Leopold-Franzens-Universität Innsbruck
Institute for Experimental Physics

Description of the project "Characterizing large-scale quantum computers via cycle benchmarking" for the Canada award 2020

Quantum computers offer a fundamentally more powerful way of solving problems compared to their classical counterparts. However, qubits — the basic processing units in a quantum computer — are fragile. Any imperfection in the control of the qubits or noise in the system can cause errors that lead to incorrect solutions in the computation. Gaining control over a small-scale quantum computer with just a few qubits is the first step in a larger, more ambitious endeavour. A larger quantum computer may be able to perform increasingly complex tasks, like machine learning or simulating complex systems to discover new pharmaceutical drugs.

A major roadblock for the development of a useful quantum computer is to characterize its performance and capabilities, in particular, to assess the inevitable errors that accumulate during the execution of a quantum algorithm. As the number of qubits increases, the number of measurements and post processing steps required to fully characterize a quantum operation explodes with the system size. Thus, it is already unfeasible in practice to completely analyze quantum operations implemented on a quantum computer with 10 qubits.

In our work we present a technique called "Cycle Benchmarking", that enables us to efficiently extract only a part of the information about a quantum operation under investigation. Since a quantum algorithm consist of a series of parallel implemented quantum operations, called a *cycle*, we are interested in the performance of such cycles. If the performance of the available cycles is known, predictions about the success probability of any algorithm comprising these cycles can be made. In addition, Cycle Benchmarking can be used to investigate the performance of specific cycles of interest, in order to characterize and possibly improve them. Importantly, the resources required for Cycle Benchmarking do not increase with the number of qubits, which makes our technique scalable.

Technikerstraße 25/4 | A-6020 Innsbruck
Telefon +43 (0) 512 / 507 52453 | Fax +43 (0) 512 / 507 52492
E-Mail alexander.erhard@uibk.ac.at | Internet http://www.quantumoptics.at/

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In the laboratory our team in Innsbruck has been developing a prototype quantum computer, where information is stored in single trapped atoms and manipulated with laser pulses. Our Canadian collaborators, Prof. Joseph Emerson and Dr. Joel Wallman, at the Institute for Quantum Computing in Waterloo, are developing methods to quantify and verify errors in quantum computers. The joint project was accompanied by several visits of our collaborators here in Innsbruck and many online meetings. The project results were published under the title "Characterizing large-scale quantum computers via cycle benchmarking" in Nature Communications. In this publication we demonstrate the effectiveness of Cycle Benchmarking on an ion-trap quantum computer with up to 10 qubits. This is the largest quantum information processor that has been rigorously characterized at the time and we expect that this method will serve as the standard characterization method for quantum computers in the future.

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