Wednesday, 25th, 10:30 **Room: C8.2.03**

MINISYMPOSIUM

MATHEMATICS AT THE INTERFACE OF COLLECTIVE BEHAVIOR AND EMERGENT PHENOMENA IN BIOLOGY

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Minisymposium Keywords: collective behavior, emergence, complex biological systems, mathematical modeling, animal behavior

Collective behavior and emergent phenomena are a hallmark of complex biological systems. Repeated interactions among the units composing such systems often result in population level activities far beyond the capabilities of any single individual in the group. As a consequence, these collective behaviors are not easily reducible to the behavior of any particular individual. However, understanding the mechanisms that underlie the processes of complex biological systems is important to developments in engineering, technology, and advancing basic knowledge of natural systems generally.

The scientific study of collective behaviors and emergent phenomena in biological systems presents challenging problems. Some of these challenges are linked to high autocorrelation in the system, the dynamical nature of the interaction networks, and the broad range in the sizes and quality of available data sets to validate mathematical and computer models. Furthermore, there is often a significant gap between researchers with training in the collection of data and researchers with training in developing theoretical tools that are most appropriate for analyzing the data or modeling the mechanisms that underlie complex systems.

The goals of this minisymposium are to 1) promote increasing collaboration between experimentalists working in collective animal behavior and theoreticians working to develop methods appropriate for gaining a deeper understanding of the biological principles of collective biological systems; and 2) highlight recent developments in research into collective behavior and emergent phenomena in biology, with special emphasis on the role that mathematical and theoretical methods are playing in this increasingly interdisciplinary field. The talks for this minisymposium will cover the application of techniques from dynamical systems modeling, Bayesian methods, agent-based modeling, etc. to understand the biological principles of collective animal behavior and large-scale emergent phenomena in biology. Furthermore, recent applications to topics ranging from robotics to crime dynamics, stemming from both the biological, and mathematical or theoretical research into collective behavior will also be presented.

Minisymposium: Mathematics at the interface of collective behavior and emergent phenomena in biology

MODELS OF COLLECTIVE BEHAVIOR

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Keywords: Collective behavior, Mathematical modeling, Complex biological systems.

Many biological systems, like animal collectives, are so complex that approaches like those of Physics (simple models giving good predictions) are rare. We will describe two modelling approaches. One is top-down, in which from basic principles thought of being relevant in animal evolution, some relationships are obtained that can be tested experimentally. We will show how estimation theory, control theory and game theory are first-principles approaches that can be of vaule to the study of collective animal behavior. A second approach is bottom-up, driven for the data. In this category I will describe three modalities with different degrees of simplicity and ability to predict. I will show tests of all these approaches in data from fish collectives, for which I will also describe a novel tracking system. I will finalize with some attempts at trying to combine the insights of top-down approaches with the ability to predict of bottom-up approaches.

Minisymposium: Mathematics at the interface of collective behavior and emergent phenomena in biology

RATIONAL COLLECTIVE DECISION MAKING, IN THE LAB AND IN THE WILD

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Keywords: Collective behavior, Mathematical modeling, Decision-making.

Humans and animals face many decisions that can be informed by social information. Classic examples include a tourist choosing a restaurant in an unfamiliar city, or a school of fish collectively deciding on a foraging location that balances food and predation risk. How groups makes decisions, and how individuals utilise social information has been the focus of much research, and several studies have purported to show that rational, self-interested behaviour can explain the characteristic features of collective decision-making. In this talk I will show how previous models fall short of a genuinely rational theory as they attempt to account for apparently irrational behaviours. I will demonstrate a fully rational model of social information use and reveal some of the surprising predictions that such a model makes. This theory will highlight the importance of understanding the observer and the experimental setting as part of the model, and I will discuss how the predictions the model makes can be reconciled with observations in the laboratory and in the wild.

Minisymposium: Mathematics at the interface of collective behavior and emergent phenomena in biology

DETERMINING CAUSE-AND-EFFECT RELATIONSHIPS FROM RAW TRAJECTORY DATA OF COLLECTIVE BEHAVIOR

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Joint work with Maurizio Porfiri (Department of Mechanical and Aerospace Engineering, New York University, New York, USA), Sachit Butail (Department of Mechanical Engineering, Northern Illinois University, DeKalb, USA)

Keywords: Collective behavior, Network theory.

In animal groups, leaders are generally considered as individuals who initiate new maneuvers, which are quickly adopted by other group members. Seen this way, the behavior of a leader causes some of the followers to change their course of action, which, in turn, drives the response of other group members. This chain of cause-and-effect relationships is ultimately responsible for the response of the whole group. In this work, we put forward a principled approach to apprehend causal relationships underlying collective behavior from raw trajectory data of individual group members.

Our approach integrates network theory and maximum likelihood estimation to combine inferences from three different classifiers—correlation based, nonlinear time series analysis based, and information theoretic—in an optimal sense. In this approach leaders are identified as individuals with the largest degree of influence on others in pairwise interactions.

From the correlation based approach, we infer leadership based on the time delay at which the cross-correlation between two time series is maximized, such that for a pair of individuals the leader would most frequently anticipate the behavior of the other. However, since actual leader-follower pairs in animals have variable time delays with intermittent change of roles, a linear relationship with constant delay assumed under cross-correlation may fail to reveal causality. To address this issue, we tap into modern techniques in time series analysis and information theory, which have been shown to deal with nonlinearities and time-varying delays. From time series analysis, we adopt the notion of extreme event synchronization, which is amenable to nonlinear relationships and has been successfully used in the reconstruction of weather networks. Leaders in this approach are identified on the basis of average delay and synchronization strength between two time series. From information theory, we utilize transfer entropy, whose application in neuroscience has demonstrated its potential to unravel functional relationships from noisy measurements. Based on transfer entropy, leaders are identified as individuals whose behavior best predicts the actions of the rest of the group.

We demonstrate our approach first on a simple self-propelled particle model, and then on a well-accepted data-driven model of fish motion from the literature. We systematically vary the number and strength of leadership in these synthetic datasets and identify them independently using the optimal classification approach. Our results show that the optimal approach outperforms the individual classifiers in terms of the accuracy of classification over a wide range of scenarios spanning different interaction strengths and uncertainty levels.

Upon validation of the approach, we turn to a preliminary experimental study, in which one fish in a shoal was exposed to acute caffeine concentration while the others were untreated. Caffeine concentration was expected to elicit an anxiogenic response on the treated individual resulting in an increased level of activity, which should have been associated with a potential leadership trait by followers. In agreement with our hypothesis, our approach revealed that the caffeine-treated individual influenced the behavior of the group, by acting as a leader.

Minisymposium: Mathematics at the interface of collective behavior and emergent phenomena in biology

WHEN CONDORCET IS WRONG (ALMOST ALWAYS) AND WHAT TO DO ABOUT IT

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Keywords: Collective behavior, Group decisions, Decision-making.

The Condorcet 'jury theorem' is a mathematical result frequently referred to in support of the 'wisdom of the crowd' effect, in which group decisions or estimates are more accurate than those of constituent members. However the Condorcet result makes a number of simplifying, but crucially important, assumptions. Here we explore how Condorcet reasoning makes systematic errors in predicting benefits of costs from pooling opinions, when applied to optimal decision-makers. We also show a very simple mechanism for resolving such errors, such that group decisions are always beneficial.

Minisymposium: Mathematics at the interface of collective behavior and emergent phenomena in biology

A COMPARISON OF POLARIZATION INDUCING MECHANISMS FOR MODELING COLLECTIVE MOTION

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Keywords: Collective behavior, Mathematical modeling, Synchrony, Collective motion.

Herds of sheep, flocks of birds, and schools of fish are fascinating examples of when individuals come together to form a group that can move and respond essentially as one unit. Over the past few decades a large number of so called self-propelled particle models have been proposed to explain how the group level structure and dynamics we observe in real world herds, flocks and schools emerges from repeated local interactions between individuals in the groups. The local interaction rules are typically based on some combination of three social forces: attraction, repulsion and orientation. Often the capacity of a model to produce polarized motion depends critically on an explicit orientation term and/or some type of asymmetry in the interactions between individuals. Here we show that introducing asynchrony in heading updates or using anticipated future positions of neighbors, rather than current positions, in heading updates induces polarization in an attraction only model with symmetric interactions. In the absence of asynchrony and anticipation this model only produces no group, milling groups and swarms. We also compare and contrast the effects of including each of the following four polarization inducing mechanisms separately into this model: asynchrony, anticipation, an explicit alignment term, and asymmetric interactions implemented via a blind zone. And based on this comparison we speculate that it may be advantageous to use asynchrony or anticipation, instead of explicit orientation terms or asymmetric interactions, to model certain real world phenomena that involves polarized collective motion.