Theory and Applications of Hybrid Quantum-Classical Optimization Algorithms

(Teoria i zastosowania hybrydowych algorytmów optymalizacji kwantowo-klasycznej)

Ludmila Botelho

Supervisor: dr hab. Jarosław Miszczak

25.06.2024

In the last decades, the scientific community witnessed the fast evolution of computers, resulting in powerful devices combined with sophisticated methods for computing difficult tasks, which allowed us to revolutionize the way we understand and process information. Alongside, the scientific community witness the emergence of a new paradigm: the Quantum Technology is a promising field that potentially provides computational advantages. In particular, the iconic Shor's and Grover algorithms, called the attention of the computer science community with the theoretical possibility of building algorithms which are faster compared to the currently known for conventional computers.

Alongside, as we approach the physical limits of the current architecture, the search for alternatives computational methods also contributes to the research and development of the so-called Quantum Computers. However, the efforts to build a fault tolerant quantum processing systems resulted in modest successes. The quantum devices implemented at the moment are limited by scale and noisy, been known as Noisy Intermediate Scale Quantum (NISQ) computers. In this scenario, quantum-classical hybrids methods, such as Variational Quantum Algorithms (VQAs) and Quantum Annealing, appeared as candidates to perform optimization tasks in such limited scenario. In particular, the possibility of applying error mitigation, post-selection, and a better understanding of the energy landscapes can enhance the quality of VQAs results for NISQ devices.

Besides, one can also ask what a quantum computer can do at moment. For instance, it is interesting to know if a quantum computer is ready to perform tasks related to art and creativity. More specific, by adapting them into optimization problems formulated to be solved into annealing devices.

In this thesis, I proposed a discussion about how to improve NISQ friendly protocols in gate-based approach. We introduce two methods: the first one is a scheme for error mitigation in variational quantum circuits through mid-circuit post-selection. The approach is based on investigating valid subspaces obtained through different encodings such as one-hot, k-hot,

binary, and domain-wall encoding that frequently appear in encoding combinatorial optimization problems and in quantum chemistry. The second is a heuristic strategy that uses classical homotopy optimization, since it has potential application in dealing with highly non-linear functions. This strategy simplifies the search for good QAOA parameters while keeping the PQC unchanged. To showcase this approach, we investigate the weighted Max-Cut problem on Barabasi-Albert graphs. Finally, we also worked on applications of Quantum Annealing for Music Theory. We consider the problem of music composition from various aspects, among them the composition of melody and rhythm. For music reduction, we treated the problem as a variant of job scheduling, where each machine is a instrument and the jobs are music phrases. Using the available commercial quantum annealers, we generate music pieces that are displayed in the course of the thesis.