Collective Motions of Animals and Robots
May 27-31, 2024, Cargèse France

Invited talks

Gil Ariel,
Bar Ilan University, Israel

Bacterial swarming: experiments and modelling

Bacterial swarming is a collective mode of motion in which cells migrate rapidly over surfaces, forming dynamic patterns of whirls and jets. The talk will present a physical point of view of swarming bacteria, with an emphasis on the basic physical principles underlying the swarm. Both experimental and modelling results will be described and discussed in the context of the main biological properties as well as contemporary theories of collective motion and active matter. The key point is that physics and biology are interlocked, forming a highly complex system with fascinating biological, physical and mathematical properties, who are still not fully understood.

Cécile Cottin-Bizonne
UniversitéyClaude Bernard, Lyon, France

Collective Motion: From Active Colloids to Driven Bacteria.

In the first part, we will focus on active interfaces by considering a sediment of self-propelled Janus colloids. At low densities, they behave like a perfect hot gas, but at intermediate densities, we observe new collective phenomena, such as the formation of clusters. This leads us to question whether wetting-type effects occur in these active fluids. In this context, we investigate an analogy to the classical capillary rise effect in the realm of active matter. Specifically, we examine how a non-phase separated sediment of self-propelled Janus colloids behaves when in contact with a vertical wall. In the second part we will turn to collective motion of driven active particles: magnetotactic bacteria (MTB) which remarkably, possess a magnet within their body and can thus be steered by a magnetic field. Coupled with their sensitivity to magnetism, these bacteria are sensitive to oxygen gradients (aerotaxis), and tend to accumulate where oxygen concentration is most favourable, forming a densely populated aerotactic band. Those systems can be seen as swimming compasses, whose organization also depends on the hydrodynamic or chemical fields, thus leading to very rich behaviors.

Leticia F. Cugliandolo
Sorbonne University, Paris

Active Brownian many-body systems: structure and dynamics

Active Matter systems exhibit a much richer phenomenology than their passive counterparts and pose manifold fundamental statistical physics questions. I will describe our recent results on two-dimensional many-body active Brownian particle and dumbbell models. In particular, I will discuss their peculiar phase diagrams, steady state structure and dynamics, and will put special emphasis on the analysis of topological defects and cluster motion.

Ramiro Godoy-Diana
ESPCI, Paris, France

Collective fish swimming dynamics: insights from laboratory experiments

I will discuss our recent work using laboratory experiments with live fish to study the problem of collective fish swimming from different perspectives. In the first part I will discuss the case of interactions between a pair of neighbouring fish as the basic building block of a group of swimmers, using data from a forced flow swimming channel. In addition to experiments with live fish, I will present our efforts with robotic models and numerical simulations to gain some insight into the physical mechanisms at play in such a *minimal fish school*. In the second part, I will discuss our results from another type of experimental setup: a free-swimming arena. We experimentally studied the group dynamics of a large population of fish swimming in shallow water in a rectangular tank. The structure of the group is characterised by two order parameters, milling and polarisation. A first experiment was designed to investigate the role of vision in the establishment of collective swimming dynamics, which was continuously monitored while the visual range of the fish was progressively altered by controlled illumination of the swimming arena. A second experiment, using a variation of the same free-swimming setup, was used to investigate the role of confinement in collective swimming dynamics.

Hamid Kellay
Bordeaux University, France,

From active and motile particles to flexible, deformable and motile superstructures: a new type of soft robots.

We study assemblies of rodlike robots made motile through self-vibration. When confined by circular scaffolds, dilute assemblies of these rods act as a 2D gas of particles. Above a critical surface fraction, some of the bots line up in one or more tight clusters along the corral boundary while, in the bulk, gas-like behavior is retained. We find that the unified pushing of the clustered bots on the boundary can drive collective motion: by selecting corrals that are deformable but free to move, we take advantage of surface cluster formation to force the robots to work together. The deformability of the arena allows the assembly to go through narrow slits or to circumvent obstacles. Simple tasks such as pulling a load, moving through an obstacle course, or cleaning up an arena are demonstrated. Rudimentary control of these superstructures (robots+scaffold) using light is also proposed. In a similar fashion, rudimentary fish like robots can also be used to make aquatic superstructures. These experiments and some results will be discussed.

Bertrand Maury
DMA, ENS & Paris Saclay University, Paris

Paradoxical effects in collective motions: Capacity Drop and Faster is Slower effect.

The so-called Faster is Slower (FiS) effect is commonly observed in real-life or experimental situations. In the context of evacuation processes, it expresses that increasing the speed (or, more generally, the eagerness to egress) of individuals may induce a reduction of the flow through the exit door. We propose an investigation of the various ingredients which can be mobilized to reproduce this class of phenomena. As for Social Force Models and Cellular Automata, an additional frictional term is the key ingredient to recover the FiS effect, but friction is not strictly necessary. We shall detail in particular how, in the context of non-frictional granular models, the pathologic character of an underlying discrete Laplace operator can be identified as an alternative explanation of the FiS effect.

Stefania Melillo,
La Sapienza, Roma

Characterization of lab-based swarms of Anopheles gambiae mosquitoes.

Mosquito copulation is a crucial determinant of its capacity to transmit malaria-causing*Plasmodium* parasites as well as underpinning several highly-anticipated vector control methodologies such as gene drive and sterile insect technique. For the anopheline mosquitoes responsible for African malaria transmission, mating takes place within crepuscular male swarms which females enter solely to mate. However, the mechanisms that regulate swarm structure or that govern mate choice remain opaque. We used 3D-video tracking approaches and computer vision algorithms developed for the study of other complex biological systems to document swarming behavior of a lab-adapted *Anopheles gambiae* line in a lab-based setting. By reconstructing trajectories of individual mosquitoes lasting up to 15.88 s, in swarms containing upwards of 200 participants, we documented swarm-like behavior in both males and females. In single sex swarms, encounters between individuals were fleeting (< 0.75 s). By contrast, in mixed swarms, we were able to detect 79 'brief encounters' (> 0.75 s; < 2.5 s) and 17 longer-lived encounters (> 2.5 s). We also documented several examples of apparent male-male mating competition. These findings represent the first steps towards a more detailed and quantitative description of swarming and courtship behavior in one of the most important vectors of malaria.

Alexandre Nicolas
University Claude Bernard, Lyon, France

How to model the dynamics of pedestrians? -- Walking a fine line between game theory, physics and transportation science

Over the decades, Statistical Physics has extended its realm by gradually relaxing the constraints obeyed the `particles' that it considers, allowing them to move away from deterministic equations of motion, then to be self-propelled and even to undergo non-reciprocal interactions. I will argue that a whole new zoo of active assemblies call for the introduction of an even broader class of interactions, whenever the particles are endowed with decision-making capabilities. In this context, the choices of motion of the entities in interaction get intertwined. This will motivate a glimpse into game theory. In a second stage, focusing on the example of pedestrian crowds, a relevant issue for transportation science, we will delve into the visible implications of these decisional capabilities and explore to what extent the anticipation that comes along with them can be integrated into a tractable modelling framework. Effectively, this will come down to reducing the dimensionality of the problem along the time component, by an astute change of variables in the interactions. Finally, I will expose a way to delineate the regimes where these specific features of crowds (as compared to more basic self-propelled particles) come into play.

References for the second stage

Echeverría-Huarte, I., & Nicolas, A. (2023). Body and mind: Decoding the dynamics of pedestrians and the effect of smartphone distraction by coupling mechanical and decisional processes. Transportation Research part C: emerging technologies, 157, 104365.
Cordes, J., Schadschneider, A., & Nicolas, A. (2024). Dimensionless numbers reveal distinct regimes in the structure and dynamics of pedestrian crowds. PNAS Nexus, 3(4), pgae120.

Marina Papadopoulou
Swansea University, UK

Animal groups into the Swarm-Verse: understanding collective motion across species & ecological contexts

From the foraging of ungulates and primates to the bait ball of fish under attack and the murmurations of starlings, the dynamics of animal groups fascinate us with the mystery of their underlying social interactions. Identifying unique and common traits across systems is necessary to understand the self-organized mechanisms of their emergence, as well as the ecological and evolutionary processes that shape this diversity. In this talk, I will present ongoing projects on several species, such as schools of Amazon mollies, flocks of European starlings, and troops of chacma baboons, emphasizing on the importance of comparisons across systems and the value of biohybrid methods to study animal collectives. Our studies focus on three main goals: (1) investigate the role of individual heterogeneity in collective behaviour, (2) identify inter- and intra- specific variation in collective motion and decision-making, and (3) disentangle the emergence of complex patterns of collective escape. We approach these through the remote sensing of groups' movement in the laboratory and the field, the use of robotic predators and conspecifics (namely the RobotFalcon and the Robofish), and the development of data-inspired agent-based models. Finally, I will introduce the Swarm-Verse: a framework to study collective motion through conceptual 'swarm spaces' that capture variation across many pairwise and group-level metrics, and highlight the application of our findings in the field of swarm robotics and wildlife conservation.

Julien Pettre
Inria, Rennes, France

Modelling and simulation of human crowds: the emergence of machine learning models and the question of training data.

As the field of crowd simulation evolves, the importance of the data that feeds the simulation models becomes ever more prominent. Initially useful for calibrating and evaluating simulators, the evolution of modelling methods towards data-driven or machine-learning techniques is making the importance of data even more significant. But the very definition of crowd data is evolving in the field, and the issue of the difficulty of acquiring it is a concrete obstacle to progress in the field. In this presentation, I will talk about the opportunities offered by virtual reality for acquiring data more easily that is useful for modelling crowds, and I will discuss the limitations for taking into account certain phenomena, including physical interactions within crowds.

Franck Ruffier
Aix Marseille Univ, CNRS, ISM, France

From individual to collective behaviors based on optical flow

Numerous individual behaviors can be explained by optic flow-based robots [1]. Insects such as bees maintain optic flow constant by adjusting their ground speed in tapered corridors [2] and their height over moving floor [3] as well as during landing [4]. The same behaviors were reproduced on aerial robots using the same optic flow regulation scheme [5, 6]. Furthermore, bees oscillate up and down while foraging and bees wobble around hover. Again, the same behaviors were reproduced on flying robots to assess distance travelled and to stabilize attitude based on optic flow: (i) the distance travelled can be gauged because the optic flow divergence created by these up-and-downs [7] and (ii) around hover, the presence of unobservable states on the basis of optic flow leads to slight attitude oscillations, reminiscent of insect wobble [8].

At the same time, several collective behaviors can be explained using a simulation based on optic flow and early vision [9]. To simulate these collective behaviors, the same rules are followed by all the individuals. The first rule is attraction, based on the optical size of the individuals as perceived by each individual in his visual field. The second rule is alignment based on optical flow composed on translational and divergence terms. Using these two rules, we can recreate the three main collective behaviors: (i) swarming, like a group of bees or mosquitoes flying together in the same area, (ii) schooling, like a flock of birds flying together from one place to another, and, (iii) milling, as in a group of fish circling in a swirling motion. Vision is enough to trigger these 3 main collective behaviors known in the animal world [9].

[1] Roubieu *et al, Bioinspir Biomim,* 2014
[2] Portelli *et al*, *PLoS One*, 2011
[3] Portelli, Ruffier & Franceschini, *J Comp Physiol A*, 2010
[4] Franceschini, Ruffier & Serres, *Curr Biol*, 2007
[5] Ruffier & Franceschini, *Robot Auton Syst,* 2005
[6] Expert & Ruffier, *Bioinspir Biomim,* 2015
[7] Bergantin *et al*, *J R Soc Interface*, 2021
[8] de Croon et al., *Nature*, 2022
[9] Castro, Ruffier & Eloy, *PR Research,* 2024

Clément Sire
Laboratoire de Physique théorique, CNRS, Toulouse, France

Measuring the social interactions between fish and a robot-fish.

In robotic platforms, it is essential to define autonomous models controlling the robot. In addition, when a robot is expected to mimic the behavior of real animals or is even interacting with them, the model implemented in the robot should reproduce the behavior and social interactions observed for the corresponding animal. In the context of fish schools, I will present three general methods to generate realistic models which can be implemented in a robot interacting with fish: mathematical model based on the reconstruction of social interactions between fish, deep learning models trained on real fish trajectories, and a novel parameter-free kernel method. I will then present the implementation of mathematical and deep learning models in the LureBot, a robot-fish interacting with real fish. In particular, the collective dynamics of the fish and robot will be characterized, and we will discuss the different sources of the "reality gap" between the behavior of the robot and actual fish. Ultimately, this robotic platform constitutes a powerful tool to study the social dynamics of fish and their response to a controlled perturbation.

Guy Theraulaz
CRCA, CNRS, UMR 5169, Université Paul Sabatier, Toulouse, France

Data-driven modeling of collective behavior in schooling fish

Abstract: Swarms of insects, schools of fish and flocks of birds exhibit an impressive variety of collective movements. These puzzling phenomena raise questions about the interaction rules that govern the coordination of individuals' motion and the emergence of large-scale patterns. While numerous models have been proposed, there is still a strong need for detailed experimental studies to foster the biological understanding of such phenomena. I will first describe the methods that we have developed in the recent years to characterize the social interactions involved in the coordination of swimming in Rummy-nose tetra (*Hemigrammus rhodostomus*) from trajectory data gathered at the individual scale. This species of tropical fish performs a burst-and-coast type of swimming that consists of sudden heading changes combined with brief accelerations followed by quasi-passive, straight decelerations. Our results show that both attraction and alignment behaviors control the reaction of fish to a neighbor. I will present how these results can be used to build a model of spontaneous burst-and-coast swimming and social interactions of fish, with all parameters being estimated or directly measured from experiments. This model shows that the simple addition of the pairwise interactions with the two most influential neighbors quantitatively reproduces the collective behavior observed in groups of fish. The model also shows that there must exist a minimum

level of alignment and attraction between fish to maintain group cohesion and allow the emergence of schooling and milling. Then I will show that when fish are under stress, they change the intensity with which they interact with each other, so that they collectively reach a critical state at the boundary between schooling and milling, a zone where the sensitivity of the school to perturbations is also maximal. Finally, I will present a swarm robotic platform with which we investigate the impact of collision avoidance based on speed control on the group behavior. This platform combines the implementation of the fish behavioral model and an engineering control system to deal with real-world physical constraints. Remarkably, and as already observed in the model simulations, even when robots only interact with their most influential neighbor, our results show that the group remains highly cohesive and polarized while reproducing the behavioral patterns observed in groups of fish in experimental conditions. Overall, our results suggest (1) that fish have to acquire only a minimal amount of information on their environment to coordinate their movements when swimming in groups, and (2) that they can self-tuned the intensity of their social interactions when they are stressed so that collectively the school enters a critical state, allowing fast behavioral changes in response to threats.

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Iker Zuriguel
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Bottleneck flow of macroscopic active matter: animals and robots as a benchmark to understand pedestrian evacuations.

When a group of active particles or live beings pass through a narrow gate, the number of interactions among the agents experiences a remarkable increase leading to the emergence of interesting collective behaviour. Although this bottleneck scenario is interesting for different disciplines, it is the field of pedestrian dynamics the one in which probably becomes more important. Indeed, flow through gates mostly determine total evacuation times in crowded places provoking people accumulation that may ultimately cause stampedes, falls and fatalities.
Along this talk, I will compare the outcomes of experiments with robots and sheep with pedestrians. These distinct frameworks will allow demonstrating the physical origin behind the Faster is Slower effect. At the same time, I will present several unresolved issues such as whether a suitably placed obstacle in front of a gate may improve the flow or not. The dissimilar results obtained in different systems and conditions will be used to highlight the differences and similarities among pedestrian, sheep and robot collective motion.
