ABSTRACTS for the 24th Student Research Symposium in Memory of Professor Stephen Berko

Session I:

Blake Stacey *Multiscale Structure in Eco-Evolutionary Dynamics*. What does biological evolution look like to a physicist? I will quickly survey a couple ways in which ecology, evolution and physics intersect in the domain of complex-systems science.

Joseph Rauch *A tradeoff between ecological stability and evolutionary success of cooperative alleles in public goods interactions*. Numerous examples of cooperators and cheaters coexisting in stable populations are observed throughout nature. We consider this coexistence using a model system of yeast cells that produce the extracellular enzyme invertase, which breaks down complex sugars into simple ones. All cells in the population can then take up the simple sugars, which act as a public good. Cheater cells in the population can also use the public good without making an investment. In this way the two subpopulations engage in a public goods game, which can result in a stable equilibrium between cooperators and cheaters. Upon varying the conditions in which the game is played (temperature, ethanol in media, death rate), we observe experimentally a negative correlation, or trade-off, between the resilience of the cooperating population to environmental changes, and their evolutionary success as measured by the fraction of cooperators in the population at equilibrium. This same tradeoff is also predicted by the Ecological Public Goods Game, a model that had been previously proposed to describe interactions between cooperators and defectors in public goods situations. We extend this model by allowing players to employ more sophisticated strategies in which they make a decision about whether to cooperate or not based on the decisions made by the other participants in the game. Although employing these complex strategies generally helps to increase the evolutionary success of cooperators, it still does not escape the tradeoff and comes at the cost of reducing ecological resilience. Surprisingly we find that this change of strategy is not enough to help them beat the tradeoff, which seems to be a very general feature of the public goods game.

Gabe Bronk *The physical attachment of distant chromosomal regions can play a functional role: A quantitative theoretical and experimental study of yeast mating type switching*. Recent discoveries in multiple organisms indicate that distant chromosomal loci become attached together by protein-chromatin interactions, and emerging evidence suggests that in some cases these attachments play a functional role, regulating gene expression or recombination. We are testing whether two distant loci (MAT and RE) on yeast chromosome III become bound together during the process of mating type switching and unbound when not undergoing mating type switching. Most notably, our preliminary comparison of our simulations to data from mating type switching experiments provides quantitative evidence for a functional role of this intrachromosomal attachment – i.e. this attachment serves to increase the likelihood of recombination between the loci HML and MAT, which causes the cell to become mating type alpha – i.e. the yeast can turn on the attachment in order to increase its likelihood of successfully switching to mating type alpha.

Ben Hancock *Role of reorientation statistics on emergent structures in self-propelled particles*. Active Brownian particles, such as self-phoretic colloids, are a class of self propelled particles which
swim at fixed speed with orientation that gradually changes through rotational diffusion. Some bacteria obey Run-and-Tumble dynamics, in which particles swim along a fixed orientation until a tumble event occurs that randomly selects a new orientation. At long time and length scales the diffusive-drift limit of the above dynamics appear to be identical. In this talk we compare the large scale behavior of these particles when under the influence of external potentials and investigate the role of their respective reorientation process.

Raunak Sakhardande  *Computational and theoretical analysis of chiral rafts in colloidal membranes.* In contrast to bulk liquids or crystals clusters of finite size are rare and their assembly usually requires sophisticated engineering. Recent experiments conducted on monolayer membranes composed of two species of chiral rodlike molecules leads to the spontaneous formation of thermodynamically stable, rafts with a well-defined finite size. To understand the fundamental forces driving this self-limited assembly, we combine Monte Carlo simulations and a mean field theory to explore the phase diagram of a monolayer of bidisperse rodlike molecules as a function of interparticle interactions and chirality. The simulations demonstrate that differences in chirality between the two rod species can stabilize finite-sized rafts. We present a phase diagram which predicts parameter ranges over which finite-sized rafts are stable.

Session II:

Walter Schwenger  *Bacterial Flagella as a Model Rigid Filament of Tunable Shape.* Networks of biological polymers play an important role in many vital cellular functions. Many of these filaments have been extensively studied within the soft condensed matter field as rigid, semi-flexible, or flexible rods. In this work, we present bacterial flagella as a rigid filament, but show that the geometry unique to the flagella creates novel and unique properties. Flagella are purified from *Salmonella typhimurium* with a naturally rigid helical shape. Mutant bacteria provide a means of controlling the exact shape of this helix as well as other *in vitro* methods. Through observing dynamics, rheology, and structure of flagella networks, we show that the geometry of these filaments give rise to unique properties compared to other rigid rod colloids. This makes bacterial flagella an interesting model colloid to study in soft condensed matter systems.

Andrew Balchunas  *Using Microfluidics to Explore the Phase Space of 2D Colloidal Membranes.* In the presence of non-adsorbing polymer, monodisperse filamentous viruses assemble into colloidal membranes, which are 2D liquid-like one-rod-length-thick monolayers of aligned rods. Colloidal membranes are of particular interest because their properties are accounted for by the same theoretical models that are used to describe the biophysics of conventional lipid bilayers. However, bulk membrane formation only occurs over a very limited range of depletant concentrations and ionic strengths. In order to explore the properties of the colloidal membranes under a much wider range of molecular parameters, we have developed a microfluidic technique that allows for *in-site* exchange of the enveloping polymer suspension. This allows us to access the region of phase space where membranes are metastable. Using our technique we can measure how the colloidal membrane area depends on applied osmotic pressure, allowing us to determine its equation of state. We also characterize the dynamics of the constituent rods by using single molecule tracking techniques.
Joia Miller  *Tuning raft interactions in colloidal membranes using chirality.* Two-dimensional colloidal membranes composed of rods of different lengths display rich phase behavior. In particular, chirality of constituent rods stabilizes assembly of colloidal rafts, micron sized droplets enriched in one type of rod floating in the background membrane. Colloidal rafts interact via long-range repulsive interactions that are mediated by local rod twisting due to their rods' inherent chirality. We explore the behavior of rafts suspended in an achiral background of rods. Even in the achiral limit we observe assembly of stable or meta-stable finite-sized rafts. However, in contrast to the chiral limit, the long-range interactions between rafts in an achiral membrane are attractive. We quantify this interaction and propose possible causes for the transition between attractive and repulsive interactions, including density fluctuations in the membrane bulk and surface-wetting of rafts.

Mahsa Siavashpouri  *Hierarchical self-assembly of DNA origami rods into the membrane and twisted ribbon.* The connection between the macroscopic properties of a liquid crystalline material and the microscopic features of the constituent molecules is the essential theme that permeates the field of liquid crystals. Previous studies have shown that monodisperse rod-like colloids such as filamentous bacteriophage self-assemble into 2D membranes and 1D twisted ribbons in presence of attractive interactions mediated by non-absorbing polymers. The microscopic properties of the colloidal particles play an important role in determining the physical properties of these mesoscopic assemblages. Using structural DNA nanotechnology, we present the design and structure of DNA origami six-helix bundles with tunable microscopic properties, which can be used as a new building block for the self-assembly of rod-like colloidal particles. We demonstrate that formation of higher order structures from the assembly of colloidal rods is universal. By tuning the chirality, aspect ratio and flexibility of the DNA origami particles we can control the physical properties of the entire self-assembled structures.

Berko Award talks:

Adam Wang  *Controlling Coupled Chemical Oscillators: Toward Synchronization Engineering and Chemical Computation.* The collective behaviors of coupled oscillators are ubiquitous in biological systems, with examples including quorum sensing, cardiac muscle contractions, and networks of neurons. In an effort to better understand the generic properties of such oscillators, we investigated emulsions of diffusively coupled microdroplets containing the oscillatory Belousov-Zhabotinsky (BZ) reaction with a photo-inhibitive catalyst. We created packed 2D arrays of BZ droplets via microfluidic techniques and studied the behavior of particular geometries with optically-induced boundary conditions. We used optical perturbations to alter periods and phases of oscillation in a controlled fashion, and also to completely suppress oscillations in the BZ droplets. Furthermore, we exploited the observed inhibitory coupling to establish a basis for computation through a chemical substrate by creating a functional NOR gate in a simple 1D arrangement of three BZ droplets.
Jacob Gold  Inhibitively Coupled Chemical Oscillators as a Substrate for Logic Gates and Larger Circuits. We investigate the Belousov-Zhabotinsky (BZ) reaction in an attempt to establish a basis for computation with inhibitively coupled chemical oscillators. The system consists of BZ droplets suspended in oil. Interdrop coupling is limited to the non-polar inhibitory species Br₂. We consider a linear arrangement of droplets to be a NOR gate, where the center droplet is the output and the other two are inputs. Oxidation spikes in the inputs, which we define to be TRUE, cause a delay in the next spike of the output, which we read to be FALSE. Conversely, when the inputs do not spike (FALSE) there is no delay in the output (TRUE). We are able to reliably produce NOR gates with this behavior in microfluidic experiment. We also discuss potential future methods for connecting multiple gates to form larger circuits.

Feodor Hilitski  Measuring mechanics of active microtubule bundles, one filament at a time. Microtubule (MT) bundles are ubiquitous structural elements of the cellular organization. For example, cellular motility is driven by the interaction between ordered doublets of parallel MT filaments inside cilia and eukaryotic flagella. Sliding of the antiparallel MTs in mitotic spindle is responsible for the separation of genetic material during cell division. Additionally, in vitro experiments demonstrate that MTs and molecular motors self-assemble into diverse array of structures ranging from synthetic cilia-like beating filaments to non-equilibrium nematic liquid crystals. The diversity of behavior exhibited by both in vivo and in vitro systems is due in part to the complex structure of the constituent MT bundles. Here we combine optical trapping techniques with fluorescence microscopy to construct MT bundles in a controlled and systematic way, by addition of one filament at a time. This approach allows us to probe pairwise interactions between MT filaments. First, we measure the depletion force acting on the individual filament in bundle’s axial direction in the presence of macromolecular crowding agents. Further, we add motor protein clusters to antiparallel bundles and observe the onset of extensile behavior. Measuring extension velocities and forces in such bundles allows us to explore the degree of cooperation between kinesin motors.

Lishibanya Mohapatra  How cells control the size of their organelles? Cells contain a number of micron-scale structures, whose physiological functions are related to their size. Examples include cytoskeletal elements like mitotic spindle and cilia. Each of these structures is characterized by a narrow size distribution and is composed of molecular building blocks that diffuse in the cytoplasm. A key question in cell biology is how the size of these structures is maintained in light of constant turnover of their molecular components. The limiting-pool mechanism has been studied extensively in this context. It posits that the size of the structure grows until the pool of available building blocks is depleted. Using theory and simulations, I will illustrate the properties of the limiting-pool mechanism and highlight the importance of additional size-control mechanisms that are required if the cell is to generate multiple structures of well-defined sizes using a common pool of building blocks. I will end by commenting briefly on using size distributions to characterize and distinguish between multiple size-control mechanisms.