

Classical Simulation of Short-Time Quantum Dynamics

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Recent progress in the development of quantum technologies has enabled the direct investigation of the dynamics of increasingly complex quantum many-body systems. This motivates the study of the complexity of classical algorithms for this problem in order to benchmark quantum simulators and to delineate the regime of quantum advantage. Here, we present classical algorithms for approximating the dynamics of local observables and nonlocal quantities such as the Loschmidt echo, where the evolution is governed by a local Hamiltonian. For short times, their computational cost scales polynomially with the system size and the inverse of the approximation error. In the case of local observables, the proposed algorithm has a better dependence on the approximation error than algorithms based on the Lieb-Robinson bound. Our results use cluster-expansion techniques adapted to the dynamical setting, for which we give a novel proof of their convergence. This has important physical consequences besides our efficient algorithms. In particular, we establish a novel quantum speed limit, a bound on dynamical phase transitions, and a concentration bound for product states evolved for short times.

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I. INTRODUCTION

The study of the dynamics of quantum many-body models is a highly active area of research in quantum information science, both from the perspective of physics and of computation. Probing dynamics provides access to a wealth of physical phenomena and can enable the solution of hard computational problems. Existing quantum simulators are already allowing us to explore quantum dynamics of high complexity. To assess the potential for quantum speed-up, it is important to understand the reach of classical methods for these tasks. Unless all quantum computations can be classically simulated, i.e., $BPP = BQP$, classical algorithms will be unable to approximate quantum dynamics in an arbitrary setting. Nevertheless, there exist restricted regimes in which efficient classical simulation is possible. An important special case is evolution for short times, during which the quantum information will not spread much. Tensor-network methods illustrate this point, as they provide provably efficient means of simulating

unitary dynamics in one spatial dimension for short times [1,2].

In this work, we characterize the computational complexity of short-time dynamics under a local Hamiltonian more generally. Locality in this context means that the Hamiltonian can be written as a sum of operators supported on small subsystems. We do not require geometric locality and we do not restrict the Hamiltonian to a finite-dimensional lattice. Instead, we only impose that every term in the Hamiltonian overlaps with a constant number of other terms. These conditions are satisfied by a wide class of physically relevant Hamiltonians, including parent Hamiltonians of quantum low-density parity-check (LDPC) error-correcting codes [3]. Dynamics governed by Hamiltonians of this type are amenable to *cluster expansions*, which have long been used in both classical and quantum statistical mechanics of lattice models [4–8], leading to results such as the uniqueness of Gibbs states [9,10], efficient approximation schemes for partition functions [11,12], the decay of correlations [13–15], and concentration bounds [16,17]. Despite their long history, cluster expansions have typically been applied to equilibrium properties, while dynamics have been rarely considered.

The paper is structured as follows. In the remainder of this section, we summarize the main results and give an overview of their implications for the complexity of quantum dynamics. In Sec. II, we define the cluster notation

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