Autonomous work extraction within a Szilard engine model

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A fundamental question of thermodynamics related to Landauer's principle is how much work can be extracted from a physical system in a known state, given access to a thermal bath. In recent years, particular attention has been given to this question with respect to small quantum systems, where the standard theory of thermodynamics is not necessarily applicable. Here, we consider one particular aspect of work extraction procedures: autonomy. We call a procedure autonomous if the energy-conserving evolution of the involved systems is described by a time-independent Hamiltonian and no external control is needed. To tackle this question we investigate the work extraction process of a one-dimensional Szilard engine in a semi-classical model. We consider a quantum particle interacting with a heat bath and a piston, which is modelled as a heavier classical particle.

Within this semi-classical model, we have done numerical simulations of the time evolution of the piston for different boundary conditions. We varied between an elastic box and a box that thermalizes the piston's momentum when it reaches a wall. In the elastic case very large fluctuations in the piston's position can be observed. Hence, the energy extracted from the piston's position is highly unordered and cannot be regarded as work. This changes when we use thermal boundary conditions. There are still fluctuations in the piston's position, but we can observe an increased probability to find the piston close to the wall.
Another interesting feature is that a smaller mass of the quantum particle led to a more deterministic position of the piston in the long run. Moreover, the potential energy of the piston was higher in these parameter settings. In a classical picture this corresponds to weaker but more numerous interactions between particle and piston; the limit of a vanishing particle mass corresponds to quasi static evolution of the piston. This is in agreement with standard thermodynamics of reversible transformations, which tells us that optimal work extraction can only be achieved in the quasi static limit.

Our main finding is that work extraction in a Szilard engine is possible if we allow for friction in the form of thermal boundary conditions. This raises the question whether friction is necessary for a Szilard engine to produce ordered energy. At least in our model it seems to be essential.