

A High Performance Computing Infrastructure for the Efficient Execution of Hybrid Quantum-Classical Algorithms

Thesis submitted by

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in partial fulfillment of the requirements for the degree of

Bachelor of Science

A High Performance Computing Infrastructure for the Efficient Execution of Hybrid Quantum-Classical Algorithms

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February 16, 2021

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Abstract

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1

Introduction

As an introduction to the work that was done during this thesis, this chapter starts with presenting a brief overview on the relevance of quantum computing, and describing the motivation behind this work. After that, the objective of this work is described and an outline of this report is given.

1.1 Motivation

Quantum computing is a new model of computation that promises to solve certain problems more efficiently than classical computers by making use of quantum mechanical phenomena such as superposition and interference. The idea of quantum computing originated from Benioff [1], who proposed a quantum mechanical model of the Turing machine in 1980. This idea was later extended as Manin [2] and Feynman [3] independently suggested that quantum computers have the potential to solve certain computational problems intractable by classical computers. Since then, researchers have been searching for applications for quantum computing. Some noteworthy developments in the field of quantum computing include Shor's algorithm for factoring integers [4] and Grover's algorithm for unstructured database search [5]. These quantum algorithms promise an exponential and quadratic speedup respectively over their best-known classical counterparts. The finding of such speedups have catalyzed research towards quantum computers, and more applications have since been found in fields including chemistry [6], cryptography [7], and machine learning [8].

Until recently, quantum computing had been a mainly theoretical field. These days, however, thanks to recent technological advances, various quantum devices are being actively developed. Furthermore, technological giants such as IBM, Microsoft, Intel, and Google are investing heavily in the development of quantum computers. The applications of these current quantum devices are very limited however, due to their inability to store information for a long time and their sensitivity to errors. For instance, Fowler, Mariantoni, Martinis, *et al.* [9, Appendix M] estimate that to factor a 2000-bit number using Shor's algorithm would require a quantum computer with about a billion physical qubits, and error rates below 4×10^{-13} . In contrast, devices today have about 50 to 100 physical qubits and error rates above 0.1.

These small and error-prone quantum devices, referred to as noisy intermediate-scale quantum (NISQ) devices, may be unfit to run quantum algorithms like Shor's algorithm,

but they may still prove to be useful and perform tasks intractable by classical computers [10]. To deal with the limitations of NISQ devices, hybrid quantum-classical algorithms (HQCAs) are being actively researched. These HQCAs combine classical and quantum computations as visualized in Figure 1.1. Hybrid quantum-classical algorithms

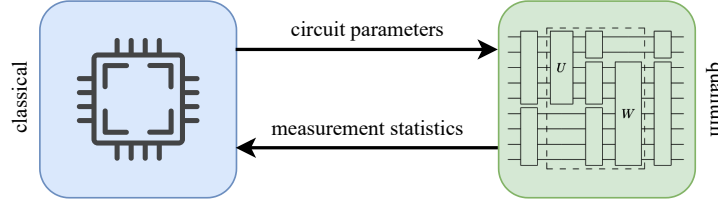


Figure 1.1: General structure of a hybrid quantum-classical algorithm. The data interchange between the classical and quantum part is often repeated many times.

typically involve a small quantum computation inside of a classical optimization loop, greatly reducing the amount of quantum resources needed. This makes them suitable to run on NISQ devices, and are expected to be one of the first useful applications for quantum computing [11]. It is important to note that NISQ devices running HQCAs will likely not be revolutionary by itself. Instead, it should be seen as an important stepping stone towards more powerful quantum devices and algorithms.

Research towards HQCAs often involves executing quantum circuits on actual quantum chips or through quantum circuit simulation. To support this kind of research, classical and quantum computing facilities are needed. Furthermore, these facilities need to be connected and able to interchange data in a timely manner for this kind of research to be feasible. This is especially challenging given that both quantum and classical resources are shared with other users.

1.2 Objective

The purpose of this thesis is to propose an infrastructure for the efficient execution of hybrid quantum-classical algorithms. This work is in collaboration with TNO, QuTech, and SURF, and is focused on the efficient execution of HQCAs using QuTech’s quantum computing platform Quantum Inspire [12] and SURF’s high performance computing (HPC) center. To allow for the efficient execution of HQCAs, the SURF HPC and Quantum Inspire job schedulers should be synchronized to minimize the execution of the algorithm. A key part in this is figuring out sources of overhead and current bottlenecks. In a hybrid setup like this, overheads such as quantum and classic scheduling wait times, data transfers, and resource initialization can quickly increase the run time of HQCAs.

1.3 Outline

This report is structured as follows. Chapter 2 provides the reader with a background on computational complexity, quantum information, and quantum computation. Chapter 3 takes a deeper look into well-known HQCAs and their working.

2

Background

This chapter is focused on making the reader familiar with concepts used throughout this report. First, an introduction to computational complexity is given to establish a mathematical framework to describe the efficiency of computer algorithms. Second, the basic ideas of quantum information theory are presented. Finally, an overview of quantum computation is given.

2.1 Computational Complexity

2.2 Quantum Information

2.3 Quantum Computation

3

Hybrid Quantum-Classical Algorithms

3.1 Variational Quantum Eigensolver

3.2 Quantum Approximate Optimization Algorithm

Bibliography

- [1] P. Benioff, “The computer as a physical system: A microscopic quantum mechanical hamiltonian model of computers as represented by turing machines”, *Journal of statistical physics*, vol. 22, no. 5, pp. 563–591, 1980.
- [2] I. I. Manin, *Vychislimoe i nevychislimoe*. Sov. radio, 1980.
- [3] R. P. Feynman, “Simulating physics with computers”, *Int. J. Theor. Phys*, vol. 21, no. 6/7, 1982.
- [4] P. W. Shor, “Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer”, *SIAM review*, vol. 41, no. 2, pp. 303–332, 1999.
- [5] L. K. Grover, “A fast quantum mechanical algorithm for database search”, in *Proceedings of the twenty-eighth annual ACM symposium on Theory of computing*, 1996, pp. 212–219.
- [6] S. McArdle, S. Endo, A. Aspuru-Guzik, S. Benjamin, and X. Yuan. (2018). Quantum computational chemistry. arXiv: 1808.10402 [quant-ph].
- [7] C. H. Bennett and G. Brassard, “Quantum cryptography”, *Theoretical Computer Science*, vol. 560, no. P1, pp. 7–11, 2014.
- [8] J. Biamonte, P. Wittek, N. Pancotti, P. Rebentrost, N. Wiebe, and S. Lloyd, “Quantum machine learning”, *Nature*, vol. 549, no. 7671, pp. 195–202, 2017.
- [9] A. G. Fowler, M. Mariantoni, J. M. Martinis, and A. N. Cleland, “Surface codes: Towards practical large-scale quantum computation”, *Physical Review A*, vol. 86, no. 3, p. 032 324, 2012.
- [10] J. Preskill, “Quantum computing in the NISQ era and beyond”, *Quantum*, vol. 2, p. 79, 2018.
- [11] S. Endo, Z. Cai, S. C. Benjamin, and X. Yuan, “Hybrid quantum-classical algorithms and quantum error mitigation”, *Journal of the Physical Society of Japan*, vol. 90, no. 3, p. 032 001, 2021.
- [12] T. Last, N. Samkharadze, P. Eendebak, R. Versluis, X. Xue, A. Sammak, D. Brousse, K. Loh, H. Polinder, G. Scappucci, *et al.*, “Quantum inspire: Qutech’s platform for co-development and collaboration in quantum computing”, in *Novel Pattern-ing Technologies for Semiconductors, MEMS/NEMS and MOEMS 2020*, International Society for Optics and Photonics, vol. 11324, 2020, 113240J.

Acronyms

HPC High Performance Computing

HQCA Hybrid Quantum-classical Algorithm

NISQ Noisy Intermediate-scale Quantum