Navigating the space of transitions in collective behavior

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From neurons in a brain [1] to fish in a school [2] to ants in a colony [3] to primates in a society [4], we are captivated by the emergent behavior of collectives. In particular, collective behavior often displays distinct aggregate states, with evident transitions among these states. How do living systems deal with and use these collective transitions in optimizing biological function?

There has been lots of speculation that living collectives address challenges of emergent behavior by making use of phase transitions. These challenges include navigating tradeoffs such as speed versus accuracy and robustness versus adaptability. Collectives also face a challenge of distributed control, since agency and adaptation are often shared across many individuals and their local interactions.

Much existing work in this area has focused on continuous phase transitions, as they create increased collective sensitivity and distributed correlations. Continuous transitions also have known connections to scale invariance and universality. We expand from this type of work in two ways: (1) we focus on not just the adaptive benefits from being near critical, but more broadly on the advantages and challenges of collectives adaptively tuning their location with respect to such transitions [5]; (2) we find and analyze not just continuous but also discontinuous transitions, which are likely just as biologically relevant.

To better consider the adaptive requirements of navigating the space of collective transitions, we make use of bifurcation theory. We argue that the language of bifurcations is a powerful way to characterize collective transitions that still maintains aspects of universality while avoiding problems with taking thermodynamic limits in adaptive systems.

Across the examples we study — neurons, fish, ants, primates — we find that collective transitions correspond to transcritical, saddle-node, and cusp bifurcations, with the co-dimension setting the number of parameters that must be adaptively tuned to make use of the transition. We also connect back to the theory of continuous phase transitions, with the simplest mean-field Ising phase transition corresponding to a cusp bifurcation when incorporating nonequilibrium dynamics.

[1] Daniels, Bryan C., Jessica C. Flack, and David C. Krakauer. “Dual Coding Theory Explains Biphasic Collective Computation in Neural Decision-Making.” Frontiers in Neuroscience 11 (2017): 1–16.
[2] Poel, Winnie, Bryan C Daniels, Matthew M G Sosna, Colin R Twomey, Simon P Leblanc, Iain D Couzin, and Pawel Romanczuk. “Subcritical Escape Waves in Schooling Fish.” Science Advances 8 (2022): eabm6385.
[3] Lynch, Colin and Bryan C. Daniels. “The cusp bifurcation and its consequences for ant foraging.” In preparation.
[4] Daniels, Bryan C., David C. Krakauer, and Jessica C. Flack. “Control of Finite Critical Behaviour in a Small-Scale Social System.” Nature Communications 8 (2017): 14301.
[5] Romanczuk, Pawel, and Bryan C. Daniels. “Phase Transitions and Criticality in the Collective Behavior of Animals — Self-Organization and Biological Function.” In Order, Disorder and Criticality, by Yurij Holovatch, 179–208. World Scientific, 2023.

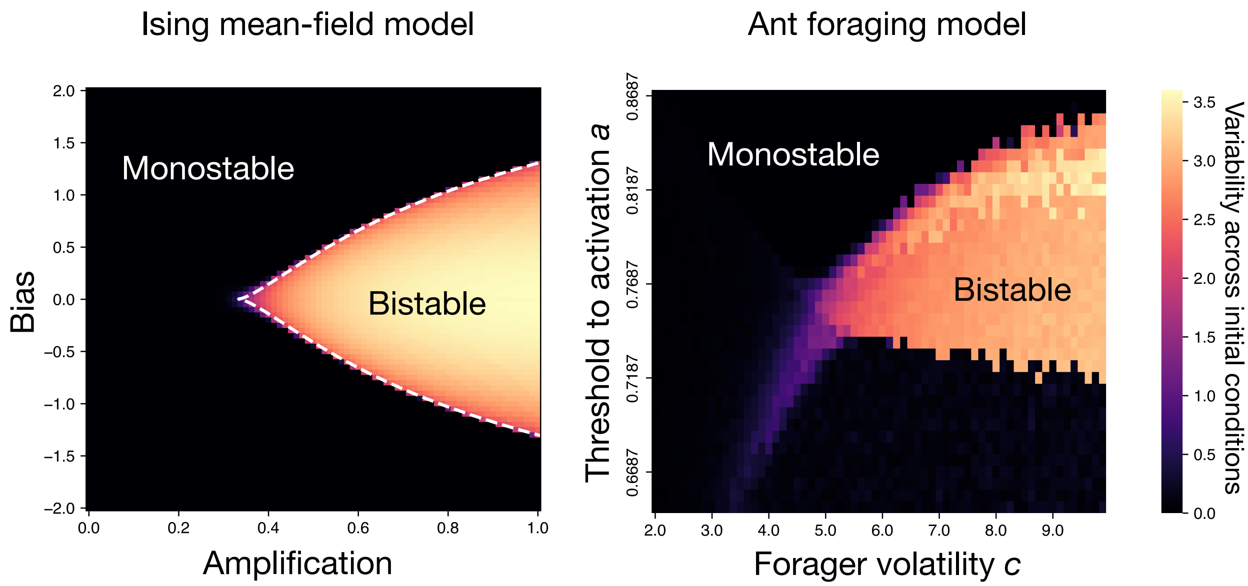

Figure 1: **Collective transitions correspond to bifurcations in both a simple model from physics and in a more complicated ant foraging model.** Plotting the variability in behavior across initial conditions (colors) highlights transitions between monostable and bistable collective dynamics. Increasing interaction strength (horizontal axis) creates bistability in both cases, but only when individual biases or thresholds (vertical axis) are tuned to the correct region. In the Ising model, dashed curves indicate the location of saddle-node bifurcations that create discontinuous jumps, and these curves join at the co-dimension 2 cusp bifurcation that corresponds to a continuous phase transition. Analogous dynamics are seen across many types of models of collective behavior, including the ant foraging model analyzed here.