Distributed Quantum Thermodynamics: Local Operations and Resource Engines

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Understanding how thermodynamic laws constrain distributed quantum systems is essential for quantum technologies and nonequilibrium physics. Clarifying the roles of locality and communication is crucial for describing realistic quantum devices under thermal constraints.

We introduce a framework for quantum thermodynamics that clarifies the role of locality and communication in thermodynamically constrained processes. In the first part, we develop Local Thermal Operations and Classical Communication (LTOCC), a resource-theoretic model describing transformations between spatially separated systems subject to thermal restrictions. We establish a hierarchy of LTOCC protocols and their inclusion relations, highlighting their connection to semilocal thermal operations (SLTO). To support this formalism, we introduce thermal and bithermal tensors, extending stochastic constructions to thermodynamic settings and providing new mathematical tools for analysing constrained quantum processes. Within this framework, we derive fundamental limits on correlations and entanglement detection in thermodynamic scenarios, including a no-violation in the single-copy CHSH and a separation between thermal and athermal operations in the multi-copy regime.

In the second part, we refine theory of resource engines and introduce operational notions of engine performance, including efficiency. We study engines operating under thermal, SLTO, and LTOCC restrictions, deriving analytic lower bounds via the construction of tree-states – free states reachable from Gibbs states through simple two-level protocols. For SLTO engines, we provide a complete structural characterization encompassing free states, faithful monotones, and catalytic advantages. Together, these results offer complementary perspectives on distributed quantum thermodynamics, linking locality-constrained operations with the capabilities and limitations of thermodynamic machines.

(based on arXiv:2410.14550 (accepted for PRE at https://journals.aps.org/pre/accepted/10.1103/s965-zwzm) and arXiv:2501.06202)