

Shortcuts to state transitions for active matter

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Shortcut schemes provide an effective strategy to accelerate quasi-static processes in passive systems by introducing auxiliary controls that enable rapid transitions between equilibrium states. However, extending such shortcut frameworks to active systems remains challenging, since active particles inherently consume free energy and exhibit persistent directed motion that continuously drives the system away from equilibrium. Understanding how to achieve controlled and efficient state transitions in active matter is therefore an important problem in nonequilibrium statistical physics.

In this work, we develop a shortcut framework to realize swift state transitions in active systems operating in the weak activity regime. By introducing an auxiliary potential, the system is guided to follow a predefined distribution trajectory connecting an initial and a target state. This approach enables the system to reach the desired final distribution within a finite time, while maintaining control over the nonequilibrium dynamics throughout the process.

Since any finite-time transformation inevitably involves energetic costs, we further establish a thermodynamic description of dissipation associated with the shortcut protocol. Specifically, we derive a thermodynamic metric from the dissipative work accumulated during the process. This metric naturally induces a Riemannian manifold structure in the space spanned by the control parameters. Within this geometric framework, the protocol that minimizes the dissipative work corresponds to the geodesic path in the parameter space. This geometric interpretation provides both a conceptual understanding of optimal control in active systems and a practical method for constructing efficient driving protocols.

To illustrate the applicability of our framework, we present two representative examples of interacting active particles confined in an external harmonic trap. In both cases, the particles interact via internal potentials, and the control parameters correspond to the strengths of the external confinement and the interparticle interactions. In the first example, involving attractive harmonic coupling between each particle and the center of mass of the system, the auxiliary potential can be derived exactly, allowing analytical characterization of the optimal protocol. In the second example, involving repulsive Gaussian-core interactions, an exact auxiliary solution is not available; instead, we employ a variational approach to construct an approximate auxiliary control. Numerical results demonstrate that the geodesic protocols obtained from our geometric framework significantly reduce dissipative work compared to simple linear driving protocols, highlighting the efficiency and robustness of the proposed method.