Interdisciplinary challenges: from non-equilibrium physics to life sciences

Rome, April 17-21, 2023

Centro Congressi Frentani

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CNR Istituto dei Sistemi Complessi

CoBBs Lab

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We are pleased to welcome you to the 4th Edition of the Interdisciplinary Challenges workshop series. We thank you all for participating and contributing to this interdisciplinary and motivated scientific community of Early Career Researchers. Please, reach to any of us if you have questions at info@interchall.com

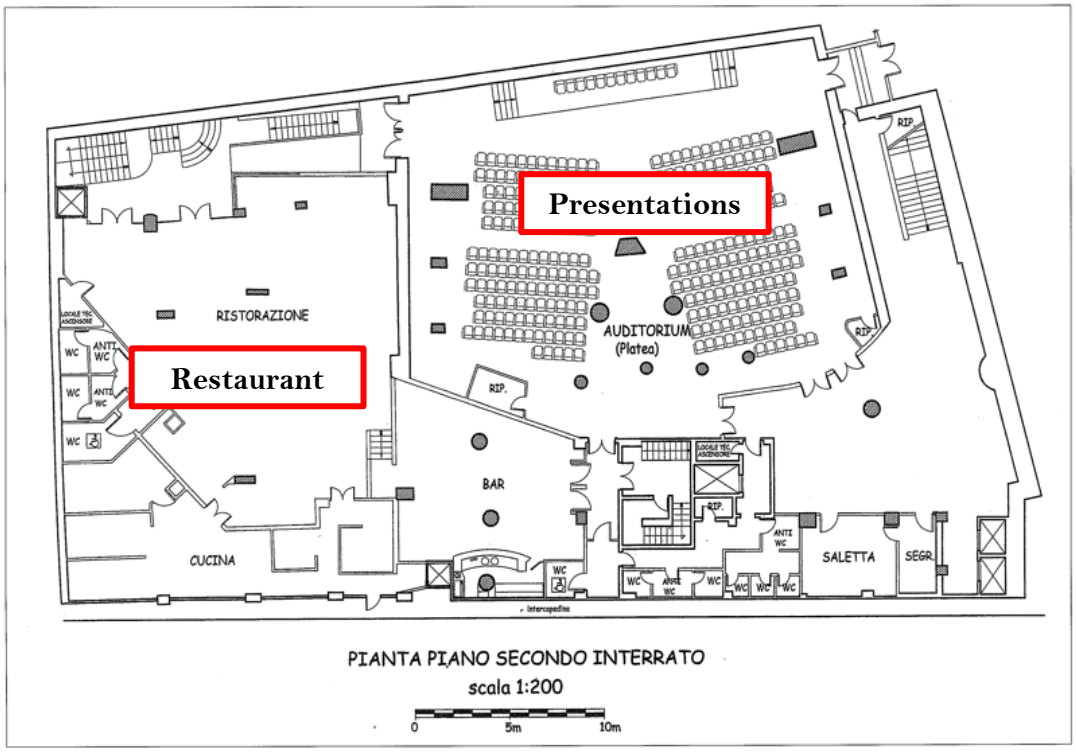
We are looking for volunteers who would like to be involved in the organization of the next year Workshop to preserve this event in the coming years, as it has been done before. Do not hesitate to ask us about it if you want more information!

Detailed Program

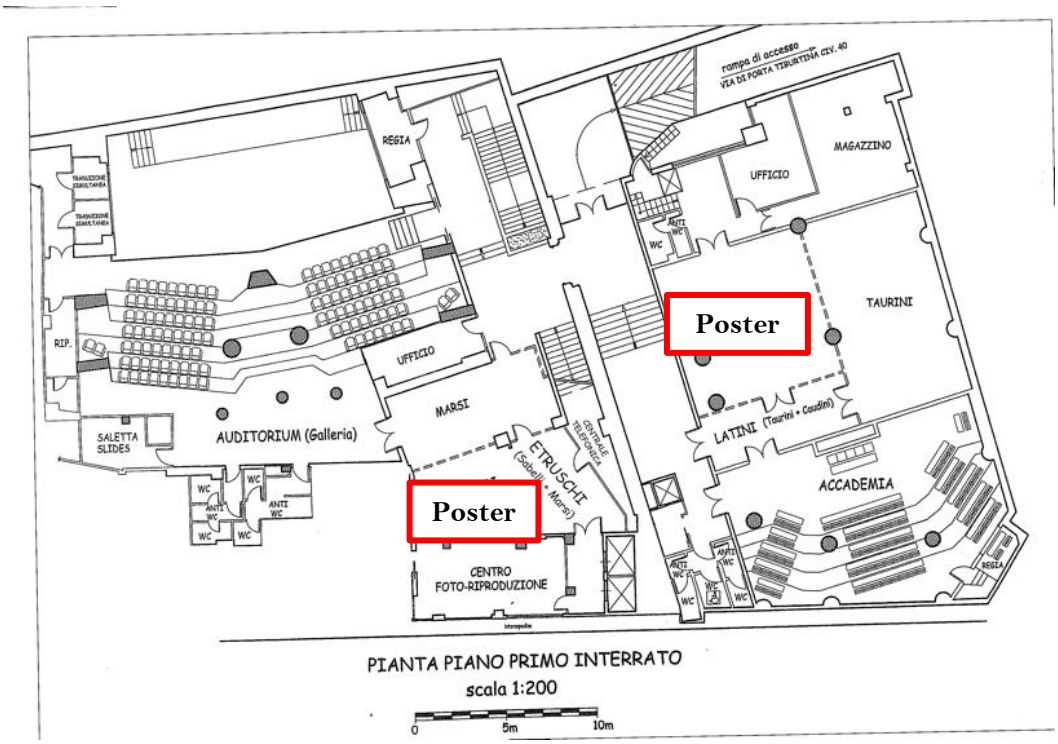
		Monday	Tuesday	Wednesday	Thursday	Friday
MORNING			*Active Matter*	*Biopolymers*	*Collective behaviour*	*Single cell and multicellular dynamics*
	09:00-09:30		Daniel Pearce	Laura Caccianini	Xiaowen Chen	Claudio Maggi
	09:30-10:00		Sofia Magkiriadou	Giada Forte	Lorenzo Caprini	Caterina Tomba
	10:00-10:30		Pasquale Digregorio	Alfredo Sciortino	Giulia Pisegna	Alison E. Patteson
	10:30-11:15		Coffee Break	Coffee Break	Coffee Break	Coffee Break
			Active Matter	*Cell-mimetic and intracellular organization*	*Collective behaviour*	*Morphogenesis*
	11:15-11:45		Ivan Maryshev	Carla Fernández-Rico	Severine Atis	Billie Meadowcroft
	11:45-12:15		Sophie Marbach	Melissa Rinaldin	Quentin Martinet	Lea-Laetitia Pontani
	12:15-12:45		Suropriya Saha	Nicolas Martin	Andrea Giovanni Reina	Szabolcs Zakany
	12:45-14:30		Lunch Break	Lunch Break	Lunch Break	
			Energetics	*Size, shape and growth of Cells*	*Neural networks*	
AFTERNOON	14:30-15:00	School presentation	Jordi Piñero	Philippe Roudot	Christopher W. Lynn	
	15:00-15:30	Alfonso Perez-Escudero	Jonathan Rodenfels	Farshid Jafarpour	Federica Gerace	
	15:30-16:00	Baudouin Saintyves	Riccardo Rao	Amit Singh Vishen	Luca Saglietti	
	16:00-16:30	Coffee Break	Coffee Break	Coffee Break	Coffee Break	
	16:30-18:00	Poster Session	Q&A	Poster Session	Q&A	

Maps of the auditorium

Second Basement Floor (-2): auditorium and restaurant



First Basement Floor (-1): Poster sessions



Invited speakers abstracts

Is more data always more complex? A counterexample in Caenorhabditis elegans
Alfonso Perez-Escudero

Animal behavior is extremely complex, to the extent that it may seem beyond human comprehension. Recent years have witnessed an explosion of experimental techniques that provide experimental data with unprecedented detail and quantity, making it even harder to deal with the resulting complexity. However, this revolution is also getting us nearer to the point where we can achieve a full understanding of some relatively simple animals. Just like the last pieces of a puzzle are easier to fit than the first ones, achieving this complete understanding may help us deal with the complexity. To illustrate this concept, I will present a comprehensive mapping of food preference in Caenorhabditis elegans, which shows a surprising universality in a system that was believed to be contingent on a myriad of details.

Granulobots: Leveraging mechanical properties of a decentralized, multi-unit, dense robotic aggregate for sensorless tasks
Baudouin Saintyve

Designing robotic systems that can autonomously interact with their environment to solve tasks remains a major challenge. Conventional approaches use multi-sensor feedback loops to control displacements. This is often coupled with algorithmic and hardware complexity, which tend to be detrimental to energy efficiency, reliability, and form factor, all key aspects in autonomous systems. Here we I will present a new decentralized and modular robotic platform that I have developed, Granulobot, to demonstrate tasks based on aggregate mechanical properties. Granulobots consist of active, gear-like particles that magnetically interact with each other and produce torques. They can self-assemble into aggregates that can reconfigure in real-time. The apparent complexity of a system with many degrees of freedom is made an advantage by leveraging the material-like properties of aggregates. In particular, aggregates can transition between rigid and liquid-like states with a wide range of effective viscosities. This enables the robot to move in complex environments through holes and over obstacles by setting a single "material" parameter, and without centralized control or real-time sensor-based feedback. Such minimal control, enabled by the modular design of Granulobots, advances robotic autonomy by exploring a morphological form of computation and feedback that greatly reduces the number of control parameters that must be taken care of by the embedded systems or operators.

Controlling active matter with geometry and topology
Daniel Pearce

Active matter is the study of materials that are able to move themselves, for example as locomotion or changing their shape. During this talk I will discuss how we can take advantage of the interplay between topological defects, geometry and topology to exercise control over active materials. By studying active nematic fluids on a curved surface, we can influence the position and orientation of topological defects according to their charge. This means specific nematic textures can be generated. By studying active contractile actomyosin gels, it is possible to show that only active topological defects with charge +1 can generate curvature, and the sign is related to the phase of the defect. This frees the process from the constraints of the Poincare-Hopf theorem and allows complex surfaces to be generated. This is demonstrated by recreating the shape of a freshwater hydra from the positions of the topological defects. Finally, I will show how these ideas can be applied in the design of new active, nematic solid materials with potential functionality.

From fundamental studies in biology to active photonic materials: an outlook
Sofia Magkiriadou

In this talk I will share some of my itinerary through the fields of active matter, biophysics, and optics. I will then discuss interdisciplinary connections between these fields, and ways to explore these in experiments. In the field of active matter, colloidal scientists have gradually been mastering the control and understanding of active particles. This enables us to progress towards experimental model systems at higher density and complexity. Thus, we can begin to envision active matter in the continuum: active materials. At the same time, biological systems, such as the interior of bacterial cells, can also be thought of as active materials and have at times been described as such. For instance, in some bacterial species the available energy has been associated with intracellular dynamics or with the cell's physical state. Inspired by these observations, I will then ask: how can we use model colloidal systems to uncover basic principles of out-of-equilibrium physics, in order to elucidate biological questions? Beyond biology, can we use this knowledge to create new active materials? I will entertain this question by discussing ideas for the use of active colloidal particles in the development of optical devices with dynamical properties.

Active turbulence in nematic liquid crystals
Pasquale Digregorio

Active materials are systems of many particles where single constituents consume energy from the environment and convert it into mechanical work. Active matter models are inspired by macroscopic living systems and biology, and their study is primarily aimed towards a theoretical understanding of collective phenomena like flocking, clustering and other types of self-organisation. Within a living cell, motor proteins like kinesin are responsible for the transport of intracellular components. The functioning of this active transport is well known and it has been employed to build synthetic assemblies of microtubules, which are stirred at the level of the single components and evolve out of thermal equilibrium. The presence of molecular motors drives chaotic flow at the large scale, which resembles inertial turbulence and is therefore called active turbulence. We use a model of nematic liquid crystals in the presence of a microscopic active stress to study this system. The onset of active chaotic flows leads to a sustained proliferation of topological defects that retain some unique properties compared with passive liquid crystals. We analyse the morphology and dynamics of these topological defects to deduce fundamental properties of active turbulence.

Mitotic spindle in terms of active matter
Ivan Maryshev

Microtubules and molecular motors can work cooperatively to construct a mitotic spindle – a complex structure that orchestrates many spatiotemporal processes during cell division. The central part of the spindle contains nematically aligned microtubules organized by sliding motors, while closer to the spindle poles, filaments are focused by clustering motors and can form radial arrays. I will try to shed light on the mitotic spindle self-assembly using the Boltzmann formalism and Landau theory. In Particular, we will discuss how to derive macroscopic hydrodynamic equations by coarse-graining the interactions between individual elements and how to construct a phenomenological continuum model of spindle formation.

The Nanocaterpillar's Random Walk: or how to move precisely with random sticky feet?
Sophie Marbach

Particles with sticky feet - or nanoscale caterpillars - in biological or artificial systems, beat the paradigm of standard diffusion to achieve complex functions. Some cells (like leucocytes) use ligand-receptor contacts (sticky feet) to crawl and roll along vessels. Sticky DNA (another type of sticky feet) is coated on colloids to design programmable interactions and self-assembly. Predicting the dynamics of such sticky motion is challenging since sticky events (attaching/detaching) often occur on very short time scales compared to the overall motion of the particle. Even understanding the equilibrium statistics of these systems (how many feet are attached in average) is largely uncharted. Yet, controlling the dynamics of such particles is critical to achieve these advanced functions -- for example facilitating rolling is critical for long-range alignment of DNA coated-colloids in crystals. Here we present advanced theory and experimental results on a model system. We rationalize what parameters control average feet attachment and how they can be compared to other existing systems. We investigate furthermore how various motion modes (rolling, sliding or skipping) may be favored over one another.

Scalar active mixtures: the non-reciprocal Cahn-Hilliard model
Supriya Saha

Pair interactions between active particles need not follow Newton's third law. In this work, we propose a continuum model of pattern formation due to nonreciprocal interaction between multiple species of scalar active matter. The classical Cahn-Hilliard model is minimally modified by supplementing the equilibrium Ginzburg-Landau dynamics with particle-number-conserving currents, which cannot be derived from a free energy, reflecting the microscopic departure from action-reaction symmetry. The strength of the asymmetry in the interaction determines whether the steady state exhibits a macroscopic phase separation or a traveling density wave displaying global polar order. The latter, which is equivalent to an active self-propelled smectic phase, coarsens via annihilation of defects, whereas the former structure undergoes Ostwald ripening. The emergence of traveling density waves, which is a clear signature of broken time-reversal symmetry in this active system, is a generic feature of any multicomponent mixture with microscopic nonreciprocal interactions. Further, we explore the notion of nonlinear non-reciprocity and consider a model in which the nonreciprocal interactions depend on the local values of the scalar fields. For generic cases where such couplings exist, we observe the emergence of spatiotemporal chaos in the steady-state associated with a local restoration of PT symmetry in fluctuating spatial domains.

Cost and benefit of information processing in nonequilibrium environments.
Jordi Piñero

Organisms maintain themselves by harvesting free energy from their environments. While the acquisition and use of information carry unavoidable thermodynamic costs, it can also increase the amount of free energy acquired from a nonequilibrium environment. We develop a framework for analyzing this trade-off of information processing in nonequilibrium environments using stochastic thermodynamics. We derive an upper bound on the net thermodynamic gain that can be achieved by introducing any additional control mechanisms for a given system coupled to a nonequilibrium environment. We illustrate our approach with some biologically inspired examples: chemical cycles, sensing and cross-membrane transport.

Energetics of Biological Systems
Jonathan Rodenfels

Living biological systems are metabolically active, open systems that constantly exchange matter and energy with their environment. They function out of equilibrium and use metabolic pathways to obtain energy from chemical bonds derived from nutrients to fulfill the system's energetic requirements. To understand how cells and organisms function, we need to determine how metabolic energy is partitioned among the complex array of cellular processes that are necessary for life at any scale, from isolated biochemical networks to quiescent and highly proliferative cells to organismal growth and development. To investigate the energetics of biological systems, we use isothermal calorimetry to quantitatively measure the flow of energy in form of heat between biological systems and their surroundings. Focusing on cleavage stage development of zebrafish embryos, we show that the heat dissipation rate increased over time and with cell number. Unexpectedly, we found that the heat dissipation rate oscillated with periods matching the synchronous early embryonic cell cycle. By combining these measurements with perturbations, imaging, metabolomics and theory, we will show that the energetic costs and metabolic changes associated with a given biological process can be estimated, and thus, provides a means towards understanding the energetics and possible constraints of biological systems.

Nonequilibrium thermodynamics of chemical reaction network
Riccardo Rao

Cellular functioning is based on coupled biochemical processes enabling the conversion of chemicals and energy from on form to another. A notable example is metabolism, through which cells convert the energy stored in energy-rich molecules, such as sugars, into a form that is readily usable, typically ATP. A mechanistic understanding of cellular energetics would greatly enhance our understanding of cell biology, but is hindered by (i) the complexity of cellular processes (metabolism, for instance, may involve thousands of chemical reactions and species), and (ii) the fact that cells operate far from thermodynamic equilibrium, i.e. a continuous supply of energy is required. In my presentation, I will first review the nonequilibrium thermodynamics of generic networks of chemical reactions, such as metabolism. Leveraging the notion of conservation law, I will introduce an algorithmic way of identifying a minimal description of the fluxes of chemicals and energy operated by network, as well as the thermodynamic forces that drive the network far from equilibrium. I will finally show how these tools can be used to assess energy conversion in central energy metabolism, the core of cellular metabolism.

Looping DNA: a study on the cohesin complex with light and electron microscopy
Laura Caccianini

Throughout a cell's life, DNA must be accessed to express genes, copied and equally partitioned when the cell divides, and simultaneously this 2 meter long fiber is compacted in a micron-scale space. DNA looping is a preferential mechanism of DNA-related compaction across species. In eukaryotes, some DNA-loops are generated by cohesin. The cohesin complex is known to keep sister chromatids together through cell division and to extrude DNA loops in an ATP-dependent manner. During my PhD I used single molecule tracking, in live mouse embryonic stem cells, to characterize the diffusive behavior and the DNA-binding kinetics of cohesin and its cofactors. Optical microscopy is a powerful technique that enables target-specific imaging in living organisms, but it has an intrinsic resolution limit set by diffraction. Wanting to understand the molecular mechanisms behind cohesin-based looping, I turned to cryo-electron microscopy (EM). I am currently working on solving the structure of the reconstituted cohesin complex bound to DNA. In parallel I am pursuing a Correlative Light and Electron Microscopy (CLEM) approach with the goal of studying the

cohesin complex in its native environment. Combining the use of target specific live cell imaging and EM will reveal the mechanism of cohesin complex function

Bridging-mediated compaction of mitotic chromosomes
Giada Forte

Chromatin compaction from interphase to mitosis is still not fully understood. In the last decade loop extrusion performed by condensins has become the main hypothetical mechanism to explain the formation of the highly compacted cylindrical chromosomes visible during mitosis. However, it is now evident that SMC complexes, such as condensins, not only load onto chromatin to extrude loops, but they also create bridges between distant loci. In this talk I will explain an alternative model we developed, where the compaction is driven by the interplay between two types of condensin-like proteins: one stabilising loops and the other binding multivalently to chromatin to form bridges. Characteristics of mitotic chromosomes observed by experiments arise naturally in our simulations, which then complement models based solely on loop extrusion.

From nematic defects to polar order: polar flow of gliding filaments steered by nematic defects
Alfredo Sciortino

Cells have the amazing ability of reshaping themselves to perform different functions, from division to motion. In order to do that, they exploit active forces exerted by the cytoskeleton, a set of active filaments with partnered molecular motors that not only provide a structural scaffold to the cell but can also dynamically self-organize in order to exert the right forces at the right time. However, how exactly the microscopic interaction between filaments and motors can lead to specific organizations of the cytoskeleton is unclear. To shed light on these issues, we reconstitute minimal experimental systems based on purified cytoskeletal proteins and investigate their ability to self-organize. Specifically, by using an experimental setup in which cytoskeletal filaments propelled by molecular motors actively glide on a surface, we show how different microscopic interactions between filaments lead to diverse macroscopic patterns. We then use this system to investigate how patterns are shaped by changing the topology of the system (from planar to spherical) and by the introduction of defects in the alignment of filaments (nematic defects). Our results shed light on the self-organization properties of the cytoskeleton but also indicate strategies to control pattern formation processes in general by playing with defects and with the topology of the system.

Arresting Decomposition in Elastic Matrices for Making Nanostructured Materials
Carla Fernández-Rico

Phase separation is a fascinating physical process that is not only responsible for the internal organization of living cells but also a powerful tool for engineering the structure of functional materials. Nature has evolved the ability to control phase separation to make composite materials with an exquisite range of optical and mechanical properties. Striking examples of these are the blue colours shown by many birds. In this work, we demonstrate control over spinodal decomposition processes at the microscale using polymer matrices. We demonstrate that the length scale of the resulting composite material is tuneable and controlled by the mechanical properties of the polymer matrix. We also show that the threshold for phase separation is stabilized with increasing elasticity, and that the preferred demixing pathway is spinodal decomposition. These results open up a range of possibilities for both fundamental and applied research, including the development of polymer composites with structural colour.

Dynamic instability of cytoplasmic compartments
Melissa Rinaldin

Early embryos are the epitome of self-organization. Following the cell cycle oscillator, their internal structure is continuously re-organized into precise patterns at remarkable speeds. For example, the mm-sized egg of the frog Xenopus Laevis, divides every 30 minutes in equally-sized cells. Physical processes such as autocatalytic growth, active transport, and reaction- diffusion can allow these embryos to keep up with fast cell cycle times, however their understanding in early development remains largely elusive. Here, we present recent data from experiments of in vitro cytoplasmic extract obtained from frog egg and exhibiting cell-free division. We show that the properties of the cell cycle oscillator regulate the pattern of cytoplasmic compartments. Specifically, by perturbing the oscillator, we establish that the interface of cytoplasmic compartments is unstable. We demonstrate that such instability emerges from competing waves of autocatalytic microtubule growth, and can generate compartment fusion, strongly affecting the embryonic early pattern formation. Altogether, our results propose that the cell cycle oscillator plays a critical role in partitioning the cytoplasm of early embryos, keeping the dynamic instability of cytoplasmic compartments at bay.

Droplet-based dynamic protocells
Nicolas Martin

Compartmentalization is a central hallmark of living cells that allows them to perform complex tasks by dynamically coordinating matter and energy fluxes in space and time. Recent years have witnessed a growing interest in the bottom-up assembly of synthetic micro-compartments that mimic the dynamic cellular organization. Microdroplets produced by liquid-liquid phase separation, such as complex coacervates, have become increasingly popular to build dynamic membrane-free compartments. These droplets provide new approaches to understand membraneless organelles ubiquitously found in living cells while shedding light on the transition from non-living to living matter. In this talk, I will show how liquid-liquid phase separation processes in water such as complex coacervation are being exploited to create dynamic protocells and organelles. I will in particular discuss examples of spatiotemporal control of biomolecule localization and chemical reactions via the design of stimuli-responsive coacervate droplets. Recent directions towards the construction of more advanced synthetic cells that integrate multiple functions in a droplet will also be discussed.

Automated pattern recognition for live cell microscopy in high-dimension: the cost of blind faith and how to avoid it.
Philippe Roudot

The recent progress in 3D live microscopy has been a breakthrough toward the imaging of cellular processes in physiologically relevant tissues (e.g. embryos, organoids...). Combined with advances in machine learning to detect cellular objects, these datasets enable the quantitative modeling of the heterogeneous and stochastic nature of cellular functions in vivo. However, this effort is challenged by the variable signal quality across and within imaging experiments. This variability results in unpredictable errors in pattern recognition with a non-linear impact on the statistics of interest. Since manual robustness evaluation is nearly impossible in those dense 3D+time datasets of ever-increasing size, we propose an estimator of cell segmentation accuracy that is detector-independent and does not require any ground truth nor priors on object appearance. In a nutshell, our method learns the dynamic parameters of each cell to detect inconsistencies in local displacements induced by segmentation errors. On a test dataset presenting contrasting densities and dynamics (organoids and collagen matrix), our approach was able to identify the best segmentation tool

between state-of-the-art deep learning algorithms. In future works, this framework will be used to guide the modeling through insight into measurement artifacts.

Growth Fluctuations in Bacteria
Farshid Jafarpour

Genetically identical bacterial cells, even in identical environments, exhibit significant variability in their phenotypic behavior such as their growth rates, division sizes, and generation times. With recent advances in single-cell technologies, we now can measure not only the distributions of these quantities but also the correlations between these variables both within and across generations. These statistical descriptions have paved the way for more accurate models of cellular growth and division. In this talk, I will discuss how the details of these new phenomenological models, such as fluctuations in single-cell growth rates and the mechanism of cell-size control, affect various population-level quantities.

A mechano-osmotic feedback couples cell volume to the rate of cell deformation
Amit Singh Vishen

Mechanics has been a central focus of physical biology in the past decade. In comparison, how cells manage their size is less understood. In this talk, I will present a recent work in which it is shown that a parameter central to both the physics and the physiology of the cell, its volume, depends on mechano-osmotic coupling. Cells change their volume depending on the rate at which they change shape when they spontaneously spread, or when they are externally deformed. Cells undergo slow deformation at constant volume, while fast deformation leads to volume loss. This phenomenon is explained by a mechanosensitive pump and leak model. The model and experiments suggest that volume modulation depends on the state of the actin cortex and the coupling of ion fluxes to membrane tension. This mechano-osmotic coupling defines a membrane tension homeostasis module constantly at work in cells, causing volume fluctuations associated with fast cell shape changes, with potential consequences on cellular physiology.

Inferring collective dynamics in groups of social mice
Xiaowen Chen

Social interactions are a crucial aspect of behavior in many animal species. Nonetheless, it is often difficult to distinguish the effect of interactions from independent animal behavior (e.g. non-Markovian dynamics, response to environmental cues, etc.). In this talk, I will address this question in social mice, where we infer statistical physics models for the collective dynamics for groups of 15 mice, housed and location-tracked over multiple days in a controlled environment. We reproduce the distribution for the co-localization patterns using pairwise maximum entropy models, and find that the resulting local fields successfully predict the transition rates. To capture the long-tailed waiting time distributions, we develop a novel inference method that can tune the dynamics while keeping the steady state distribution fixed. These models are biologically meaningful, and are able to distinguish the effect of social-impairment drugs on autism in the mice model.

Collective phenomena in active Brownian particles
Lorenzo Caprini

Systems of active matter extract energy from the environment and convert it into directed motion that is responsible for fascinating collective phenomena. After introducing simple stochastic models, such as active Brownian particles and active Ornstein-Uhlenbeck particles, to describe the behavior of active systems, I will provide an overlook of their collective effects. Purely repulsive active particles show motility induced phase separation, a non-equilibrium coexistence between a low and a high-density phase, that is characterized by the spontaneous alignment between the particles' velocities in the denser phase. Despite the absence of alignment interactions, the system displays spatial velocity correlations which are characterized by an exponential shape and have no passive counterparts. Attractive non-aligning active particles show coarsening and cluster formation, as usual in passive systems, but also the onset of a first-order phase transition from a disordered phase, with small clusters traveling in random directions, to an ordered phase, showing a flocking cluster. In both cases, I will present suitable theoretical predictions supporting the numerical results and explaining how velocity alignment can spontaneously emerge from the interplay between persistent active forces and particle interactions.

Natural swarms in 3.99 dimensions
Giulia Pisegna

Recent data on strongly correlated biological systems show the validity of scaling laws as one of the fundamental traits of collective behaviour. Field theoretical techniques, such as the Renormalization Group, thus became useful tools to describe living systems as bird flocks, cell colonies and insect swarms. Experiments unveiled traces of critical dynamics in the latter system, exhibiting an inertial dynamics in the velocities and a dynamical critical exponent $z \sim 1.2$. To rationalise this evidence, we develop an inertial active field theory in which the velocity is coupled to its generator of internal rotations, namely the spin, through a mode-coupling interaction. Supported by the indication of weak density fluctuations in insect swarms, we study its near-critical regime with a one-loop Renormalization Group approach under the assumption of incompressibility. The presence of friction in the dynamics of the spin rules a paramount crossover between two fixed points: the unstable underdamped fixed point with $z = 1.3$ and the stable overdamped fixed point with $z = 1.7$, where dissipation takes over. We show how finite-size systems with weak dissipation, such as swarms, can actually exhibit the critical dynamics of the unstable fixed point thus providing a theoretical result which is in fair agreement with experimental data.

Growing in flows: from scaling laws to microbial jets
Severine Atis

Biological systems can self-organize in complex structures, able to evolve and adapt to widely varying environmental conditions. In this talk, I will illustrate how simple growth dynamics, when coupled with environmental properties, can lead to a diversity of self-organization phenomena in two experimental model systems: reaction waves propagating in disordered flows, and living microorganisms growing on viscous substrates. Resulting from the balance between molecular diffusion and nonlinear chemical kinetics, autocatalytic reactions can generate self-sustained fronts which propagate like progressive waves. I will show that in the presence of a disordered flow, the front fluctuations display scaling laws consistent with the universal behavior predicted by the Kardar-Parisi-Zhang stochastic growth model. Controlled by the mean flow amplitude, the system encompasses three distinct universality classes associated with different front morphologies and dynamical behaviors. I will then focus on mutual interactions between microbial growth and fluid flows. I will show that the metabolic activity of an expanding population of microorganisms can produce strong hydrodynamical flows when grown on top of a viscous medium. These flows in turn affect

the growth dynamics and can drive positive feedback phenomena such as accelerated propagation, fragmentation of the initial colony and the formation of growing microbial jets.

From active colloids to programmable micromachines
Quentin Martinet

Engineering micromachines open interesting perspectives to probe and manipulate matters at small scale but it also encounters the challenge of assembly and reconfigurability at this size. We previously demonstrated a new approach, templated assembly, which exploits optical forces and the activity of the colloids to create autonomous, mobile, stable and reprogrammable architectures. We show the assembly and control of a family of self-spinning cogwheels with varying teeth numbers, formed by colloidal microswimmers that power the structure. Leveraging the angular momentum of optical vortices, we control the direction of rotation of these centrosymmetric structures. We study pairs of interlocking cogwheels that roll over each other in a random walk and curvature-dependent mobility. We take advantage of this feature to achieve self-positioning of cogwheels on structures with variable curvature and program micro-robots. We finally highlight their practical relevance for operation at small scale with the ability to pick up, transport and release a load. This work highlights untapped opportunities of manufacturing at microscale using self-positioning components and constitutes a step towards autonomous machinery with external control and programmable micro-robots.

Undecided individuals can restore agreement when asocial behaviour hinders group consensus
Andrea Giovanni Reina

Populations often need to make consensus decisions despite the sporadic asocial change of opinion by its individuals and the presence of minorities of stubborn asocial individuals. We show that one of the most prominent models of opinion dynamics—the voter model—is unable to lead to any consensus upon the introduction of minimal asocial behaviour. We show that an alternative model of comparable simplicity based on inhibitory signals—the cross-inhibition model—can instead reach a consensus notwithstanding high levels of asocial behaviour. The results predicted by the mean-field models are confirmed by experiments with swarms of 100 locally-interacting robots. Our analysis helps explain why inhibitory signals evolved in biological systems that need group consensus despite operating in noisy contexts, such as social insect colonies and neuronal populations. We also demonstrate the relevance of our findings for designing resilient swarms of minimalistic robots.

Emergence and function of irreversibility in neural systems
Christopher W. Lynn

Living systems are fundamentally irreversible, breaking detailed balance and burning energy at microscopic scales to execute biological functions. The human brain, for example, expends up to 20% of the body's metabolic output to carry out computations and perform cognitive tasks. But how do large-scale violations of detailed balance – from the collective firing of neuronal populations to whole-brain activity – enable higher-order functions, such as cognition and movement? Moreover, how does the collective irreversibility of these complex systems emerge from the fine-scale dynamics of individual units (neurons or brain regions) at the scales below? Here, I will discuss recent work that aims to begin addressing these questions.

Probing transfer learning with a model of synthetic correlated datasets
Federica Gerace

Transfer learning can significantly improve the sample efficiency of neural networks, by exploiting the relatedness between a data-scarce target task and a data-abundant source task. Despite years of successful applications, transfer learning practice often relies on ad-hoc solutions, while theoretical understanding of these procedures is still limited. In the present work, we re-think a solvable model of synthetic data as a framework for modeling correlation between data-sets. This setup allows for an analytic characterization of the generalization performance obtained when transferring the learned feature map from the source to the target task. Focusing on the problem of training two-layer networks in a binary classification setting, we show that our model can capture a range of salient features of transfer learning with real data. Moreover, by exploiting parametric control over the correlation between the two data-sets, we systematically investigate under which conditions the transfer of features is beneficial for generalization.

How to win the lottery with a single ticket
Luca Saglietti

Curriculum learning -- seeing training examples in a curated order -- seems to be a requisite for effective learning in animals and humans. Yet, its application in neural networks yields surprisingly alternating results. In this work, we explore the interplay between over-parameterization and the effectiveness of curriculum. In particular, we investigate a question about the necessity of curriculum strategies when the learning model is already able to achieve good generalization by simply discovering a good solution nestled within its complex structure. In an online setting, we provide a theoretical analysis of the learning dynamics of a two-layer network trained on a XOR-like Gaussian mixture. Taking the signal-to-noise ratio in the Gaussian mixture as a proxy of the hardness of the learning examples, we show that a curriculum effect can be traced only when the degree of parametrization of the model -- the number of hidden units -- is barely sufficient to solve the learning problem. In the over-parameterized regime, this effect vanishes as the "lottery-ticket" phenomenon allows perfect learning regardless of the order of the training examples. Empirically, we show similar results in simple experiments in ML benchmarks and with more complex network structures.

Sperm cells in micro-traps: motility sorting and swimming precision
Claudio Maggi

Sperm swimming is crucial to fertilise the egg in nature and in assisted reproductive technologies. In this talk I will show how we have implemented a passive technique for the amplification of motile bull sperm concentration. This is realised by building micro-chambers capable of trapping swimming sperms yielding a significant enhancement of motile cells density in the traps. Fabricating chambers with different shape and size highlights the ingredients that are key to optimal trap design. In the second part of the talk I will show we have used an array of micro-cages to trap the sperms' cell bodies and accurately track the spatial modes of the sperms' flagella during their beating cycle. By studying accurately the fluctuations of the dynamics of the flagellum we find that the maximum precision of this motion is close to the estimated precision of one single dynein molecular motor actuating the flagellar axoneme. I will discuss how the maximum precision of individual molecular motors is related to their energy dissipation by the thermodynamic uncertainty relation and how the precision level of the whole flagellum can be explained by a schematic model with strong motor-motor coupling.

Tissue responses to dynamic changes of curvature
Caterina Tomba

The formation of epithelial tubes takes place during organogenesis and this structural feature is then maintained in several organs. For instance, during neurulation, epithelial tissue deforms in tubular shape, as an intermediate process at the origin of the central nervous system. Then, in the gut, this tubular geometry is essential to transport gases and liquids in the body. These shape changes at the tissue level involve processes at the cellular scale, like cell shape changes, rearrangement and proliferation. Today, for example, the understanding of the mechanisms underlying epithelial tube formation remains elusive due to the complexity to access to both the tissue and the cellular scale observation in 3D environments. Our goal is to better understand the coupling between cellular processes and tissue folding at different temporal and spatial scales. We developed a technique to fast fold an initial flat tissue in a given curvature. Its principle is to generate a differential stress in a bilayer film of PDMS (polydimethylsiloxane) that allows us to obtain an out-of-plane curvature in self-rolling substrates [Tomba et al., Dev Cell 2022]. For example, we showed that epithelia, to comply with curvature, transiently and actively swell while adapting to large curvature induction.

Bacteria surface sensing and biofilm development
Alison E. Patteson

The ability of bacteria to colonize and grow on different surfaces is an essential process for biofilm development. Here, we report the use of synthetic hydrogels with tunable stiffness and porosity to assess physical effects of the substrate on biofilm development. Using time-lapse microscopy to track the growth of expanding Serratia marcescens colonies, we find that biofilm colony growth can increase with increasing substrate stiffness, unlike what is found on traditional agar substrates. Using traction force microscopy-based techniques, we find that biofilms exert transient stresses correlated over length scales much larger than a single bacterium, and that the magnitude of these forces also increases with increasing substrate stiffness. Our results are consistent with a model of biofilm development in which the interplay between osmotic pressure arising from the biofilm and the poroelastic response of the underlying substrate controls biofilm growth and morphology.

Mechanochemical rules for shape-shifting filaments that remodel membranes
Billie Meadowcroft

Membrane reshaping proteins are important for a number of physiological cellular processes such as vesicle and viral budding, cell division and membrane repair. Recently, a new mechanism for reshaping membranes has been proposed via the study of ESCRT-III filaments. This mechanism involves the sequential exchange of filament composition to increase filament curvature which drives the deformation and scission of membranes. However, the relationship between the filament composition and its mechanical effect is lacking. We develop a kinetic model for the assembly of composite filaments that includes protein–membrane adhesion, filament mechanics and membrane mechanics. We identify the physical conditions for such a membrane remodelling and show this mechanism is efficient because sequential polymer assembly lowers the energetic barrier or membrane deformation. Beyond their biological application, our findings lay the groundwork for designing shape-shifting materials at the nanoscale.

Biomimetic emulsions: from morphogenesis to cell-cell communication
Lea-Laetitia Pontani

We use biomimetic oil droplets to understand the physical basis of collective remodeling in biological tissues. In particular, we focus on the interplay between adhesion and mechanical forces to control the emergence of tissue architecture during morphogenesis. To do so we designed biomimetic emulsions in which we can control the adhesion strength between the droplets. We then study the mechanical behavior of these adhesive emulsions under an applied perturbation. For instance, we can flow them in microfluidic channels exhibiting a constriction that applies a mechanical stress on the emulsion. In such experiments, we measure how adhesion tunes the way in which the droplets deform or rearrange their positions to go through the constriction. Conversely, oil droplets are used inside developing zebrafish embryos as local biocompatible force sensors: how the droplet deforms inside a specific tissue allows us to quantify the local forces at stake. In particular, we currently use this technique to unravel the role of mechanical forces for neuronal development in the zebrafish. In parallel to these approaches based on oil droplets, we also make inverted emulsions (water droplets in oil) to study cell-cell communication within tissues. Indeed, in developing tissues, chemical information can be transmitted between the cells through channels. If these channels open as a function of the stress applied on the cell, the intercellular communication in such developing tissues can be patterned by the forces at play within the tissue. To tackle that question in a simplified framework, we developed another type of biomimetic emulsions in which water droplets are connected by lipid membranes and can communicate between each other through channels that are either passive or sensitive to an applied stress, i.e. mechanosensitive. Studying the dynamics of molecular transport as a function of an applied stress will therefore shed light on mechanosensitive pathways of patterning in morphogenesis.

Skin colour patterning: the example of the ocellated lizard
Szabolcs Zakany

The colour patterning of animal skin is a striking example of how living matter spatially self-organises. In most cases, this process happens during embryogenesis. However, in the case of the ocellated lizard (Timon lepidus), the adult pattern is established post-hatching, thus giving a great opportunity to study the dynamics of skin patterning in vivo. The final distribution of green and black skin-scales arranged in a 'labyrinthine' pattern is reached through a series of scale colour switches, which can be modelled in different ways. First, we consider a phenomenological model in terms of a 'stochastic cellular automaton' where the skin-scales provide the spatial discretisation. This description gives an interesting link with the Ising model: in this picture the lizard pattern is a frustrated anti-ferromagnet. Second, we consider an effective model of interactions between chromatophores which takes the form of a reaction-diffusion system in a domain with varying thickness, representing skin-scales. In this model, the patterning is the consequence of a Turing instability, and the peculiar scale-by-scale colouring and colour switching is a consequence of the skin-scale geometry. An extra feature of the model is that the precise colour of a green (or black) skin-scale has a subtle dependence on the number of nearest neighbour skin-scales which have the same colour. This prediction could be successfully verified in real lizards.

Poster List

Monday 17 April

1. Ziepke Alexander, Ludwig-Maximilians-University Munich
2. Chatzittofi Michalis, Max Planck Institute for Dynamics and Self-Organization
3. Koehler Lara, Université Paris Saclay
4. Zippo Emanuele, Gutenberg University of Mainz
5. Jimenez Edison Rafael, Universit of Bordeaux
6. Diaz Hernandez Rojas Rafael, Sapienza University of Rome
7. Knight Jacob, Imperial College London
8. Zhang Yiwei, University of Luxembourg
9. Pineros William, University of Luxembourg
10. Banerjee Tirthankar, University of Luxembourg
11. Manacorda Alessandro, University of Luxembourg
12. De Luca Filippo, Ludwig-Maximilians-Universität (LMU) Munich
13. Willems Vivien, University of Bordeaux
14. Lin Zi, University of Bordeaux
15. Ledesma-Motolinía Mónica, Benemérita Universidad Autónoma de Puebla 16. Richardson Alex, University of Edinburgh
17. Bonfanti Silvia, NOMATEN
18. Ariosto Sebastiano, Uninsubria
19. Conforto Filippo, University of Edinburgh
20. Chiang Michael, University of Edinburgh
21. Brezin Louis, Boston University
22. Blot Natalie, Ecole Superieure de Physique et Chimie Industrielle de la Ville de Paris

Wednesday 19 April

1. Derivaux Jean-François, University of Padova
2. Materne Anne, Max Planck Institute for the Physics of Complex Systems
3. Al-Asmar Alid, Toulouse III University
4. Abdoli Iman, Leibniz-Institut für Polymerforschung Dresden e. V.
5. Nejad Mehrana, University of Oxford
6. De figueiredo Yoann, CNRS-LOMA-University of Bordeaux
7. Pellicciotta Nicola, La Sapienza university
8. Massana-Cid Helena, Sapienza University of Rome
9. González Albaladejo Rafael, Universidad Complutense de Madrid
10. De Remigis Eugenia, Sant'Anna School of Advanced Studies, Pisa
11. Sharma Jyoti, Scuola Superiore Sant'Anna,Pisa, Italy
12. Frangipane Giacomo, Sapienza
13. Los Rachel, TU Delft
14. Lacerda Pedro, Eötvös Loránd University
15. Zabo Andras, Eötvös Loránd University
16. Pedrosa Bustos María, University of Granada
17. Muzika Frantisek, ICH PAN
18. Horiike Yoshiaki, University of Copenhagen
19. Salicari Leonardo, University of Padova
20. Forastiere Danilo, Università degli studi di Padova

21. Potestio Raffaello, University of Trento
22. Pallucchi Riccardo, Sapienza university of Rome

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