Spectrum-Aware Quantum Control beyond Classical Spectral Access

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Abstract
Quantum algorithms are typically designed without direct access to the spectral structure that governs their success. In adiabatic and variational quantum computation, performance is often limited by localized dynamical bottlenecks associated with narrow energy gaps, yet resolving such structure requires exponentially costly spectral analysis. This renders large-scale quantum control effectively blind to the many-body features that determine error.

Here we show that spectrum-aware control can be achieved without explicit spectral reconstruction. We introduce an adaptive ramp scheduling strategy that redistributes computational resources along the control path according to state-derived indicators of dynamical difficulty. Using a supercomputer-trained Quantum Dynamics Twin, we estimate scalable proxies of low-energy spectral activity without storing the exponentially large quantum state. The resulting schedules concentrate circuit depth near dynamically sensitive regions while preserving fixed computational budgets.

The approach scales to 156 qubits, beyond exact classical simulation of generic variational dynamics, and yields consistent performance improvements across representative optimization problems. Experiments on IBM quantum processors demonstrate 10–30% increases in empirical success probability. These results establish a scalable route to spectrum-informed quantum control in regimes where classical spectral access is unattainable.