetic cytoskeletons can be rationally designed and controlled to imitate features of natural cytoskeletons, including ATP-triggered polymerization, morphology control and vesicle transport in cell-sized confinement. Also, they possess engineerable characteristics, including assembly and disassembly powered by DNA hybridization, light or aptamer-target interactions. Moreover, we incorporate membrane-spanning DNA origami signalling units to allow for mechanochemical signal transduction across the GUV membrane (Jahnke, Illig et al., biorxiv 2022). This work underpins DNA nanotechnology as a key player in building synthetic cells from the bottom up.

BP 26.5 Thu 16:30 H15

Synchronization, enhanced catalysis of mechanically coupled enzymes and how to design them — •Michalis Chatzittofi[1], Jaime Agudo-Canalejo[1], Tunrayo Adeleke-Larodo[2], Pierre Illien[3], and Ramin Golestanian[1,2] — [1]Department of Living Matter Physics, MPI -DS, D-37077 Göttingen, Germany — [2]Rudolf Peierls Centre for Theoretical Physics, University of Oxford, OX1 3PU, UK — [3]Sorbonne Universite, CNRS, Laboratoire Physicochimie des Electrolytes et Nanosystemes Interfaciaux, 75005, France

Enzymes are the catalysts of the chemical processes that take place in living organisms. These processes, during which chemical energy is converted to mechanical energy and heat, occur stochastically as a result of a noise-activated barrier-crossing event. Despite this stochasticity, it has been shown recently that two mechanically coupled enzymes can synchronize their catalytic reaction [1]. Even more interestingly, the coupling enhances the catalysis of the two enzymes. This effect can be understood as arising from a bifurcation in the deterministic dynamics of the system. In this work, we use a similar approach to describe the dynamics of an enzyme by assuming that the enzyme is attached to a passive molecule. The goal is to design the properties of the enzyme so that its motion favours a chemical reaction, for example dissociation or a shape switch of the molecule. A bifurcation in the deterministic dynamics can cause a change in the molecules state after one enzymatic reaction. The stochastic simulations, also show that the enzyme's activity affects the state of the molecule.

[1] J. Agudo-Canalejo, et al., Phys. Rev. Lett. 127, 208103 (2021).

BP 26.6 Thu 16:45 H15

Dynamic formation and size control of cell-like compartments — •Sebastian W. Krauss, Pierre-Yves Gires, Mithun Thampi, and Matthias Weiss — Experimental Physics I, University of Bayreuth, Germany

A fundamental feature of living matter is its spatial organization into individual units, with the replication of template-like entities during cell division supposedly being the most familiar process linked to this feature. Yet, spatially ordered arrays of cell-like compartments ('protocells') also emerge spontaneously in homogeneous, isotropic Xenopus egg extracts in the absence of template structures and genetic material. We show that the geometry of these patterns has properties of a random-packing problem, i.e. randomly placed seeds grow at a uniform

rate until competition for material becomes limiting. We also show that the pattern undergoes a coarse-graining over time while maintaining its overall organization. Moreover, fluorescence imaging reveals the cytoskeleton to be the driving force behind the compartmentalization. In line with this notion, a perturbed dynamics of microtubules is observed to result in strongly reduced protocell areas. Altogether, our experimental observations suggest that space compartmentalization in living matter relies on few but robust generic physico-chemical principles.

BP 26.7 Thu 17:00 H15

New insights into the DNA origami silicification reaction mechanism by in situ small angle X-ray scattering — •Amelie Heuer-Jungemann[1,3], Martina Ober[2], Lea Wassermann[1], Anna Baptist[1], and Bert Nickel[2,3] — [1]Max Planck Institut für Biochemie, Am Klopferspitz 18, 82152 Martinsried — [2]Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 München — [3]Center for Nanoscience, LMU München, Geschwister-Scholl-Platz 1, 80539 München

DNA origami allows for the formation of arbitrarily shaped nanostructures with nm precision control. Yet, many potential real-life applications have been hampered due to the biologicL instability of DNA origami: Silicification provides an excellent way of increasing DNA origami stability. However, so far, it remains unclear how silicification affects the internal structure of the DNA origami and whether the whole DNA framework is embedded or if silica just forms an outer shell. By using in situ small angle x-ray scattering (SAXS), we were able to show that silica growth is not restricted to the outer origami surface, but also occurs on the inner surface, penetrating the whole structure and induces substantial condensation of the structure at early reaction times. Remarkably, we found that thermal stabilization of the origami up to 60°C as well as resistance towards degradation by nucleases could already be observed for sub-nm silica deposition in the highly condensed state. In this state DNA origami addressability could also be retained, resulting in the first fully site-specifically addressable silica nanostructure.

BP 26.8 Thu 17:15 H15

Energy transfer between coupled colloidal clusters — •Andreas Ehrmann and Carl Goodrich — Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria

Can biology-inspired complexity be obtained without biochemical components? Can we replicate ubiquitous biological processes using only model physical building blocks like DNA-coated colloids that have simple but programmable interactions? The last decades have seen tremendous progress in understanding the self-assembly mechanisms that enable the formation of complex, sub-micron scale structures, but embedding these structures with bio-inspired functional behaviors remains a considerable challenge. Here, we demonstrate a scheme for transferring energy between two colloidal clusters, in analogy to ATP hydrolysis. By coupling the two clusters, we show how the one acting as a receiver catalyzes a structural transition in the one acting as a fuel source, releasing energy that drives the receiver into a higher energy structural state. The coupled system shows a significantly reduced mean-first passage time. This work demonstrates that a fundamental and enabling biological process can be replicated without complex biochemical reactions. In contrast, theories of active matter often focus on the effect of energy consumption, not on the mechanism itself. However, the mechanism is intimately connected to the type of physical phenomena that can result. In a next step, we extend the scheme to convert energy into work by driving a net flux in the receiver, which is not possible in equilibrium and requires a fuel source.