Stochastic thermodynamics: Fundamental limits to precision and efficiency in the micro- and nano-world

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Stochastic thermodynamics provides a universal framework for analyzing micro- and nano-sized non-equilibrium systems. Prominent examples are single molecules, molecular machines, colloidal particles in time-dependent laser traps and biochemical networks. Thermodynamic quantities like work, heat and entropy can be identified at the level of individual fluctuating trajectories. They obey universal relations like the fluctuation theorem which sharpen the second law of classical thermodynamics.

A particularly striking example is the thermodynamic uncertainty relation, discovered in 2015. It reveals a fundamental trade-off between the temporal precision of a process and its thermodynamic cost, quantified by the associated entropy production. This relation provides a model-free upper bound on the performance of molecular motors in terms of experimentally measurable velocity fluctuations. Moreover, for steady state heat engines, this relation shows that reaching Carnot efficiency with a finite power necessarily implies diverging power fluctuations.

More broadly, in the emerging field of thermodynamic inference, consistency constraints derived from stochastic thermodynamics can be used to infer otherwise hidden properties of non-equilibrium systems. In this talk, I will introduce the main concepts and illustrate them with representative examples.