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Thesis abstract

Efficient control and simulation of quantum dynamics

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Quantum simulation is one of the most promising potential applications of quantum technology. With the recent hardware developments in quantum computing, we are moving from a qualitative to a quantitative regime of quantum simulation, where even small errors can corrupt the scalability due to error accumulation. The origin of these errors is two-fold: on the hardware level, noise and decoherence disrupt the qubits; on the software level, quantum simulation algorithms are approximate implementations, introducing systematic errors to the computation. On the one hand, hardware noise can be effectively suppressed by the quantum control technique of dynamical decoupling. On the other hand, systematic simulation errors can be controlled through efficient implementations of the Trotter product formula. This thesis reports advances on both fronts by providing better characterisations of the errors in quantum simulation and dynamical decoupling.

In terms of simulation algorithms, we establish a better understanding of the simulation precision and more efficient ways to quantify it. This is related to the Trotter approximation error, for which we establish lower bounds as well as more effective upper bounds through an explicit dependency on the input state. Furthermore, we examine the procedure of discretising physical models to make them amenable for digital simulation before the background of the Trotter product formula and establish sufficient conditions for the validity of this approach.

Regarding dynamical decoupling, we quantify its efficiency when the system is coupled to a bosonic environment (e.g. thermal and pink noise). We also establish a unification result of dynamical decoupling with randomised kicks and the quantum Zeno effect, where the dynamics of a quantum system gets projected onto a subspace through frequent measurements. This allows us to find efficiency estimates for the randomised dynamical decoupling. Lastly, we develop a new dynamical decoupling scheme via generalised kicks through a quantum channel that acts on the environment. This scheme explicitly uses noise degrees of freedom and classical uncertainty to suppress environmentally induced errors.

The results in this thesis are based on studying the mathematical properties of quantum dynamics more broadly. To this end, we give a clear characterisation of the dynamics of mixed quantum states in the general setting of possibly infinite-dimensional Hilbert spaces. Furthermore, we establish a general method to obtain error/efficiency estimates for implementing quantum dynamics admitting physical symmetries characterised via Lie group representations.

Together, these results enhance both the accuracy and robustness of quantum simulations, potentially pushing the field closer to practical, large-scale applications.

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