Quantum Computing: The Future of Technology and Its Impact on Modern Science

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Abstract

Quantum computing aims to enhance computational capabilities by exploiting the unique properties of qubits, enabling breakthroughs in fields like cryptography, optimization, and simulation that are impossible for classical computers. This technology has the potential to help discover solutions for incurable diseases like cancer and Alzheimer's disease, revolutionizing transportation and space exploration with the discovery of new, stronger materials.

This paper explains the basics of quantum computing, explores active research centers in this topic, it identifies the challenges that we face in further developing complex quantum computers, and highlights key achievments and significant milestones in the field, from various companies and contributors.

The paper explores the field of Quantum Machine Learning, identifying key benefits such as faster data searching and encryption-breaking capabilities, respectively. It also explores the potential development of quantum neural networks which can process information in ways that classical neural networks cannot.

Keywords

Quantum Technology

Quantum Computers

Willow quantum chip

Quantum Supremacy

Quantum Machine Learning

Quantum Communication

Quantum Hardware

1. Introduction

Quantum Computing is the technology that combines classical information theory and classical computing with quantum physics. It is a revolutionary computing approach that solves complex problems exponentially faster than classical computers. It has an immense potential but also presents significant challenges. It can be useful in different fields such as cryptography: it could break current encryption methods and develop new ones. In the pharmaceutical industry to simulate molecules and reactions for drug discovery, for discovering new solutions for diseases. In material science to predict material properties for advanced manufacturing and in Artificial Intelligence and Machine Learning to speed up training times and enhance problem-solving capabilities. The main difference between a classical computer and a quantum computer is that instead of using bits, the quantum computer uses qubits. A classical computer solves a problem by trying on solution at a time, and a quantum computer tries every possible solution at the same time and finds the correct solution almost instantly. Instead of personal daily usage, a quantum computer is used to solve complex problems in different specific areas. A quantum computer uses superposition and entanglement to perform computations. Theese theoretical concepts are explained in the background section of this paper.

2. Theoretical Background

This section will focus on explaining the main notions and concepts of the domain and their inter-relations.

2.1 A qubit

The qubit is the main unit of information in quantum computers. It can be in state 0 or 1 or any superposition of both simultaneously, until it is measured. In Fig. 2.1.1 we can view the spherical representation of a qubit. The state of one qubit is dependent on the state of another and one qubit can take part in millions of processes at the same time. Qubits can lose their quantum state quickly, and it is a challenging task to keep them stable long enough to perform complex calculations. This is called quantum coherence. Quantum operations are prone to error due to the environmental interference and noise. It is a difficult task to develop error-correcting codes for quantum calculations, but without it, quantum computers do not produce reliable results for us to be able to trust the results of a computation, as errors are made faster than they are corrected. This is what we call quantum error correction.

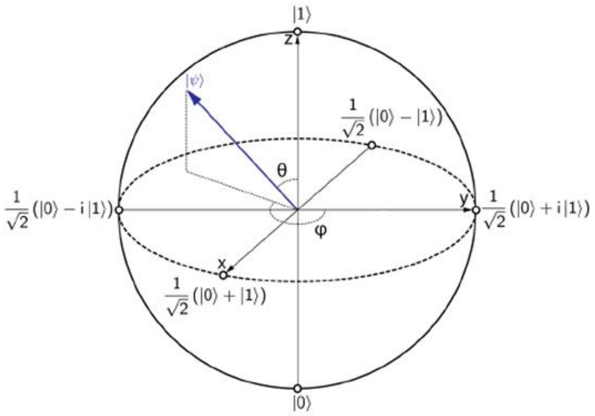

Fig. 2.1.1 Qubit state in the Bloch Sphere [1]

2.2 Superposition

Superposition refers to the property of a qubit, or a quantum system to be able to be in multiple states in the same time. Due to this property, quantum computers are able to process multiple information at the same time.

2.3 Entanglement

Entanglement is a quantum phenomenon where two or more qubits become interconnected in such a way that the state of one qubit directly affects the state of the other, no matter the distance between them.

2.4 Interference

Interference refers to the way quantum states can add together or cancel each other out. Constructive interference increases the probability of certain outcomes, while destructive interference decreases it. Quantum algorithms use interference to amplify the correct answers and reduce the likelihood of incorrect ones.

2.5 Quantum Gates

Quantum Gates are similar to classical logc gates, but in quantum computing. They manipulate qubits by changing their states through quantum operations. Some examples for quantum gates are: Pauli-X gate (classical NOT), Hadamard gate (related to superposition), CNOT gate (related to entanglement), Phase gate (affects interference patterns).

3. Dissemination Resources

3.1 Research centers

This section covers the main research centers that are dedicated to researching, discovering and advancing in the field of quantum computing.

IBM Quantum

IBM Quantum is one of the most important research centers in the domain of quantum computing, next to Google's quantum laboratory. IBM Quantum's main goal is to advance in the field of quantum computing and also make it accessible to a broader audience. Quantum computers make most of the world's existing encryption algorithms obsolete. IBM developed many of the foundational technologies that will secure the world in the quantum era, and now offers the tools and services needed to implement them. They are committed to responsible quantum computing.

They have a well defined roadmap on how they are planning to advance in the field, and what are the necessary steps towards achieving quantum-centric supercomputing: They want to obtain systems with more qubits, improved error rates, and they plan on developing quantum processors with over 1000 qubits in the coming years.

Quiskit is an open-source software development kit (SDK) offered by IBM that allows developers to create and run quantum algorithms and to simulate experiments. Quiskit, the cloud based platform, is available for download at: Qiskit | IBM Quantum Computing. They offer courses on how to get started with Quiskit and publicate the latest news on their website.

IBM collaborates with universities and other research institutions to advance in the field faster, and they provide powerful resources and expertise for theese collaboration projects. They offer online workshops and courses for quantum professionals as well as beginner courses for beginners to help understand the world of quantum computation.

Google Quantum AI

Google Quantum AI is the research team of Google, focused on advancing quantum computing technology. Their mission is to build quantum computers capable of solving problems that are currently intractable for classical computers in fields like medicine, energy, and artificial intelligence. They are available at: Google Quantum AI.

Google's Sycamore processor achieves quantum supremacy in 2019, performing a computation in 200 seconds that would take the world's fastest supercomputer 10,000 years.

In 2023, the team achieved the first-ever demonstration of a logical qubit prototype, showing that it's possible to reduce errors by increasing the number of qubits in a scheme known as quantum error correction.

Google Quantum AI recently introduced (2024) the *Willow quantum chip*, which significantly reduces errors as it scales up. This breakthrough in quantum error correction is a major step towards developing large-scale, practical quantum computers.

Figure 3.1 Google's quantum computer

Microsoft Quantum Lab

Microsoft's quantum research enter is part of the Azure Quantum initiative: Azure Quantum . They are working to achieve scientific breakthroughs in chemistry and material science. They main scope is to solve humanity's hardest problems like climate change and food insecurity. They are developing a topical qubit that is unique, small, fast, and controllable, which will unlock a scaled Quantum Supercomputer. Microsoft is focusing on creating stable, topological qubits, which are believed to be more robust against errors compared to other types of qubits. They are working on implementing the concept of quantum networking: the potential to unlock capabilities by connecting remote quantum computers and solving problems distributed on quantum clusters. The stages of quantum networking include the development of a quantum internet that would mean that long distance quantum communication will be possible. They are on the road for building a quantum supercomputer. They achieved major scientific breakthrough in the domain and have a well defined roadmap for the future.

Figure 3.2 Google’s roadmap in QC

In Figure 3.2 we can see Google Quantum AI’s roadmap. It aims to achieve large-scale, error-corrected quantum computing. Key milestones include:

- 2019: Sycamore processor demonstrated quantum supremacy with 54 qubits.
- 2023: Achieved significant progress in quantum error correction.
- 2024: Willow chip with 105 qubits, marked exponential error correction improvements.

Future: Develop a large-scale quantum computer with 1 million qubits and extremely low error rates.

MIT Center for Quantum Engineering

‘Bridging quantum science and engineering’

Located in Massachusetts, their mission is to accelerate the practical aplication of quantum technologies for the benefit of humankind. They defined their set of objectives as:

- Define the emerging discipline of quantum engineering
- Educate and train tomorrow’s quantum workforce
- Partner with academia, government, and industry
- Create a quantum ecosystem that advances quantum science and technology development

They have a platform for research, education, and engagement in support of quantum engineering, available here. Their research areas include: quantum simulation, quantum networks and quantum sensing. They define quantum engineering as the new discipline that designs and builds large-scale quantum machines.

Max Planck Institute of Quantum Optics

Located in Germany, their research areas include: quantum matter, fundamentals of quantum optics, conducting various experiments related to extremely short timescales and experiments with single photons and individual atoms. They are organising different scientific events, and publicating their research on their website: Latest Top Publications.

3.2 Journals and Conferences

Important journals, articles and conferences discussing the theme of quantum computing and the development of new quantum technologies are the: Ramezani, S. B., Sommers, A., Manchukonda, H. K., Rahimi, S., & Amirlatifi, A. (2020). *Machine Learning Algorithms in Quantum Computing: A Survey. 2020 International Joint Conference on Neural Networks (IJCNN).* The paper shows the current state of knowledge in applying Machine Learning Algorithms on Quantum Computers. It highlights the advantages of using quantum computers for Machine Learning tasks, and discusses various applications of Machine Learning in Quantum Computing, including pattern recognition, prediction, and decision-making.

The paper H. Padmanaban, “Quantum Computing and AI in the Cloud”, J. Computational Intel. & Robotics, vol. 4, no. 1, pp. 14–32, Mar. 2024. discusses how quantum computing has the ability to process information in parallel through qubits, it talks about how machine learning algorithms are reshaping the industries using automation.

4. Research Questions

4.1 Challenges

There are a few reasons why quantum computers were held back so far:

Quantum Coherence

It means how long qubits can hold their quantum state before they collapse. Qubits can be in quantum state a given period of time, until the problem is solved. But this period of time is not long enough currently to have enough time to solve complex problems before they collapse.

Error Correction

The error threshold should be low enough to trust quantum computers. Quantum operations are prone to error due to the environmental interference and noise, which can lead to the accumulation of errors and degradation of the quality of calculations. It is a difficult task to develop error-correcting codes for quantum calculations, but without it, quantum computers do not produce reliable results for us to be able to trust the results of a computation, as errors are made faster that they are corrected. Developing reliable error correction techniques is essential for building practical quantum computers.

Scaling Quantum Systems and Qubits

Creating large-scale quantum systems capable of solving complex problems involves developing techniques to scale qubits without compromising coherence and stability. Researchers are exploring various materials and techniques, such as superconducting qubits and trapped ions, to enhance the stability and coherence of qubits. And also, controlling individual qubits becomes increasingly complex as the number of qubits grows.

4.2 Significant Milestones

1994: Shor’s Algorithm

The Distributed Shor’s Algorithm [7] is one of the most important quantum algorithm proposed by Peter Shor. Shor’s algorithm can factor a large integer with certain probability and costs polynomial time in the length of the input integer. The key step of Shor’s algorithm is the order-finding algorithm.

Shor's algorithm can break widely-used cryptographic systems like RSA, which rely on the difficulty of factoring large numbers. However, recently some researchers have pointed out that using Shor’s algorithm to crack the commonly used 2048-bit RSA integer requires physical qubits of millions, that is not possible at the moment.

The techniques used in Shor's algorithm can also be used to solve different types of optimization problems, potentially leading to advances in logistics, scheduling, and resource allocation. While practical implementation of Shor's algorithm on a large scale is still a challenge due to the need for a significant number of qubits and robust error correction, its potential applications continue to drive research and development in quantum computing.

1996: Groover’s Algorithm

Improves search efficiency in unstructured databases, reducing the time needed to find information, offering a quadratic improvement over classical algorithms. The algorithm works in a quantum system in a superposition of all possible states. The solution marks the correct state by flipping its sign, while leaving other states unchanged. The Grover diffusion operator amplifies the probability amplitude of the correct state. The algorithm is iterated at least sqrt(N) times, where N is the number of items in the database. Each iteration increases the probability of measuring the correct state.

It can be applied to a variety of problems, including optimization and solving NP-complete problems that involve exhaustive search.

2018: Bristlecone

Google's 72-qubit quantum processor, designed to test and improve error rates and scalability. It was a significant step in achieving quantum supremacy.

The processor had 72 qubits arranged in a 6x12 grid, with lower error rates then ever before, from 0.6% to 1% depending on the type of the gate used.

Google developed a benchmarking tool to evaluate the capabilities of quantum processors by applying random quantum circuits and comparing the results to classical simulations. Although quantum supremacy had not yet been achieved with Bristlecone, it was a significant step towards future processors.

2019: Sycamore

The Sycamore processor [9] with 53 qubits developed by Google was the real step towards the demonstration of quantum supremacy. Despite having fever qubits that its predecessor, it was designed with a specific architecture that allowed achieving quantum supremacy. The processor was designed as a diagonal array of qubits as seen in Figure 4.2.1. The processor contains 142 transmon qubits of which 54 qubits have individual microwave and frequency controls and are individually read out. The remaining 88 transmons are operated as adjustable couplers remaining in their ground state during the algorithms (couplers). It had improved qubit quality, more efficient error rates and better overall system performance. While they were targeting 0.1% error two-qubit gates for error correction, a quantum supremacy demonstration could be achieved with 0.3-0.6% error rates. As seen in Figure 4.2.1, the sycamore processor is shielded from the electromagnetic environment by a mu-metal shield and a superconducting aluminium cap, inside the shield. The processor control wires are routed, through PCB circuit board, to coaxial connectors shown around the edge.

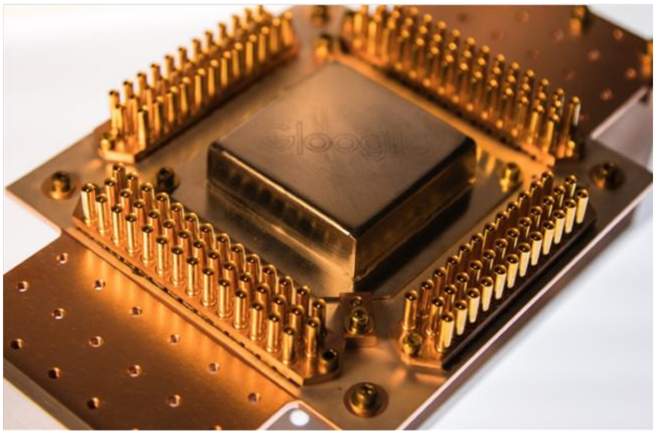

Figure 4.2.1 The Sycamore Processor

2021: IBM Eagle

The IBM Eagle processor, with 127 qubits was released on November 16, 2021. It was twice as powerful as its predecessor, Hummingbird, created in 2020 with 65 qubits. At the moment of the release, IBM believed that the 'Eagle' processor will be the backbone of the quantum processors of the future.

2023: Heron

IBM's most advanced quantum processor, unveiled on December 4, 2023, part of the IBM Quantum System Two, which is the first modular utility-scaled quantum computer system, unveiled together with its processor, Heron. The Heron processor has 156 qubits arranged in a tunable-coupler architecture.

Heron had a revision and the second release increased the qubit count from 133 to 156, reduceing the impact of an important source of noise.

5. Main achievment

5.1 Quantum Machine Learning

The integration of quantum computing with artificial intelligence offers significant enhancements in computational capabilities by utilizing the principles of superposition and entanglement. This integration aims to overcome the limitations of traditional machine learning algorithms, which can struggle with processing large datasets and performing complex calculations.

One of the primary benefits of this integration is the potential for faster processing times. Quantum computers can significantly speed up the training and execution of machine learning models, leading to quicker results and more instant decision-making capabilities. Additionally, the increased efficiency of quantum algorithms allows for more accurate and effective analysis of data.

However, integrating quantum computing with artificial intelligence also presents several challenges. One major challenge is the current limitations of quantum hardware. Developing robust and scalable quantum hardware that can support sophisticated machine learning algorithms is essential for realizing the full potential of this technology. Furthermore, the complexity of quantum algorithms necessitates advanced methods for error correction to ensure reliable computations. Robust error correction techniques are crucial for maintaining the integrity of data processed by quantum systems. But with the development of new techniques and even the newly released Willow quatum chip, the integration of Artificial Intelligence in Quantum Computing can be here sooner than expected.

Another significant challenge is ensuring interoperability between quantum and classical systems. For quantum computing to be seamlessly integrated into existing AI infrastructures, it is vital to develop protocols and standards that allow these different types of systems to work together effectively. This interoperability will enable hybrid computing solutions that leverage the strengths of both quantum and classical computing.

While the integration of quantum computing and artificial intelligence holds enormous promise for transforming various industries, it requires overcoming significant technical challenges. As these technologies advance, they have the potential to revolutionize fields such as cryptography, optimization, and simulation, ultimately leading to breakthroughs in areas like disease treatment, materials science, and beyond.

Quantum Neural Networks

Quantum Neural Networks (QNNs) represent an extension of classical neural networks. They leverage the principles of quantum mechanics to enhance performance and efficiency in processing complex data. By combining superposition and entanglement, QNNs create more powerful and faster machine learning models.

The advantages of QNNs include increased efficiency, as they can process information much more rapidly than classical neural networks due to quantum superposition and entanglement. Additionally, quantum models have a superior generalization capability, as they can capture complex and non-linear relationships between data, thereby improving the model's ability to generalize.

5.2 Willow quantum chip

Google’s newest and most powerful superconducting quantum computing chip, Willow, was announced on December 9, 2024. This innovataive technology offers extended quantum coherence times, improved error correction, and computational power far beyond that of classical supercomputers. It represents the next step towards building large-scale quantum computers that can revolutionize fileds like medicine, energy and Artificial Intelligence.

It was fabricated in Santa Barbara, California, USA.

The key milestone 1 of Google: The first quantum computer to surpass the best classical supercomputer on a computational task: Random Circuit Sampling was achieved by Sycamore, but this chip is 10^20 better in terms of execution time. Random Circuit Sampling is a validated benchmark for measuring quantum progress, defined in 2019 and used since then as a standard progress evaluation technique in quantum computing. It is an essential benchmark in demonstrating quantum advantage, or 'beyond classical' capabilities.

It has powerful computational capabilities with its 105 qubits, it solved a problem in under five minutes, that the worlds most powerful supercomputers would have solved in 10^25 years (10 septillion years).

The chip achieved a quantum coherence time of 100 microseconds, that represents a 5x increase relative to 20 microseconds in Sycamore. The logical qubits operate below the critical error correction threshold. This was achieved for the first time with the new Willow chip, and is a huge breakthrough in quantum computing. Also, the more qubits they use in Willow, the more they can reduce errors. This was tested practically, with different size arrays of physical qubits, ranging from a grid of 3x3, to a grid of 5x5, to a grid of 7x7. With each size increment, the error rate was reduced with 50%. They achieved an exponential reduction in error rates. This accomplishment shows a real progress on real time error reduction, which has been an outstanding challenge since quantum error correction was introduced by Peter Shor in 1995.

In Figure 5.2 we can see how the qubits are located in the qubit grid. The qubit grid is arranged in a way that allows for efficient quantum error correction, which helps maintaining the coherence and accuracy of quantum computations as the number of qubits increases.

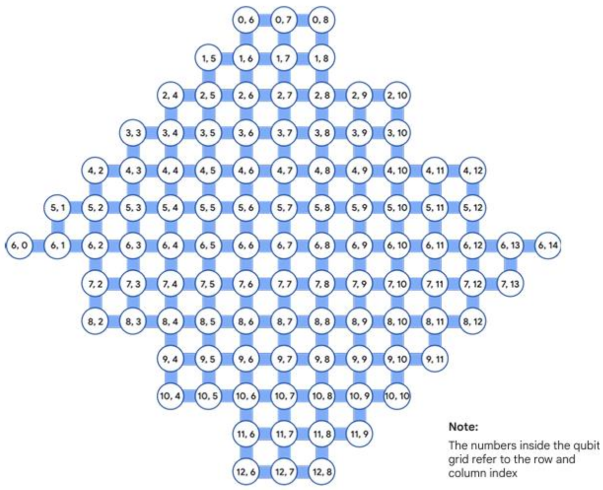

Figure 5.2 Willow's qubit grid

6. Conclusion

In conclusion, quantum computing is a new kind of computing that uses the unique properties of quantum bits (qubits) to process information much faster than traditional computers. This technology can solve complex problems in areas like cryptography, optimization, and drug discovery, which are challenging for classical computers.

Recent advancements, like Google's Willow chips, show significant progress in the field. This chip has demonstrated the potential to handle calculations in minutes that would take classical computers thousands of years.

Despite some challenges, such as error rates and hardware development, ongoing research is making these systems more reliable and practical. The integration of quantum computing with artificial intelligence promises even greater capabilities, opening doors to new applications and innovations.

Quantum Machine Learning is rapidly advancing, merging quantum computing with artificial intelligence to solve complex problems that classical computers can not solve, or achieving faster results in comparison to classical machine learning models. The simultaneous processing of data can lead to faster, more complex computations, which can help solve real-world complex problems that classical computers can not handle.

With Google's new chip, Willow, there are significant advancements in quantum computing that directly benefit Artificial Intelligence and Machine Learning by providing faster, more efficient, and more powerful computational capabilities, enabling breakthroughs in various applications and industries, such as drug discovery, cybersecurity, healthcare and a lot more. Quantum algorithms can enhance cryptographic methods, making data more secure against potential threats. It can also lead to breaking current encryption methods, but with the advancement of technology, new encryption methods can and will be discovered.

Bibliography

1. Ramezani, S. B., Sommers, A., Manchukonda, H. K., Rahimi, S., & Amirlatifi, A. (2020). *Machine Learning Algorithms in Quantum Computing: A Survey. 2020 International Joint Conference on Neural Networks (IJCNN).* doi:10.1109/IJCNN48605.2020.9207714

2. Steane, A. (1998). *Quantum computing. Reports on Progress in Physics, 61(2), 117–173.* doi:10.1088/0034-4885/61/2/002

3. Di Meglio, A., Jansen, K., Tavernelli, I., et al. Quantum Computing for High-Energy Physics: State of the Art and Challenges. PRX Quantum, 5(3), 037001 (2024). DOI: 10.1103/PRXQuantum.5.037001.

4. H. Padmanaban, "Quantum Computing and AI in the Cloud", *J. Computational Intel. & Robotics*, vol. 4, no. 1, pp. 14–32, Mar. 2024.

5. Dr. Hassan Abbas, "Quantum Machine Learning - Models and Algorithms: Studying quantum machine learning models and algorithms for leveraging quantum computing advantages in data analysis, pattern recognition, and optimization", *Australian Journal of Machine Learning Research & Applications*, vol. 4, no. 1, pp. 221–232, Jul. 2024, Accessed: Nov. 12, 2024. [Online]. Available: https://sydneyacademics.com/index.php/ajmlra/article/view/68

6. Google Quantum AI. Suppressing quantum errors by scaling a surface code logical qubit. *Nature* **614**, 676–681 (2023). https://doi.org/10.1038/s41586-022-05434-1 Suppressing quantum errors by scaling a surface code logical qubit | Nature

7. Xiao, L., Qiu, D., Luo, L., & Mateus, P. (2022). Distributed Shor's algorithm. [2207.05976] Distributed Shor's algorithm

8. Almudever, C. G., Lao, L., Fu, X., Khammassi, N., Ashraf, I., Iorga, D., … Bertels, K. (2017). The engineering challenges in quantum computing. Design, Automation & Test in Europe Conference & Exhibition (DATE), 2017. doi:10.23919/date.2017.7927104

9. Google AI Quantum and collaborators, 'Supplementary information for Quantum supremacy using a programmable superconducting processor', 2019, Available here

10. MIT Center for Quantum Engineering

11. Max Plank Institute of Quantum Optics

12. Azure Quantum | Homepage

13. Google Quantum AI

14. Meet Willow, our state-of-the-art quantum chip