Universal Performance Bound for Active Machines

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Energy conversion optimization in active matter stands as a core challenge in nonequilibrium statistical mechanics and soft-matter engineering. Active systems, composed of self-driven units that break detailed balance and time-reversal symmetry, enable autonomous work generation far from equilibrium, yet their finite-time energetic performance and optimal control remain poorly understood beyond passive thermodynamic frameworks. Here we develop a unified geometric thermodynamic framework to characterize the finite-time performance of interacting active machines composed of overdamped self-propelled particles. We demonstrate that the work performed over a cycle admits a natural geometric decomposition into two contributions: work extraction is driven by thermodynamic curvature, whereas dissipation is governed by the metric in the control-parameter space. The optimal cycle emerges from the interplay between the thermodynamic curvature and the metric. This geometric framework remains robust even in the fast-driving limit under weak persistence, extending validity beyond conventional slow-driving linear response approximations. Taking the active Brownian particle system constrained by a harmonic oscillator potential as a concrete illustration, we explore the influence of thermodynamic curvature on optimal control and work output based on linear response theory.

By mapping the nonequilibrium response of active systems onto Onsager-type quasi-linear current–force relations, we derive general scaling relations for work, heat, and dissipation. We show that key efficiency bounds—including maximum efficiency and efficiency at maximum power—are fully determined by a single dimensionless figure of merit. Distinct from fixed material coefficients in classical thermoelectric systems, this merit value is intrinsically protocol-dependent, encoding the coupling between self-propulsion, geometric output driven by thermodynamic curvature, and metric-governed dissipation. Our results reveal a formal identity between active engines and time-reversal-symmetry-broken thermoelectric devices, despite their disparate microscopic energy input mechanisms, establishing a rigorous bridge between active-matter thermodynamics and classical energy-conversion theory.

This work provides a solid theoretical foundation for designing high-performance active machines and bio-inspired micro-engines. It reveals that energetic limits of active systems are shaped not only by material properties but also by the information-geometric structure of control pathways. These universal principles transcend the divide between active and passive matter, offering insights into the optimized energy transduction of biological molecular motors and supporting the rational design of high-speed microrobots and synthetic micro-engines operating efficiently under finite-time nonequilibrium conditions.