Information Transport in Classical-Quantum Hybrid System

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Key performance measures in quantum technology, such as fidelity, entanglement, and entropy, are intrinsically nonlinear and therefore cannot generally be represented by standard operator observables. Their time-dependent flow across a quantum device is consequently beyond the reach of conventional open-system descriptions. Multi-density-matrix extensions of the Keldysh formalism have recently enabled consistent calculations of Rényi and von Neumann entropy flows into a probe heat bath coupled to a quantum system mediating energy transport among reservoirs. These studies revealed a strong suppression of entropy flow relative to standard open-system predictions, but were restricted to the hierarchy in which the probe is the weakest-coupled reservoir. Here, we extend the formalism beyond this limit, treating regimes where all system-bath couplings remain perturbative but the probe is no longer singled out as the weakest element. This brings entropy-flow theory closer to realistic hybrid quantum-classical architectures. By deriving a generalized-density-matrix master equation, we show that quantum-classical hybridization suppresses entropy flow and creates a thermodynamic bottleneck. Our results provide a consistent thermodynamic framework for nonlinear information measures in quantum devices and offer practical guidance for resource-aware quantum-hardware design.