Are there leaders in active systems?

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(Theoretical & numerical internship, possibly leading to a Ph.D.)

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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? These are components that influence the system more than how much they are influenced by them. The answer obviously depends on the specific system at hand, it is of primary importance in biology, and its understanding can also be crucial in developing controlling strategies for artificial active systems.

Yet, the very question of whether biological active systems have leaders and, if so, how to identify them, is almost entirely open. Understanding whether leaders are present 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. While some progress has been done in the physics community working on small flocks of birds [1], this was severely limited by the techniques used which are not necessarily robust to non-linear effects, memory or external perturbations. 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.

Disentangling mere correlations from causation in complex systems is a subject of huge importance in a variety of fields. 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. The skills required are a Master-level training in theoretical or statistical physics; no experience on active matter or biophysics is required.

[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