Investigation on Quantum Computers

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1. Abstract

This project focuses on comparing and evaluating the capabilities of two leading quantum computing platforms: IBM Quantum, which uses superconducting qubits, and Xanadu’s photonic quantum systems, accessed through the Pennylane programming framework (a library in Python) [1]. The primary goal is to investigate their performance across a range of algorithms, focusing on factors such as computational efficiency, accuracy, and error rates.

The study emphasises the contrasting approaches of photonic and superconducting qubit technologies, analysing their effectiveness in terms of scalability, hardware robustness, and algorithmic precision [2]. Additionally, it examines how tools like Pennylane enable seamless programming and simulation, bridging the gap between theoretical quantum concepts and real-world implementation. Through a detailed comparison of outcomes, this work aims to shed light on the current state of quantum computing platforms and their future potential in advancing scientific and industrial applications [3].

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- Xanadu Quantum Technologies: We express our gratitude to Xanadu Quantum Technololgies for granting access to their photonic quantum computing platform and for providing the powerful Pennylane framework. The flexibility and user-friendliness of Pennylane allowed us to efficiently program and simulate quantum systems, while its compatibility with various quantum backends proved invaluable in conducting comparative studies.

1. Introduction

Over the past decade, quantum computing—a field intersecting physics, computer science, mathematics, and engineering—has seen remarkable progress [4]. Diverse quantum technologies lie at the heart of this evolution, each presenting novel solutions to complex computational challenges that classical systems struggle to address. Superconducting qubits and photonic quantum computing stand out as two leading paradigms. IBM Quantum is at the forefront with superconducting qubits, while Xanadu leads in photonic quantum computing. These cutting-edge platforms are expanding the frontiers of computational capability and scalability [2], allowing researchers to delve into previously inaccessible quantum algorithms and applications.

IBM Quantum is notable for its durable superconducting qubit architecture, characterised by high coherence times, accurate gate operations, and an extensive suite of quantum programming tools provided through the Qiskit platform [5]. The IBM Quantum cloud provides access to a wide array of quantum processors, facilitating detailed testing of quantum circuits and enabling users to benchmark performance and investigate novel algorithms [6]. In contrast, Xanadu's photonic quantum systems, available through their Pennylane framework, offer a different approach by leveraging continuous-variable quantum computing [7]. This photonic platform is particularly well-suited for tasks like Gaussian Boson Sampling, which has notable applications in graph theory and machine learning [8].

Our research investigates and compares the performance of IBM Quantum and Xanadu’s photonic quantum systems through practical programming and execution of quantum algorithms. By utilizing Qiskit for IBM Quantum and Pennylane for Xanadu, we explore their respective strengths and limitations in terms of computational efficiency, scalability, and accuracy. This comparative study highlights the distinct hardware architectures, programming paradigms, and error-correction strategies of each system while assessing their practical applications in solving quantum problems.

This work also delves into the growing utility of software frameworks like Pennylane, which bridge theoretical quantum computing concepts with real-world implementations [9]. Pennylane supports hybrid quantum-classical workflows, enabling the smooth execution of quantum algorithms on both photonic and qubit-based systems, thus making it an essential tool for this research. Likewise, Qiskit’s advanced simulator and hardware interfaces provide rigorous testing of quantum programs before deploying them on physical qubits [10].

Ultimately, this study aims to shed light on the current capabilities of IBM Quantum and Xanadu systems, providing a detailed analysis of their respective advantages and challenges. By comparing their performance across a range of computational tasks, we aim to contribute to the broader understanding of quantum computing technologies, offering insights into their potential roles in scientific and industrial applications. This investigation underscores the importance of ongoing innovation and collaboration in advancing quantum computing toward practical, scalable solutions.

1. Theory and Computational Approach

**Solving the QUBO Problem with Quantum Computing**

The Quadratic Unconstrained Binary Optimi**s**ation (QUBO) problem is a type of optimi**s**ation problem**.** It involves finding the optimal solution to a quadratic function where the variables are binary, meaning they can only take the values 0 or 1. The goal is to minimise (or maximise) this function without any additional constraints on the variables. QUBO problems are particularly notable because they can represent a wide variety of combinatorial optimisation issues, making them highly versatile and applicable to numerous real-world scenarios. Their importance has surged with the advent of quantum computing, which promises more efficient solutions to these complex problems [11] .

Mathematical Formulation of QUBO

Mathematically, the QUBO problem is expressed as follows:

Minimize f(x) = ∑i ai xi + ∑i < j bij xi xj

Where:

* xi are the binary variables, i,e., xi ∈ {0,1}
* ai are the coefficients for the linear terms
* bij are the coefficients for the quadratic terms

Matrix Representation

The QUBO problem can also be formulated in matrix notation. Let Q be a symmetric matrix where Qii = ai and Qij = bij for i ≠ j. The function then becomes:

f(x) = xTQx

Where:

* x is a vector of binary variables
* Q is a symmetric matrix containing the coefficients

Solving the QUBO Problem with Quantum Computing

#then I will Begin to the explain the mathematics behind the qubo problem, and the mathmatics and physics of **what is happening in the quantum computer in relation to this. Show the qubo code that we did in relation to this explaining step by step the mathematics/physics into relation to this**

References

[1] IBM Quantum. 2024. IBM Quantum. [accessed 2024 Nov 27]. <https://quantum.ibm.com/functions>.

[2] Xanadu | Research. (2024). Xanadu.ai. <https://www.xanadu.ai/research>.

[3] Quantum circuits. (2024). Pennylane.ai. <https://docs.pennylane.ai/en/stable/introduction/circuits.html>.

[4] IBM Quantum Experience - Dashboard. (n.d.). IBM Quantum Experience. <https://quantum-computing.ibm.com/>.

[5] Welcome to Qiskit’s documentation! — Qiskit 0.7 documentation. 2019. Qiskitorg. <https://qiskit.org/documentation/>.

[6] Quantum Computing. 2021 Feb 9. IBM Research. [accessed 2024 Nov 27]. <https://research.ibm.com/quantum>.

[7] Aqeeb I, Arka, Kumar B, Kim R, Kim H, Rao Doppa J, Pande P. 2020. HeM3D: Heterogeneous Manycore Architecture Based on Monolithic 3D Vertical Integration. ACM Transactions on Design Automation of Electronic Systems. doi:https://doi.org/10.1145/3424239. [accessed 2023 Dec 6]. <https://arxiv.org/ftp/arxiv/papers/2012/2012.00102.pdf>.

[8] dougfinke. Quantum Computing Report - Market Analysis, News & Resources. Quantum Computing Report. <https://quantumcomputingreport.com/>.

[9] PennyLane. pennylaneai. <https://pennylane.ai/>.

[10] Quantum. Quantum. <https://quantum-journal.org/>.

[11] Mathworks, “Mel Frequency Cepstral Coefficients,” Mathworks.com, 2020, doi: <https://doi.org/1061245463.woff2>.

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