Are there leaders in active systems?

Nom des responsables du stage ou thèse: Cesare Nardini
(Theoretical & numerical internship, possibly leading to a Ph.D.)

Nom Laboratoire : SPEC, CEA-Saclay, UMR 3680
e-mail : cesare.nardini@gmail.com
Téléphone : 06 32 33 27 70
Lieu du stage: Saclay/Paris
Stage uniquement : OUI
Thèse uniquement: NON
Stage pouvant déboucher sur une thèse : OUI
Financement proposé : OUI (stage)

In a nutshell: Developing theoretical tools to reliably identify leaders in active systems.
Expected skills: Basic statistical mechanics methods and willingness to perform both analytical and numerical work. Curiosity on statistical methods is welcomed.

Active systems are formed of units that are able to extract energy from the environment and dissipate it to self-propel. Examples are found everywhere in nature: flocks of birds, animal swarms, suspensions of bacteria and tissues are all biological active systems. Scientists have also built several synthetic active systems in the lab using catalytic colloidal particles or micro-robots. A strong research activity is currently ongoing in describing the collective behavior of active systems and future applications may encompass the engineering self-assembling materials using active units.

Do active systems posses leaders – units that influence the system more than how they are influenced by them? The answer obviously depends on the specific system at hand and it is of primary importance in biology. Understanding it can also be fundamental in controlling the collective behaviour of artificial active systems, as this might be much easier to do so in the presence of leaders.

Yet, the very question of whether biological active systems have leaders and, if so, how to identify them, is very open. Understanding this is indeed akin to ask what are the causal relations between different agents, or between each agent and macroscopic properties such as the mean orientation of the active particles. If, for example, a bird by turning causes the all flock to turn – while this is not happening when other birds turn – the first bird is what we would call a leader. This question is crucial for biologists and some progress has been done in the physics community working on small flocks of birds [1]. Yet progress was so far severely limited by the techniques used which are not necessarily robust to non-linear effects, memory or external perturbations, and are known to lead to wrongly identify leaders in cases where there are none [2,3]. Furthermore, most methods for causal inference are limited to studying small systems, at most composed of a few tens of degrees of freedom $N \sim 10$: this is because they are based on information-theoretic quantities whose computational evaluation is exponential in N.

Well beyond the study of active systems, disentangling mere correlations from causation in complex systems is a subject of huge importance. The study of this dates back, at least, to the works of Granger [5] and Weiner that addressed the problem in linear systems (leading to the 2003 Nobel prize in economics to the former). Non-linear systems are much more complex and significant amount of work has been done in the last 20 years to build reliable techniques (see for example [5,6]).

The internship will focus on investigating whether we can reliably identify leaders in minimal models of many-body active systems by using a recently developed technique for doing so [7]. This will amount at analytical work on the information-theoretic techniques for the identification of causal relations in non-linear systems, and numerical work performed on applying these techniques to agent-based models of active matter. The work will open the way for applying similar methods to experimental data of biological systems, and it will provide insight in whether it is useful to have leaders for controlling the collective behavior of synthetic active systems. The project is suitable for being continued as a PhD.

[1] M. Nagy et al, PNAS 110 (32) 13049, 2013; [2] S. Sulimon et al., Science advances 8.6, eabj1720, 2022; [3] M. Porfiri, Animal Behavior and Cognition 5.4: 341, 2018; [4] CWJ Granger, Econometrica: journal of the Econometric Society, 424, 1969; [5] T Schreiber, PRL 85, 461, 2000; [6] RG James et al., PRL 116, 238701, 2016; [7] V del Tatto et al., arXiv preprint arXiv:2305.10817