Energy shortcuts of quantum protocols

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Adiabatic protocols are well known for their minimal work expenditure and minimal dissipation, as well as for their intrinsic robustness against uncertainties and fluctuations in the Hamiltonian parameters. However, adiabatic dynamics require to abide by the quantum adiabatic theorem, imposing very slow protocols (much slower than the typical evolution timescale of the system). Shortcut-to-adiabaticity (STA) was introduce to speed up the adiabatic dynamics at the price of adding extra driving terms. Nevertheless, the energy invested to generated such STA driving terms remains uncontrolled, and became a major concern in recent investigations.

Here, with tools from Optimal Control Theory, we determine, for arbitrary quantum systems, the Quantum-Optimal-Shortcut-To-Energetics (QOSTE) protocol which realizes with minimal energy cost the same transformation as STA and adiabatic dynamics. We also determine the QOSTE protocol for state-to-state transfer, when one is interested only in steering an initial state $|\psi_0\rangle$ to a target state $|\psi_f\rangle$, as opposed to realizing a target unitary transformation. We also show that the energy lower bounds reached by the QOSTE protocols can be interpreted geometrically in term of geodesics. We give some benchmarks with Landau-Zener model and the stimulated Raman adiabatic passage (STIRAP) in a thee-level system. The QOSTE protocols present important energy gain. Finally, we also optimize the robustness using a gradient-ascent algorithm, obtaining protocols which are much more robust while being less energy-demanding than STA techniques (counter-diabatic drives).

Our results constitute a promising step to reduce the energy cost of quantum control, which is expected to be much larger than the work invested, dissipated, or gained at the level of the driven quantum system.

References:

C. L. Latune, M. B. P. Shebeek, D. Sugny, S. Guérin: Energy shortcut of quantum protocols by optimal control. arXiv:2503.20130 (2025)