Strategies for braiding and ground state preparation in digital quantum hardware

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Summary

This thesis deals with fundamental aspects of the construction and application of digital quantum computers. By harnessing the laws of quantum mechanics, these devices could solve some problems that are too difficult for ordinary computers. Although promising, digital quantum computers are still in the early stages of their development.

One way to realize such hardware is to use materials with special energy excitations called anyons. Theory predicts that these excitations can encode and process quantum information robustly via their mutual interchange, also referred to as braiding. However, existing proposals for anyon braiding prove challenging to realize in an experiment. This issue motivates chapters 2-4, in which we develop new strategies to detect anyons.

The first strategy uses a so-called topological superconductor, which offers the possibility to run anyons (magnetic vortices) along its edge. The effect of the braiding statistics can be detected by passing these anyons by an immobile vortex in the interior of the superconductor (see chapter 2). It is also possible to pass one itinerant anyon by the other (see chapter 3). An advantage of our implementation is that the detection can be realized using only electrical fields.

The second strategy concerns parafermions — a different kind of anyon, which can be realized at the edges of a semiconductor in a strong magnetic field (so-called fractional Quantum Hall regime). To detect parafermions, we introduced several quantities that characterize their quantum correlations, or entanglement. One can perform a weak-measurement protocol to probe these quantities in an experiment.

In addition to the physics of digital quantum hardware, we investigated the potential strategies for its utilization. One promising application of quantum computers is simulating a quantum system's ground state (its lowest-energy state). Such a simulation is a computational problem that is highly relevant to material science and quantum chemistry. Chapters 5-7 introduce several new approaches to preparing ground states using digital quantum computers.

Chapter 5 is concerned with so-called variational quantum algorithms. These algorithms employ a tunable quantum circuit as a ground state

template ("ansatz"), approximating the ground state of a simulated system by optimizing the output energy of the circuit. We focus on constructing efficient ansatz circuits. The first step is designing an ansatz that provably spans the space of all quantum states via a minimal number of digital quantum operations. This ansatz allows a reduction to more practical ansatzes, in agreement with the linked-cluster theorem, which certifies the efficiency of the reduced ansatz. We confirm the efficiency of our method compared to existing alternatives by a numerical study of the weakly coupled quantum Ising model.

Another approach to preparing a ground state on a quantum computer is to simulate the natural process of cooling. Chapter 6 outlines a cooling-like algorithm that simulates a cold bath with a single qubit. We pin down the critical challenges of this approach, which come from the limited simulation time and the digital nature of quantum hardware. We propose two variants of Quantum Digital Cooling algorithms. The first – BangBang approach – is suitable for near-term applications but it is inaccurate. The second approach – LogSweep – aims to be asymptotically accurate but is only suitable for applications in the fault-tolerant regime. Numerically, applying Quantum Digital Cooling to the quantum Ising model shows a scalable performance of LogSweep within a broad interval of model parameters.

Quantum hardware also allows one to prepare the desired quantum state by employing weak measurements. In chapter 7, we propose accelerating such a method of state preparation by deciding the subsequently applied measurements on the go. Because of the vastness of the space of quantum states, optimizing this decision proves challenging. We offer two heuristic approaches to this "navigation" problem. A "compass" method uses the geometrical distance to the target state and aims to reduce it in a greedy fashion. The second method uses a graph, representing measurement operations with edges and quantum states with vertices. Using a numerical test, we identify the potential to accelerate the state preparation at least 10-fold by each of these two heuristics.