A Literature Survey on Quantum Computing in Next Generation Challenges in Circuit Design and Applications ofFuture Enabling Technologies

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ABSTRACTS

Quantum technology is developing so quickly, that there has been intense research for quantum technologies in both academia and industry in recent years. Documents and literature have been created in vast quantities as the capability of quantum computers continues to increase. After an informative introduction and a summary of key achievements and current advancements in the field of quantum computing. The second phase of the quantum revolution known as continuous research and innovation in the hardware, software, and applications of quantum computers further explained. Quantum computing has long theoretical roots, but in recent years, with the development of useful tools and technologies, the research has moved from theory to reality in Quantum Computers, Quantum Networks, Quantum Cryptography, and Quantum Machine Learning. A framework is presented for creating a quantum engineering education program that will satisfy the demands of both academics and research institutions in the world. The Control, electronics, nanofabrication, cryogenic and solid-state technologies, optics, atoms and ions, and a plan for quantum engineering fields that presents an excellent set of opportunities for education research are all used to outline a hands-on training on quantum hardware software and applications.

Keywords

Quantum computing, quantum algorithm, quantumprogramming language, quantum simulators, error correction.quantum machine learning, Quantum Engineering.

1. INTRODUCTION

The Introduction to Quantum Computing explains the basic ideas of quantum computing and looks at the several technologies that make them possible. These tools have experimental study and the investigation of the potential of quantum, ranging from quantum hardware platforms and software development kits to quantum programming languages and simulators[2]. Additionally, it discusses the most recent advancements, ongoing difficulties, ongoing advancements, and future possibilities in this rapidly evolving field[3]. Quantum computing could transform computation by solving some kinds of problems that were previously unsolvable. In Figure-1 illustrates the technology of IBM's quantum computers[1].

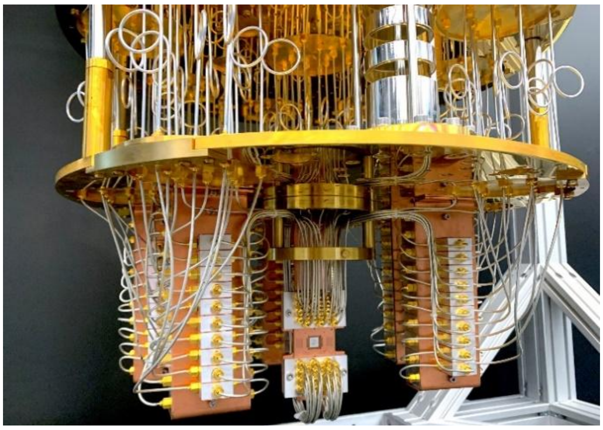

Figure-1 IBM's Quantum Computer

Major difficulties that classical computing equipment cannot address can be solved by quantum computers. Achieving actualized quantum computing could lead to several potentially revolutionary consequences, such as the development of novel pharmacological treatments and the visualization of climate models. The fragility of qubit interconnection, decoherence, external noise, and the error-prone nature of quantum systems are some of the technological obstacles that limit the applications, scalability, and reliability of quantum computing. Figure-2 illustrates the effects of quantum computing as detailed in the link https://beyondtechnology.net.

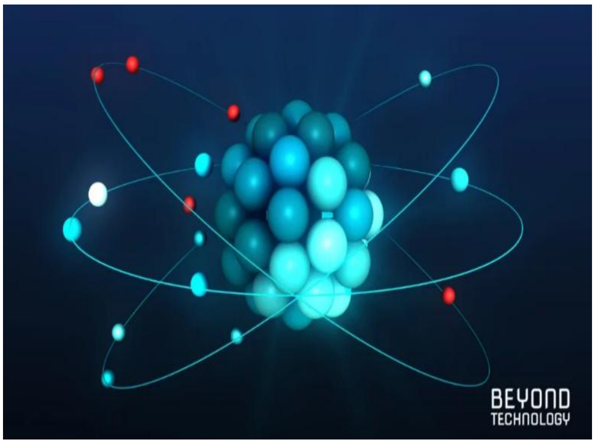

Figure-2 Quantum mechanics

1.1 The drawbacks of using quantum computing

There are drawbacks to quantum computing from both an engineering and a social standpoint. The three most important ones are that environmental sensitivity and quantum error correction provide enormous obstacles. Post-quantum cryptography raises issues with national security. It is made up of about 40,000 CPU units, with 250 million gigabytes of storage and billions of transistors and electronic switches in each. Information is encoded in bits by classical computers nowadays using a stream of electrical impulses that are binary (defined as 1 or 0). Solutions for quantum computing offer the chance to simulate complex environmental processes, enabling more accurate forecasting and addressing challenging environmental issues. Through the use of quantum cloud computing in modeling, we can improve our comprehension of environmental dynamics. The distinctions between classical and quantum computers present technical hurdles for creating and deploying quantum computing[15]. The current state of quantum technology is similar to early computers from the 1950s. Only huge corporations can afford to use these pricy machines, which are tough for even highly skilled academics and researchers to use when creating algorithms.

Error correction is a key component of quantum computing today, much like it was in the early days of classical computing. Quantum computers are challenging to calibrate and are noise-sensitive. Because qubits can take on an endless number of states, quantum faults are more challenging to fix than classical computers, which would experience a bit flip from 0 to 1 or vice versa. As shown in Figure-3 illustrates https://www.hpcwire.com.

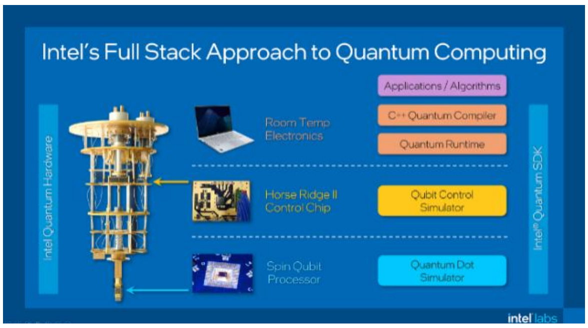

Figure-3 Intel's Full Stack Quantum Computing

The quantum mechanical feature that collapses superposition states when we take a measurement of a qubit and makes it seem as either a 0 or a 1 further complicates quantum error correction. One of the main drawbacks in the industry with quantum computing is the difficulties associated with error correction since the technology depends on reliable outputs.The physical properties of the quantum hardware and its surroundings make up the other half of the equation. Adoption is hampered by this drawback since it is hard to maintain and manipulate the quantum states of subatomic particles, which is mostly to blame for the inaccuracies in the first place.Ensuring that they are free from atmospheric pressure and shielded from the earth's magnetic field is equally crucial, as even minute variations can result in unintended movement. As shown in Figure4.1 and 4.2 Layers of Quantum Computing and Algorithms (https://qutech.nl).

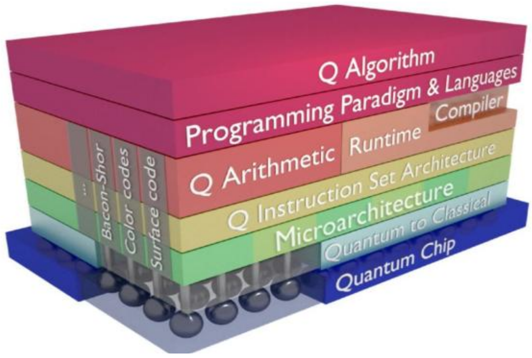

Figure-4.1 Layers of Quantum Computing and Algorithms

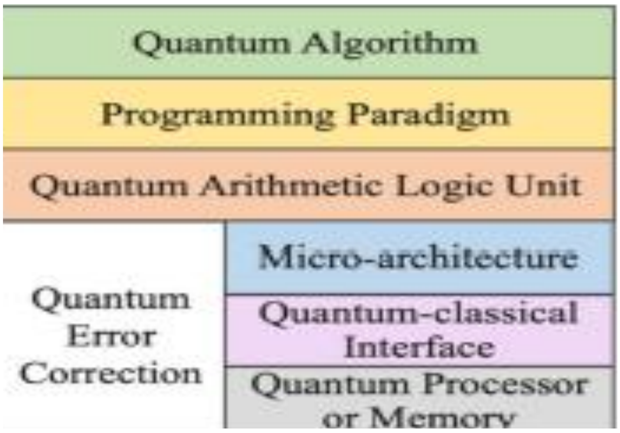

Figure-4.2 Layers of Quantum Computing and Algorithms

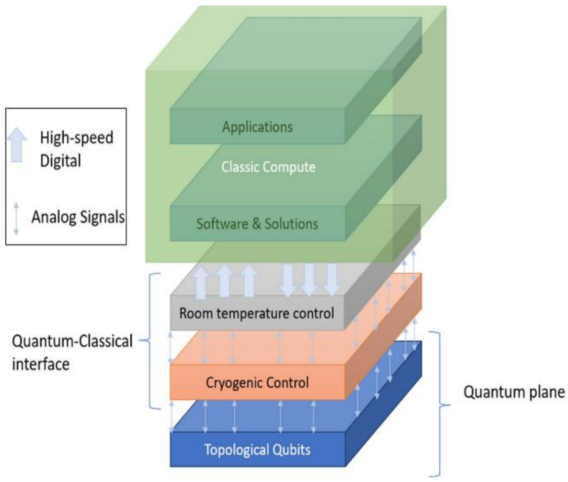

Figure-5 Quantum Architecture

As shown in Figure-5 about the Quantum Architecture (https://medium.com/). To accomplish this, the Office of Management and Budget (OMB) is required to transition to post-quantum cryptography in compliance with the guidelines that the National Institute of Standards and Technology (NIST) will publish. President Biden recently signed the Quantum Computing Cybersecurity Preparedness Act.All organizations probably won't be able to adjust fast enough, though. This can lead to previously unheard-of levels of vulnerability and, worst-case scenario, cyberattacks on vital infrastructure.

One less pressing but no less significant drawback of quantum technology is its potential impact on artificial intelligence (AI). Quantum computing has enormous promise to facilitate the development of the next generation of sophisticated AI since it is particularly good at handling complicated problems with many variables.As with any technology, there are drawbacks. These downsides for quantum computing can be divided into two categories: unfavorable outcomes that might occur from large-scale implementation of quantum computing, and technological difficulties that scientists are battling to resolve.

2. REVIEW OF QUANTUM COMPUTING LITERATURE SURVEY

The algorithms developed by Grover, Shor, Deutsch, and others, Quantum algorithms for approximation quantum computing algorithms influenced by quantum mechanics.The Simon Algorithm algorithm, Vazirani and Bernstein the Fourier transform of quantum amplified amplitude, Playground for Quantum Computing phase estimation(QPE), variational quantum eigensolver, quantum random walks, and quantum binary optimization.The Quantum computing tools developed by Google, IBM, Intel, IonQ, and Xanadu, etc.

India ranks ninth globally with 339 patents related to quantum technology, according to Itihaasa's machine learning-based study. With 23,335 patents, China is the leader in the field; the US is in second place with 8,935 patents. Python is used to design and work with quantum circuits. The user's device simulators, IBM-provided simulators, or IBM-provided prototype quantum devices are used to acquire the results. Numerous businesses and academic organizations in India are setting the standard for quantum computing. Businesses such as Infosys and Tata Consultancy Services. Creating quantum algorithms for different sectors of the economy. Many quantum computing packages are written for Python. The main justification for learning Python, though, is that many software tools designed to emulate or interface with quantum computers are written in the language.

Research Institutes for Quantum Computing in India: Governments worldwide have developed plans and suggested investments to be the first to use quantum power. More information is available at https://analyticsindiamag.com/. Quantum Computing represents a paradigm shift in computation by using the principles of quantum mechanics to process information in ways that are fundamentally different from those of classical computers. Hyderabad Harish-Chandra Research Institute Tata Institute of Fundamental Research (TIFR), Mumbai Indian Institute of Science Education and Research (IISER), Mohali Indian Institute of Science Indian Institute of Technology (IIT), Madras. The fundamental component of quantum computing is the use of quantum bits, or qubits, which can exist in states of superposition and represent multiple values at once. Theoretical work by pioneers like Richard Feynman and David Deutsch, who postulated that quantum systems may be used to simulate other quantum systems more effectively than conventional computers, is where quantum computing got its start. Recent developments in quantum algorithms, such as Grover's database searching method and Shor's algorithm for factoring huge integers, have highlighted how quantum computing has the potential to upend a variety of industries, including optimization and encryption.Significant obstacles still need to be overcome as research advances, such as qubit coherence,error correction, and quantum architectural scalability. Subatomic Computation in Undergraduate Courses.

2.1 Crucial Quantum Computer Hardware Elements

After demonstrating the possibilities of quantum computing in the previous chapters, this chapter concentrates on the hardware, while Chapter 6 examines the software required to put these computational processes and capabilities into reality. Research on quantum hardware is now underway, and startups are attempting to bring quantum computers made of trapped ions and superconducting qubits to market.The number of qubits in the current prototypical quantum computing chip and their development is often the subject of reports in the popular press, but any quantum computer needs an integrated hardware approach that uses significant conventional hardware to program, read out, and control qubits. The upcoming segment categorizes this hardware according to its roles, forming the four hardware tiers that are present in every quantum computer and explaining the anticipated correlation between classical and quantum computing resources.

Therefore, it is unclear if this class of machines will be produced using state-of-the-art quantum technologies at this time.

2.2 A Quantum Computer's Hardware Architecture

A quantum computer can employ a conventional computer for these tasks whenever it is most effective to do so since a quantum computer will eventually need to interface with users, data, and networks for tasks at which traditional computing excels. Moreover, qubit systems can be operated with ordinary computers; however, their proper operation requires well-coordinated control. The difference between Quantum Computing and Classical computing is shown in Figure-6.1 and 6.2.

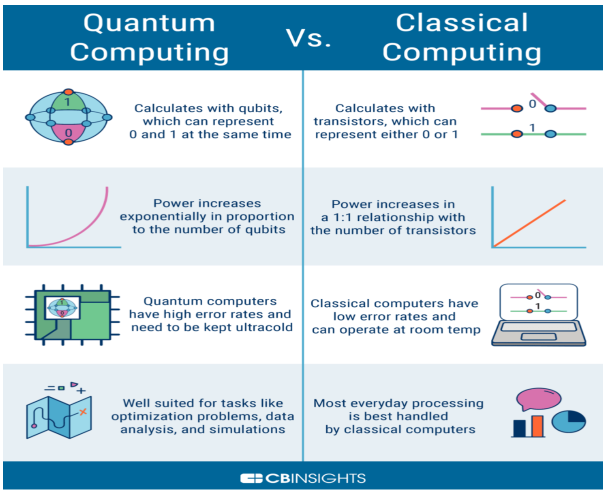

Figure-6.1 Quantum Computing and Classical Computing

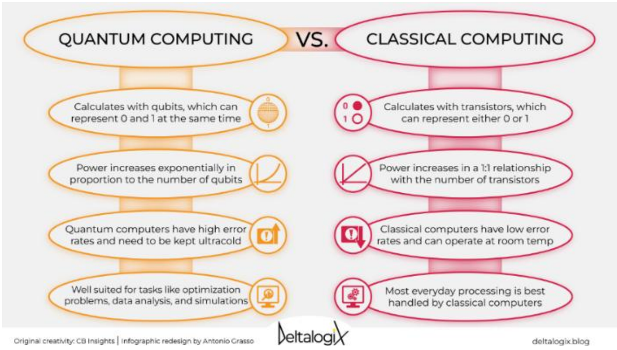

Figure-6.2 Quantum Computing and Classical Computing

2.3 Technologies Qubit

Serious searches were conducted in 1994 following the discovery of Shor's algorithm to identify a suitable physical system for the implementation of quantum logic operations. A theoretical idea earlier that year led to the demonstration of the first quantum logic gate utilizing trapped atomic ions in 1995. Since the first demonstration, developments in qubit control have made it possible to demonstrate completely functional computers at a small scale through experimentation and to perform a variety of basic quantum algorithms. Over the last ten years, numerous advancements in qubit technologies have resulted in the compact gate-based quantum computers that are currently on the market. Lowering qubit error rates in large systems while allowing measurements to be interspersed with qubit operations is the first big issue for all qubit technologies.The fascinating and quickly expanding topic of quantum computing incorporates ideas from mathematics, physics, and computer technology. The curriculum of an undergraduate program must be designed to give students exposure to current research and applications, practical skills, and foundational knowledge[15].

3. PRINCIPLES OF QUANTUM COMPUTING AND RESEARCH METHODOLOGY

A breakthrough method of computing that makes use of quantum mechanics is called quantum computing. The essential ideas that underpin quantum computing are listed below:
Quabits: Qubits are different from classical bits in that they can exist in a simultaneous superposition of both states, instead of only being 0 or 1. This makes it possible for quantum computers to process enormous amounts of data at once[16].

Superposition: Quantum computers may execute numerous operations at once because of superposition, which allows qubits to represent different states concurrently. This feature greatly boosts the processing capacity of quantum systems in comparison to classical ones.
Entanglement: Entanglement is a quantum phenomenon in which two or more qubits, regardless of their distance from one another, get entangled to the point where their states cannot be separately characterized. Entangled qubits are a resource for quantum teleportation and superdense coding, and they can be utilized to improve quantum algorithms and communication protocols[15].

Quantum Gates: Like classical logic gates, quantum gates are the fundamental components of quantum circuits. They use unitary transformations to control qubits. The Pauli-X gate, which flips the qubit state, the Hadamard gate, which produces superposition, and the CNOT gate, which entangles two qubits, are examples of common quantum gates.
Quantum Measurement: A qubit's superposition state is collapsed to one of its basic states in quantum computing. The coefficients in the qubit's state influence the probabilities of the outcomes. Measurement is a non-reversible procedure since it fundamentally changes the qubit's state.
Quantum Algorithms: Algorithms that show how much faster quantum calculations can be than classical ones are Grover's unstructured search method and Shor's integer factorization technique.These algorithms demonstrate how quantum computing has the potential to completely transform industries like database searches and cryptography[17].

Quantum Correction of Errors: Decoherence and other noise sources can lead to errors in quantum systems. Reliable quantum computation requires the development of strong quantum error-correcting codes.Many techniques, including surface codes and cat codes, are being studied to guard against inaccuracies in qubit states.

3.1. Quantum Computer Types:

Based on their underlying technologies and working theories, quantum computers can be divided into several groups. Every kind has unique traits, benefits, and difficulties. The main categories of quantum computers are as follows.High-Performance Quantum Computers are built and work with qubits using superconducting circuits. Fast gate operations and relatively simple integration with classical electronics. Established platforms with notable experimental success (e.g., IBM's Qiskit and Google's Sycamore). The challenges are limited coherence times, necessitating sophisticated error correction techniques. These circuits operate at extremely low temperatures to achieve superconductivity.

3.2 Ion Quantum ComputersIn Traps:

Employ ions as qubits that are contained in electromagnetic fields. Lasers are used to perform operations and measurements on quantum states.Benefits include high fidelity of gate operations and long coherence times. Scalability potential is achieved through methods such as quantum networking. Disadvantages include slower operation rates in comparison to superconducting qubits.

3.3. Quantum Computers with Topological Properties

Based on anyons, quasiparticles with non-Abelian statistics exist in two dimensions. The theoretical foundation suggests scalability and error correction without the need for significant overhead. These systems are thought to have inherent error resistance. They may be robust against decoherence and operational errors. The challenges are still primarily experimental, with no fully functional systems developed.

3.4. Quantum Computers with Photonics:

Utilize the superposition and entanglement ofphotons as qubits to your advantage. Beam splitters, phase shifters, and detectors are usually used for operations. The advantages of this technology include room-temperature operation, long-distance quantum communication, and high-speed processing due to the inherent properties of light. The disadvantages include limited photon interaction and difficulties in forming and maintaining entangled states.

3 5. The Quantum Annealers:

Specialized quantum computers that use quantum tunneling to address optimization issues. In comparison to universal quantum computers, challenges are more limited in their versatility and are primarily focused on particular problem types. They are a type of adiabatic quantum computation and are tailored for particular problems such as combinatorial optimization, making them accessible for certain applications. Companies such as D-Wave have developed practical implementations. Atomic Replicators are designed not for general computation but for the simulation of quantum systems. Insights into quantum physics and materials science. Helpful in chemistry for simulating molecular interactions. Usually, challenges are not universal and are focused on specific problems rather than general computational tasks16]. They can model quantum phenomena that are challenging for classical computers.

3.6. Algorithms and Protocols in Quantum

Compared to classical methods, quantum protocols and algorithms solve problems more quickly by taking advantage of the special qualities of quantum physics. A few important quantum algorithms and protocols that demonstrate the promise of quantum computing are highlighted in this section.Algorithms in Quantum.The Shor Algorithm and its goal factor huge integers efficiently, with important ramifications for cryptography (e.g., RSA encryption). The Intricacy demonstrates how commonly used cryptography schemes could be broken by quantum computers.Grover's Algorithm and its goal:Uses quadratic speedup to solve unstructured search problems or search an unsorted database.

3.7. Models of Quantum Computation

Models of quantum computation offer structures for comprehending the computational capabilities of quantum systems. These models use the ideas of quantum physics to explain how qubits behave and how manipulations of them take place. The main models for quantum computing are listed below.

4. MODEL OF A QUANTUM CIRCUIT

This paradigm is similar to classical logic circuits in that it depicts quantum algorithms as layers of quantum gates placed in a sequence[15]. After initialization and gate manipulation, qubits are measured. The parts are

- Qubits: Fundamental components of quantum data.
- Quantum gates, such as Hadamard, CNOT, and Pauli gates, are operations that work with qubits.
- Measurement: The last stage leads to the quantum state's collapse and the production of classical output.
- Benefits: Makes it simpler to study complexity and construct quantum circuits by providing an understandable and straightforward representation of quantum algorithms.

4.1 The QTM, or quantum Turing Machine

- Description: A quantum mechanical extension of the classical Turing machine. It is composed of quantum states, quantum tape, and quantum head.The Parts given below are Quantum Tape: An endless piece of tape that has been split into cells that can each contain a qubit.
- Quantum Head: Capable of both reading and writing quantum data to the tape.
- Transition Function: Uses quantum superposition and entanglement to determine the next state based on the present state and the contents of the tape.
- Benefits: Offers a theoretical framework for quantum processing that is comparable to that of a traditional Turing machine.

4.2 Adiabatic Quantum Computing (AQC)

This model describes how a quantum system gradually evolves from an initial Hamiltonian to a final Hamiltonian, where the end state represents the solution to a problem.Mechanism: Based on the adiabatic theorem, which says that if a quantum system changes with a slow enough Hamiltonian, the system stays in its ground state.Benefits: Especially appropriate for optimization issues, and employs quantumannealers for implementation.

4.3Quantum Computing Based on Measurements (MBQC)

This paradigm, also referred to as one-way quantum computing, operates by using a sequence of measurements to compute using a highly entangled resource state (such as a cluster state).Mechanism: The computation's conclusions are determined by measurements on the entangled state, and the findings can affect further measurements.Benefits: Provides an alternative viewpoint on quantum computation by highlighting the significance of measurement and entanglement.

4.4 Quantum Computing with Topological Properties:

This model performs quantum computation through the braiding of anyons. Ratherthan depending on the precise characteristics of the qubits, it depends on the system'stopology. The Parts are with anyone to Non-Abelian statistical quasiparticles with two-dimensional existence.Braiding is the act of maneuvering anyons around one another to carry out tasks. The Benefits are because the operations are topological, they may be more error-resistant, which makes it a desirable paradigm for fault-tolerant quantum computing.

4.5 Systems for Quantum Programming

Frameworks for quantum programming give programmers the tools and resources theyneed to create, model, and run quantum algorithms. These frameworks provide an intuitive interface and encapsulate complicated quantum operations, making it easier to create quantum applications. These are a few of the most well-known frameworks for quantum programming:

Qiskit:Key Features of Qiskit, an open-source framework created by IBM, include the ability to simulate quantum systems, build quantum circuits, and conduct experiments on actual quantum hardware through the IBM Quantum Experience.

Circuit Model: Users have the option of building quantum circuits programmatically or graphically.Backends: A range of simulators and actual quantum devices are available.Extensions: Contains libraries for quantum chemistry (Qiskit Chemistry), quantum machine learning (Qiskit Machine Learning), and quantum optimization (Qiskit Optimization).

Cirq:Key features of Cirq, a Python library created by Google, are for building, modeling, and executing quantum circuits on quantum computers, especially those based on superconducting qubits.Dedicated Near-Term Quantum Devices for Noisy Intermediate-Scale Quantum (NISQ) devices are the focus of this design.Users can define their quantum gates and operations with Custom Gate Creation to support hybrid quantum-classical algorithms through integration.

PyQuil: Specifically designed for Rigetti's quantum processors and simulators, PyQuil is a Python library for quantum programming with the Quil programming language. Its primary features include a low-level quantum programming language called Quantum Instruction Language (Quil) is user-friendly.Forest Platform: Access to quantum hardware and simulators through integration with Rigetti's cloud-based quantum computing platform.Support for quantum-classical hybrid algorithms is provided by hybrid algorithms.

Strawberry Fields: A quantum programming framework called Strawberry Fields,created by Xanadu, is specially made for photonic quantum computing. It enables the simulation andoperation of quantum algorithms on photonic devices.Some of its main features are Gaussian States and Operations consisting of quantum systems with continuous variables.Tools for creating models for quantum machine learning are included in quantum machinelearning.The interoperability works with other libraries and frameworks.

Quipper: This is a high-level functional programming language for quantum computingcreated by Microsoft Research and the University of Edinburgh. Its main features are to make it easier to create complicated quantum algorithms. The higher-level abstractions make use of functional programming techniques to express quantum algorithms succinctly. Quantum Circuit Compilation generates quantum circuits from high-level descriptions automatically. The combination is with traditional programming languages.Microsoft created the Quantum Development Kit (QDK), a complete package of tools for creating quantum applications that include tools for modeling and integrating with traditional languages in addition to the Q# programming language. The important characteristic of Quantum programming's domain-specific language is called Q#. Quantum Simulators offer quantum algorithm testing and debugging simulators.Azure integration: Enables cloud-based quantum algorithm execution for customers.

Ocean SDK: Created by D-Wave Technologiessoftware development kit designed specifically for quantum annealing with an emphasis on utilizing D-Wave's quantum computers to solve optimization problems. The important characteristics of Tools for solving issues consist of programs for constructing and resolving quantum annealing issues. The Hybrid solvers facilitate the combination of quantum and conventional methods to solve problems. Access to D-Wave Hardware enables direct communication with quantum systems developed by D-Wave.

5. USES AND FUTURE DIRECTIONS OF QUANTUM COMPUTING RESEARCH

Research is still being conducted in the realm of quantum computing to overcome obstacles and realize its promise in a variety of fields. The following are some notable research directions that are presently influencing the field of quantum computing[15][16][17].

5.1Fault Tolerance and Error Correction:

Because of noise and decoherence, quantum systems are very prone to errors. For effective quantum computing, reliable quantum error correction codes must be developed. The making of stronger quantum states by utilizing topological features is known as topological error correction. To investigate effective surface code implementations that use fewer physical qubits to represent logical qubits.Quantum Feedback and Control: Investigating real-time solutions for correcting errors to preserve consistency.

5.2 Development of Quantum Hardware

Large-scale efforts are focused on scaling quantum processors and enhancing the physical manifestation of qubits for improvements in gate fidelities and coherence times making superconducting qubits feasible for bigger quantum processors.Improved scalability and connection for ion-based systems: Trapped Ions.
Developing integrated photonic circuits for smaller quantum systems is known as photonic quantum computing.

5.3 Complexity and Quantum Algorithms:

Scientists are concentrating on the development ofnovel quantum algorithms and investigating their computational benefits over traditional algorithms.Examining algorithms that blend quantum and classical methods, such as Quantum Approximate Optimization Algorithms(QAOA) and Variational Quantum Eigensolvers(VQE), is known as hybrid quantum-classical algorithms. Application-specific algorithms for developing quantum algorithms specifically for domains such as materials science, machine learning, and cryptography. Complexity Classes are examining the limits between classical and quantum complexity to find issues that quantum systems can handle more effectively.

5.4 Building the foundation for quantum communication

is essential to the development of quantum networks and the quantum internet. This is the overview of quantum networking and communication.Quantum Key Distribution (QKD) is used in Quantum repeaters and entangled states are used to improve secure communication methods.Research on methods for effective entanglement distribution across vast distances is being conducted in the context of quantum teleportation and entanglement distribution.Integration with Classical Networks for creating techniques to enable the smooth operation of quantum and classical communication networks together.

5.5 Quantum Machine Learning:

Investigating how to leverage the advantages of quantum computing with machine learning to analyze data more efficiently.Creating neural network designs that take advantage of quantum features to achieve higher performance is known as quantum computing. Quantum Data Classification is based on studies on the application of quantum algorithms to classification and clustering problems.In Hybrid models to improve performance, combine conventional machine learning models with quantum circuits.

5.6 Materials Science and Quantum Chemistry

Quantum computers are useful for understanding chemical reactions and for exploring new materials because they have the potential to simulate quantum systems.The creation of quantum simulators with a focus on researching complex chemical reactions and quantum materials. Chemistry's Quantum Advantage is examining how quantum algorithms might significantly accelerate the simulation of molecular systems.Partnerships between theorists and experimentalists are encouraged to validate quantum discoveries and simulations.

5.7 Multidisciplinary Research

As quantum computing becomes more integrated with other domains, new applications and insights are being produced. These include:Studying quantum effects in biological systems and how they affect activities like photosynthesis is known as quantum biology.Investigating the use of quantum algorithms for risk assessment and optimization in financial modeling is known as quantum finance.Philosophical Implications: Examining how quantum physics and its applications to computation and information theory are interpreted philosophically.

6. CONCLUSION AND FUTURE SCOPE

Strong theoretical and practical foundations in the field of quantum computing should be provided by academics and research in the subject. Students will be well-prepared for jobs in academia, industry, or future study in quantum technologies by integrating demanding research courses with practical experience and research possibilities. Future experts in this fascinating sector will need to stay up to date on the newest advancements as quantum computing continues to develop. A certificate program in quantum computing should offer a solid foundation in both the theoretical and practical sides of the field. Future experts in this fascinating sector will need to stay up to date on the newest advancements in quantum computing since it is still evolving. Understanding the fundamentals of quantum computing lays the foundation for comprehending its potential influence on a variety of fields. These foundational ideas will spur advancements in hardware design, algorithm development, and practical applications as research progresses, ushering in a new era of computation. The variety of approaches in quantum computing is demonstrated by these models of quantum computing. Every model offers distinct perspectives and resources for comprehending how quantum systems might be utilized for computing, facilitating progress in a range of fields, including cryptography and optimization, among others. The interactions between these models will probably result in new findings and advancements in the field of quantum computing as the study progresses. The multidisciplinary nature of quantum computing research and its quick progress are its defining features. As the problems are solved and new uses are found, the field of quantum computing will develop further and might completely transform several sectors and academic fields. To advance this discipline, cooperation between governmental, corporate, and academic entities is essential.

7. REFERENCES

[1] M. Lapedus. “The Great Quantum Computing Race.” 2021. Accessed:Aug. 6, 2022. [Online]. Available: https://semiengineering.com/thegreat-quantum-computing-race/

[2] E. Gibney. “Quantum Computer Race Intensifies as AlternativeTechnology Gains Steam.” 2020. Accessed: Aug. 6, 2022. [Online].Available: https://www.nature.com/articles/d41586-020-03237-w

[3] F. Xu, X. Ma, Q. Zhang, H. Lo, and J. Pan, “Secure quantum keydistribution with realistic devices,” *Rev. Mod. Phys.*, vol. 92, no. 2,2020, Art. no. 25002

[4] J. A. Lopez-Leyva, A. Talamantes-Alvarez, M. A. Ponce-Camacho,E. Garcia-Cardenas, and E. Alvarez-Guzman, “Free-space-opticalquantum key distribution systems: Challenges and trends,” in *QuantumCryptography in Advanced Networks*. London, U.K.: IntechOpen, 2018,doi: 10.5772/intechopen.81032

[5] S.-K. Liao et al., “Satellite-to-ground quantum key distribution,”*Nature*, vol. 549, pp. 43–47, Aug. 2017

[6] J. Chow, O. Dial, and J. Gambetta. “IBM Quantum Breaksthe 100-Qubit Processor Barrier.” 2021. Accessed: Aug. 6, 2022.[Online]. Available: https://research.ibm.com/blog/127-qubit-quantumprocessor-eagle

[7] S. Roberts. “This New Startup Has Built a Record-Breaking256-Qubit Quantum Computer.” 2021. Accessed: Aug. 6, 2022.[Online]. Available: https://www.technologyreview.com/2021/11/17/1040243/quantum-computer-256-bit-startup

[8] D-Wave Systems Inc. “D-Wave Details Product Expansion &CrossPlatform Roadmap.” 2021. Accessed: Aug. 6, 2022. [Online].Available: https://www.dwavesys.com/company/newsroom/pressrelease/let-s-get-practical-d-wave-details-product-expansion-crossplatform-roadmap/

[9] D. Deutsch, “Quantum theory, the church—Turing principle and theuniversal quantum computer,” *Proc. Roy. Soc. London Math. Phys. Sci.*,vol. 400, no. 1818, pp. 97–117, 1985.

[10] M. Schlosshauer, “Quantum decoherence,” *Phys. Rep.*, vol. 831,pp. 1–57, Jan. 2019.

[11] K. C. Miao et al., “Universal coherence protection in a solid-state spinqubit,” *Science*, vol. 369, no. 6510, pp. 1493–1497, 2020.

[12] R. C. C. Leon et al., “Coherent spin control of s-, p-, d- and f-electronsin a silicon quantum dot,” *Nat. Commun.*, vol. 11, p. 797, Feb. 2020.

[13] M. Rorvig. “Qubits Can Be as Safe as Bits, Researchers Show.”2020. Accessed: Aug. 6, 2022. [Online]. Available: https://www.quantamagazine.org/qubits-can-be-as-safe-as-bits-researchers-show-20220106/

[14] S. J. Devitt, W. J. Munro, and K. Nemoto, “Quantum error correctionfor beginners,” *Rep. Progr. Phys.*, vol. 76, no. 7, 2013, Art. no. 76001.

[15] ZeboYang ,*Graduate Student Member, IEEE*, MaedeZolanvari , *Member, IEEE*, and Raj Jain , *Life Fellow, IEEE, “* A Survey of Important Issues in Quantum Computing and Communications “ IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 25, NO. 2, SECOND QUARTER 2023.

[16] PRATEEK SINGH 1, RITANGSHU DASGUPTA 1, ANUSHKA SINGH 1, HARSH PANDEY VIKAS HASSIJA 1, VINAY CHAMOLA Senior Member, IEEE, AND BIPLAB SIKDAR, “ A Survey on Available Tools and Technologies Enabling Quantum Computing (Senior Member, IEEE) on 29 April 2024.

[17] Essential Hardware Components of a Quantum Computer." National Academies of Sciences, Engineering, and Medicine. 2019. Quantum Computing: Progress and Prospects. Washington, DC: The National Academies Press. doi: 10.17226/25196.

[18] Arif Ali Khan, Aakash Ahmad, Muhammad Waseem, Peng Liang, Mahdi Fahmideh, TommiMikkonen, PekkaAbrahamsson,Software architecture for quantum computing systems — A systematic review,Journal of Systems and Software,Volume 201,2023.