What is active matter and why do we study it?

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Introduction

An active matter system is characterised by its constituent self-propelling and self-directional units that are individually capable of extracting and dissipating free energy to result in complex, systematic behaviours [1]. The context of which these active systems emerge has been found in disordered systems, soft matter, as well as statistical mechanics, both at and out of equilibrium.

Numerous examples of active systems can be found in biological systems at all scales, from fish in a school [2] and birds in a flock, to algae, bacteria, proteins [3] and actin and microtubules in subcellular domains [1]. The general properties of active systems are often emergent collective properties that provide intriguing phenomena, from self-motility, synchronous dynamics [3], order-disorder transitions, pattern formation, swarming, and lots more.

Real-world applications

First, in practical applications, we might want borrow or mimic strategies from biological systems, with the goal of creating new synthetic materials, devices, robotics and medicine [4]. Here, the use of models is integral to provide insight into how to engineer synthetic systems. For this, the models are performed both *in vitro* (nanomachines) and *in silico* (numerical modelling). Although active systems have a parameter space far from minimal, by using appropriate approximations to form our models, even with minimal ones, we can seek to derive large-scale generality [1,5]. These systems have group-level properties derived from macroscopic orders, phases, and phase transitions, that are independent of the scale of its constituents.

For instance, a good yet minimal approximation would be a model by Viscek *et. al* [6,7]. Here, clustering is induced through a combination of self-propulsion and self-orientation in response to its neighbours. The system evolves with a two-step iteration process, and the whole system is controlled by 3 parameters. Yet, its central prediction shows phase transition from disordered, individual motion to ordered, collective motion, dictated through its minimal set of parameters [6].

While it cannot be assumed that the models used *in vitro* translate directly to what is observed in reality, they are still crucial components that when combined with more sophisticated rules or understanding from other fields, would enable useful real-world applications, an example being controlling insect pest outbreaks [6].

New physics at non-equilibrium

While we can study emergent behaviours, one challenge out of these models is to address the inverse problem; to determine the rules that lead to a desired collective state [8]. In this domain, powerful tools like machine learning can be deployed to build a robust framework analogous to equilibrium statistical thermodynamics, ultimately with the aim of providing fundamental insight into a microscopic-emergent connection [9].

Non-equilibrium results when energy exchanges and dissipation at the level of individual particles' contribution lead to irreversibility within [4,10]. This is contrasted with at-equilibrium systems, where energy effects are found at the system's boundaries [1]. Whereas we have the laws of thermodynamics and statistical mechanics in the latter type of systems that tell us about their macrostates (from their energy) and likelihood (from their Boltzmann distribution), it is not clear for the former type of systems. The difficulty lies in constructing analogues to these theories using quantities equivalent to the system's free energies. Therefore, new physics can emerge in studying this so not-well understood phenomena.

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