Research Statement

Feng Ling*

General Interests: I am in pursuit of *mechanistic* understanding of *emergent* phenomena in biological settings. In particular, I use mathematical and computational tools to study problems that are *multi-scale* in nature, complex due to *activity* present in the system (*active matter/out-of-equilibrium systems*), and exhibit *diverse* behaviors that arise from *conserved* structures (*multi-stability and bifurcation*). The goal of my research is to seek the **origins and mechanisms of diversity and coordination** in complex systems, and establish the **structure-to-function maps** for such features. Below I outline experiences that shaped my interests with plans for extensions, then conclude on a brief vision of what I hope to achieve in the future.

Understanding Cilia: Cilia are micron sized, hair-like structures that push fluid around to help cells move, and transport material for the purposes of feeding, cleaning, filtration, and/or sensing. The origin of their activity arises from a complex but relatively conserved structure composed of many semi-rigid microfilaments (microtubule doublets) plus *thousands* of molecular motor proteins (axonemal dyneins). Notably, cilia can work individually as propellers for animal spermatozoa or single-celled flagellates, move together in single or a few pairs like in algae *Chlamydomonas* in ways analogous to appendages of mammals, or show up in large groups on microorganisms like *Paramecium* and *Stentors* or on epithelial tissue of mammalian brain ventricle, airway, and reproductive tracts (*e.g.*, airway cilia can have a density of up to one million per mm^2!).

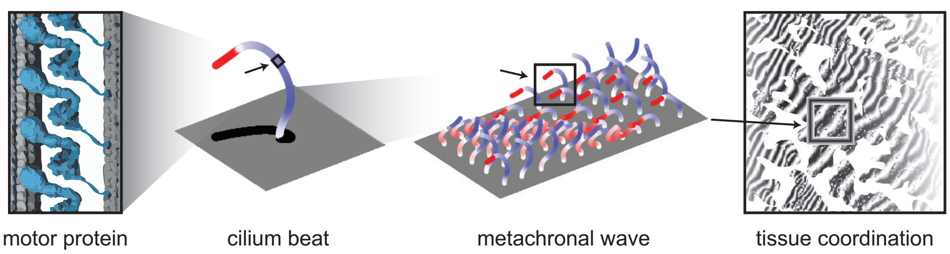

Figure 1: Cilia as a model system for multi-scale coordination: the collective motion of motor proteins drives the coordinated dynamics of ciliated tissue. Animated version (2 min). Workshop talk (7 min): youtu.be/JoyPuDofM3g

I look to answer the following questions about cilia: **(Q1)** how do nanoscale active elements work together to generate coherent oscillations for each cilium? **(Q2)** how can cilia coordinate with each other when they appear in large numbers? And **(Q3)** how does the structure of cilia and its organization give rise to the *diversity* of observed cilia motion and function?

Origin of Cilia Oscillation: (Q1) We extended the existing approach of modeling molecular motor activity using stochastic rate equations coupled to the elasto-hydrodynamics of cilia, and showed how different types of oscillations emerge depending on activity and boundary conditions [1]. This framework also provides a way to study the relationship between motor activity distribution and the direction wave travels along cilia [2]. This is important as parasites from the *Trypanosomatida* family can change their wave traveling directions to aid navigation and exploration inside infected hosts.

Origin of Cilia Coordination: (Q2) Building on a phased oscillator model of cilia, we quantified via simulation and a continuum theory how metachronal waves emerge spontaneously in ciliary array from noisy initial conditions depending on the local characteristics of individual cilium [3–5].

Instability-driven Oscillation: (Q3) I showed in a reduced model that 3D circular spinning instability arises before the onset of planar limit-cycle oscillation for buckling microfilaments [6].

*fling@usc.edu, http://gofling.me.

This moves us one step closer to the understanding of the mechanisms behind why some cilia move in 3D while others primarily move in a 2D plane. This work also inspired studies on free and pairs of cilia-like filaments [7,8], and still has potential to be applied for the analysis of filament networks.

Form-function Map of Ciliated Ducts: (Q3) We developed an active porous-media model of ciliated ducts, and showed with experimental evidence how the distribution of cilia inside the duct determines pumping performance against adverse pressure [9, 10].

Current/Future Directions: I am working on using models described above to understand the role of structural heterogeneity on the synchronization *and* flow function of ciliated tissue. This is part of an NIH funded project on predictive analysis of mucociliary clearance (movement/removal of particles dissolved in mucus of the respiratory tract), where I also had the opportunity to help out the cross-departmental proposal writing process. This collaboration showed me first hand the amount of inspiration and progress possible when working with experimentalists and their insights.

Nevertheless, the theory and tools developed for my study of cilia naturally generalizes to the study of many other emergent and collective phenomena. For example, our phased oscillator model is closely related to the general theory of *swarmalators*, where motion and synchronization are coupled to bring order and/or chaos to the entire system.

Collective Motion and RL: I led a small group effort in our lab to catch up on state-of-the-art developments in deep reinforcement learning, with some guidance from collaborators at Deepmind. We successfully applied these tools to better our understanding of optimality in fish locomotion [11] and hierarchical control of sea star tube feet [12].

I am excited to combine RL tools with analytically tractable mathematical models to study *decentralized control* and *collective motion* problems, such as how ants organize to transport objects in groups [13]. My study of octopus arm movements [14], and ongoing work on the behavior of fish schools [15] can also serve as foundations for such efforts.

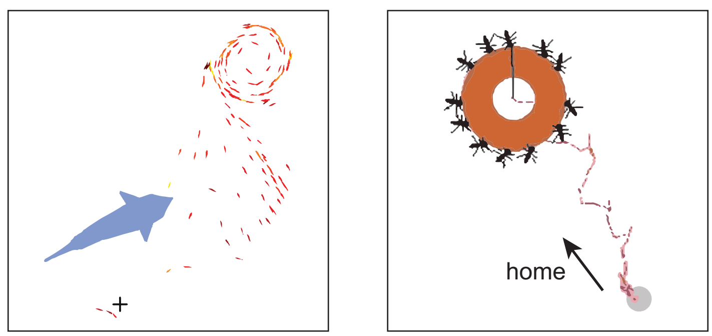

Figure 2: (left) An interactive applet for a school of dipole swimmers. (right) A group of RL ants learning to carry a donut.

Specifically, I am interested in the following: How does specialization, hierarchy and/or leaders emerge in groups driven by a common goal? How is this process affected by group size and communication overhead/network topology? What is the effect of learning and adaptation over different timescale? Is it possible to make more (efficient) progress with passive agents 'advected' by physics among active players?

Broader Vision: I plan to strengthen my grasp on theoretical tools developed by the active-matter physics community as well as concepts in evolutionary game theory, and apply them to the study of collective motion, coordination and synchronization of behaviors.

I am also interested in studying these problems at scales beyond 'simple' animals. Very recently I have been exposed to the mathematical analysis of social learners and the origin of cooperation and hierarchy [16–18]. Impressed by their elegance, however, I do see potential extensions in terms of increasing player/outcome size and geometrical/topological complexity. As the adage of emergent physics goes, "more is different," I hope to synthesize some of these thoughts with my study on the mechanical aspect of collective behavior to construct models that can produce *predictive* insights.

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