Universal bounds on fluctuations in thermal machines and thermal transport junctions

The second law of thermodynamics forbids the possibility of a perpetual machine of a second kind. It provides a universal upper bound on the efficiency of any thermal machine operating between two heat baths, famously known as Carnot Efficiency. But traditional thermodynamics was only concerned with average quantities because typically, fluctuations can be ignored for macro systems, for example, steam engines, automobile engines, etc. With the rapid technological development over the last several decades, we can now investigate systems of sizes that can range from hundreds of nanometers to a few nanometers, such as quantum dots, molecular motors, single atoms, etc, at temperatures that range from micro to nano Kelvin. As a consequence of these advancements, in the past two decades, various small-scale thermal machines have been realized using state-of-the-art experimental techniques like ultra cold atoms, single colloidal particles, single-molecule optomechanical systems, and Paul ion-trap technique, etc. Since these devices operate away from equilibrium, understanding non-equilibrium thermodynamic properties of such small-scale systems is an active area of research where one can no longer ignore the role of fluctuations of thermal and/or quantum origins and therefore a proper probabilistic description is required. Thus, a natural question arises that whether any universal bound exists on the fluctuations as well? In this thesis, we attempt to shed light on understanding properties of fluctuations in non-equilibrium systems and its impact on the performance of thermal machines by providing universal bounds on the fluctuations of the underlying currents. We will first show that, for a time-reversal symmetric continuous thermal machines, the relative fluctuation of the output current is always greater than the relative fluctuations of the input current in linear response. As a consequence, the ratio between the fluctuations of the output and input currents are bounded both from above and below, where the lower (upper) bound is given by the square of the averaged efficiency (square of the Carnot efficiency) of the thermal machine. Then we will generalize our findings to the machines with broken time-reversal symmetry. Later we elaborate an extension of our work to the finite-time quantum cycles, in particular for quantum Otto machines. All of these above studies and obtained universal results uncover a novel relationship among the recently discovered trade-off relations for individual currents, famously known as Thermodynamic Uncertainty Relation (TUR). TUR provides bound on relative fluctuations of individual current in terms of associated entropy production. Our work in the context of thermal machines reveals that TUR for individual currents are not independent of each other but follow a strict hierarchy in the operational regime.