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HARNESSING NON-EQUILIBRIUM FORCES TO OPTIMIZE WORK EXTRACTION

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ABSTRACT

Optimization of work extraction from non-equilibrium environments not only raises intriguing questions in thermodynamics and control, but also holds the potential to advance microscopic bio-inspired technologies. In this work, we explore optimal protocols for harmonically trapped particles driven out of equilibrium by arbitrary time-dependent internal or external forces. Beyond minimizing thermodynamic work, our protocols leverage the non-equilibrium driving forces to actively extract work, transforming transient dynamics into a source of energy.

We present exact solutions for the optimal protocol and the associated work valid for arbitrary driving forces and protocol durations. Additionally, we derive a quasistatic bound on the work, determined solely by coarse-grained time-integrated properties of the forces. The quasistatic work naturally decomposes into three contributions; *i)* an information-geometric term representing how the information contained in an initial non-equilibrium state can be converted to work, *ii)* the work associated with slowly dragging a particle in the presence of time-averaged forces, and *iii)* additional work extraction facilitated by protocols responding to fast dynamical modes. Our results show how non-equilibrium forces can be strategically harnessed, with the protocols effectively acting as automatic information engines.

Recently, increased attention has been given to active matter in the context of both optimal control problems and stochastic engine designs. Using our framework, we consider a range of examples from active matter, including particles with correlated reorientations, chiral particles, and particles with algebraic rather than exponential correlations. In all cases, work extraction is compared to the base case of simple two-dimensional active Brownian motion.

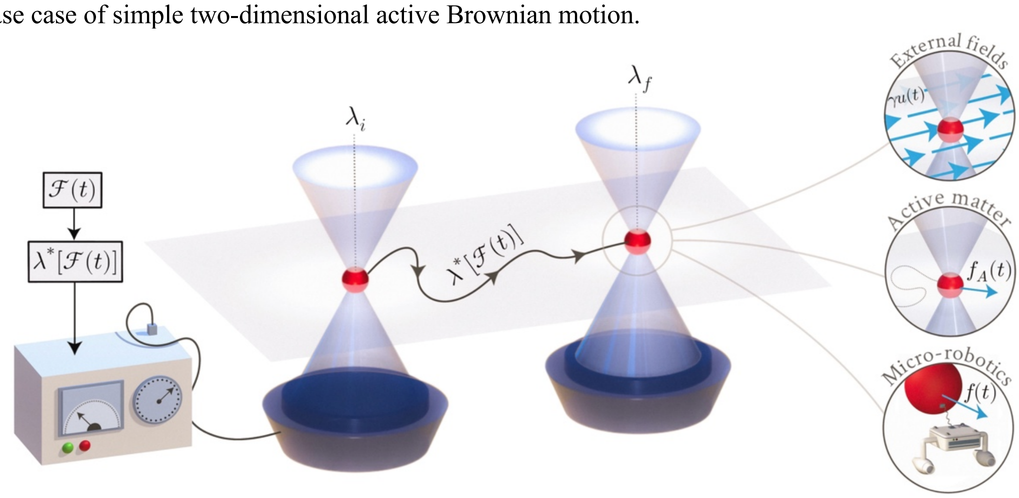

Figure 1: Optimal protocols for particle transport are derived for particles under the influence of arbitrary time-dependent forces. Given knowledge about these forces, a harmonic trap with a movable center λ(t) is tuned by the controller, at the cost of thermodynamic work. The forces may represent external drives such as applied fields or flows, or internally general forces such as in active matter. The optimal transport problem can also be interpreted in terms of micro-robotics and cargo transport, where λ(t) represents the trajectory of a micro-robot transporting a cargo that is exposed to non-equilibrium conditions.

Keywords: Stochastic thermodynamics, energy harvesting, active matter

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