ISSN (ONLINE): 2454-9762
ISSN (PRINT): 2454-9762
Available online at www.ijarmate.com

International Journal of Advanced Research in Management, Architecture, Technology and Engineering (IJARMATE)
Vol. 10, Issue 5, May 2024

A Review On Evolution of Quantum Computing

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Abstract: ***Quantum computing stands at the forefront of technological innovation, promising unprecedented computational power and paradigm-shifting capabilities. This paper investigates the multifaceted landscape of quantum computing, exploring novel methodologies and their potential applications. We delve into diverse approaches, including gatebased quantum computing, adiabatic quantum computing, and topological quantum computing, examining their theoretical foundations and technological advancements. By analyzing the strengths and limitations of each method, we elucidate the path towards harnessing quantum supremacy.***

Furthermore, we discuss real-world implementations and emerging platforms, such as IBM Q and Google's Quantum AI, highlighting their contributions to quantum computing research and development. Ethical considerations, including data security and algorithmic bias, are also addressed, emphasizing the importance of responsible innovation in this transformative field. Ultimately, this paper asserts that quantum computing represents a paradigm shift in computational capabilities, with profound implications for science, industry, and society as a whole.

I. Quantum Mechanics and Qubits: Diving into the Weird World

The world of classical computing revolves around bits, tiny switches that can be either 0 or 1. But the quantum world introduces qubits, which exhibit some bizarre features absent in their classical counterparts. Let's take a peek:

Classical Bits: Think of a light switch. It's either on (1) or off (0). That's a bit! Billions of these bits work together in our computers to represent and process information.

Qubits: Imagine a special switch that can be on, off, or both at the same time! This bizarre state, called superposition, is the heart of quantum weirdness. Thanks to superposition, a qubit holds the potential to be 0, 1, or a combination of both, until measured, when it collapses to one definite state.

Entanglement: Now, imagine connecting two of these switches in a special way. Even if you separate them, measuring one instantly tells you the state of the other, no matter the distance. This spooky connection, named entanglement, allows qubits to work together in powerful ways.

Advantages: So, why are qubits special? These strange properties unlock potential superpowers:

Exponential Speedup: Certain problems, like factoring large numbers, take classical computers ages. Qubits, exploiting superposition and entanglement, could solve them exponentially faster, revolutionizing cryptography and materials science.

Parallel Processing: Qubits can explore many possibilities simultaneously, making them ideal for complex optimization problems in areas like logistics and finance.

Quantum Simulations: Simulating complex systems like molecules or financial markets is challenging for classical computers. Qubits, with their inherent strangeness, could offer unique insights and solutions.

II. Delving Deeper into Quantum Weirdness: Superposition, Entanglement, and Gates

Following our introduction to qubits, let's dive deeper into the key principles that unlock their power:

Superposition: Imagine flipping a coin, but instead of landing on heads or tails, it spins and exists as both possibilities simultaneously. This bizarre quantum state is a superposition. A qubit can be 0, 1, or a combination of both, represented as a quantum wavefunction, until measured, when it collapses to a definite state.

Example: Suppose we have a qubit in superposition as $|0\rangle + |1\rangle$. It holds a 50% chance of being 0 and 50% of being 1, until we measure it. This "both at once" property allows qubits to explore many possibilities simultaneously, crucial for their computational power.

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Entanglement: Imagine two coins, mysteriously linked, where flipping one instantly determines the state of the other, even across vast distances. This spooky connection is entanglement. Two entangled qubits share a single fate, regardless of physical separation.

Example: Imagine two entangled qubits, A and B, initially both in superposition. Measuring A as 0 instantly "forces" B to be 1, no matter how far apart they are. This correlation, defying classical physics, allows for powerful quantum communication and teleportation protocols.

Quantum Gates: Think of gates as tools manipulating qubits. Unlike classical logic gates (AND, OR, etc.), quantum gates operate on qubits in superposition, transforming their wavefunctions. Common gates include:

Hadamard: Converts a |0> state to equal parts |0> and |1>, and vice versa.

CNOT: Flips the target qubit if the control qubit is 1, leaving it unchanged if 0, demonstrating entanglement manipulation.

Shor's Algorithm: Imagine factoring a large number classically. It's like finding two hidden prime numbers among millions of possibilities. Shor's algorithm, using superposition and entanglement, finds these factors exponentially faster.

Example: Factoring 15, Shor's algorithm efficiently finds its primes 3 and 5, demonstrating its potential to break widely used encryption schemes based on large number factorization.

Grover's Algorithm: Searching a large unsorted database classically takes linear time (checking each item). Grover's algorithm uses superposition to find the target item with a quadratic speedup, significantly faster for large datasets.

Example: Imagine finding a specific name in a phonebook. Grover's algorithm can locate it much faster than checking each entry, demonstrating its potential for efficient database search and optimization problems.

These are just glimpses into the fascinating world of quantum mechanics. Although complex, these principles hold the key to harnessing the vast potential of quantum computing, revolutionizing fields like cryptography, materials science, and artificial intelligence in the future.

III. Timeline of Quantum Computing Milestones

1. Timeline:

1900s:

1900: Max Planck introduces the concept of quanta, laying the foundation for quantum theory.

1926: Erwin Schrödinger formulates wave mechanics, a key pillar of quantum mechanics.

1935: Albert Einstein, Boris Podolsky, and Nathan Rosen propose the EPR paradox, highlighting the strange nature of entanglement.

1982: Richard Feynman proposes the idea of a quantum computer, suggesting its potential for solving problems intractable for classical computers.

1985: David Deutsch introduces the concept of quantum parallelism, a key advantage of quantum computing.

1994: Peter Shor discovers his factoring algorithm, demonstrating the potential to break widely used encryption schemes.

2000s:

2000: IBM unveils the first superconducting quantum computer with 5 qubits.

2001: Lov Grover develops his search algorithm, offering quadratic speedup over classical search algorithms.

2006: David DiVincenzo proposes the DiVincenzo criteria, outlining five key requirements for a fault-tolerant quantum computer.

2007: Google establishes its Quantum AI Lab, dedicating significant resources to quantum computing research.

2011: D-Wave Systems unveils its quantum annealing computer, designed for specific optimization problems.

2010s-Present:

2015: IBM releases IBM Quantum Experience, the first publicly accessible cloud-based quantum computing platform.

2016: Google achieves quantum supremacy with its Sycamore chip, demonstrating a quantum computation impossible for classical computers.

2019: IBM surpasses Google with its Quantum System One, the first commercially available quantum computer.

2022: Honeywell unveils its ** trapped-ion quantum computer**, offering superior coherence times compared to other platforms.

2023: Several companies, including IonQ, Rigetti Computing, and QuantumScape, make significant progress in developing their own quantum hardware and software solutions.

2. Pioneers and Contributions:

Richard Feynman: Proposed the concept of a quantum computer and highlighted its potential.

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Peter Shor: Developed the Shor's algorithm, showing the power of quantum computers for breaking classical encryption.

David Deutsch: Introduced the concept of quantum parallelism and laid the foundation for many quantum algorithms.

Lov Grover: Developed the Grover's algorithm, offering significant speedup for searching tasks.

Serge Haroche and David Wineland: Awarded the 2012 Nobel Prize in Physics for their work on manipulating individual quantum systems.

Many researchers and companies: Continuously contribute to the advancement of quantum computing through hardware development, algorithm design, and software tools.

IV. Qubit Battleground: A Look at Different Quantum Platforms

1. Superconducting Qubits:

- Description: Tiny circuits cooled to near absolute zero, exploiting Josephson junctions to represent qubits.
- Achievements: IBM's Quantum System One holds the record for most qubits (433), and Google's Sycamore achieved claimed quantum supremacy.
- Capabilities: Relatively mature technology, promising scalability and integration with existing chip fabrication techniques.
- Challenges: Decoherence (loss of information) remains a significant hurdle, and scaling to large qubit numbers with high-fidelity operations is difficult.

2. Trapped Ion Qubits:

- Description: Individual ions held in place by electromagnetic fields, manipulating their quantum states with lasers.
- Achievements: Honeywell's H1 trap holds the record for longest coherence times (20 minutes), promising high-fidelity operations.
- Capabilities: Excellent coherence times due to the isolated nature of ions, potentially leading to more error-resistant quantum computers.
- Challenges: Scaling to large qubit numbers is challenging due to complexity of individual ion control and miniaturization requirements.

3. Topological Qubits:

- Description: Harnessing unique properties of specific materials to encode qubits in non-local (topological) features, potentially immune to decoherence.
- Achievements: Still in early stages of development, with proof-of-concept demonstrations on small scales.
- Capabilities: Theoretically promising for faulttolerant quantum computing due to inherent protection against errors.
- Challenges: Significant research and development needed to overcome fabrication and manipulation challenges, and scalability is unknown.

4. Leading Hardware Providers:

- IBM: Focuses on superconducting qubits, offering the most publicly accessible platform (Quantum Experience) and actively pushing scalability boundaries.
- Google: Pioneered Sycamore chip and claimed quantum supremacy. Invests in diverse platforms, including superconducting and topological qubits.
- Honeywell: Leads the trapped-ion race with H1, emphasizing low error rates and coherence times. Focuses on building industry-specific quantum applications.
- IonQ: Offers trapped-ion quantum computers for research and development purposes, aiming for scalability and commercialization.
- Rigetti Computing: Develops superconducting quantum computers, focusing on hybrid quantum-classical solutions and cloud access.

V. Challenges on the Quantum Road: Decoherence, Error Correction, and Scalability

1. Decoherence:

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Imagine building a sandcastle – even the slightest breeze can disrupt it. Similarly, fragile quantum states are susceptible to decoherence, where interactions with the environment cause them to lose their delicate information.

Ongoing Research:

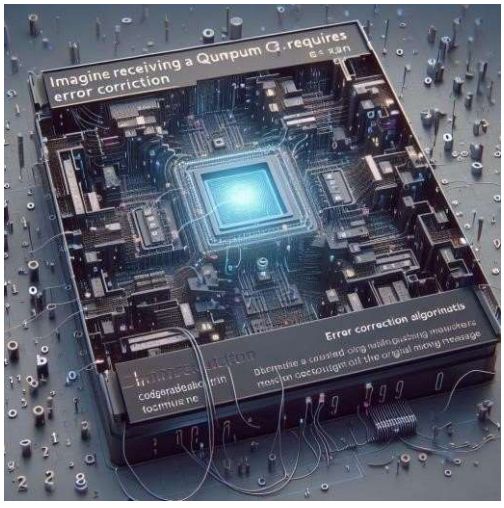
Improved isolation: Building better cryogenic chambers and shielding qubits from electromagnetic noise minimizes environmental interactions.

Fault-tolerant quantum computing: Designing error-correcting codes using multiple qubits to detect and fix errors before they disrupt calculations.

Topological qubits: Exploring materials with inherently robust quantum states, less susceptible to decoherence.

2. Error Correction:

Think of sending a message with missing letters. Quantum computations are prone to errors due to decoherence and imperfect operations. Error correction aims to identify and fix these errors, ensuring reliable calculations.



Ongoing Research:

Quantum error-correcting codes: Developing efficient codes that use redundant qubits to encode information and detect errors without sacrificing computational power.

Quantum annealing: Using specialized hardware to solve optimization problems related to error correction efficiently.

Machine learning: Applying machine learning techniques to identify and correct errors from real-time quantum computation data.

3. Scalability:

Building a single qubit is impressive, but imagine building millions for complex calculations. Scalability is crucial for practical quantum computers, requiring reliable qubit fabrication, control, and interconnection.

Ongoing Research:

Miniaturization techniques: Developing methods to fabricate large numbers of qubits on smaller chips, using techniques like nanoscale lithography.

Quantum networks: Interconnecting individual quantum processors to distribute tasks and resources across multiple systems.

Topological error correction: Exploiting the inherent errortolerant properties of topological qubits to build largescale, fault-tolerant quantum computers.

VI. Software Suites for the Quantum Frontier: Tools and Languages Beyond Foundational Algorithms

1. Quantum Programming Languages:

Qiskit: Developed by IBM, Qiskit offers a robust Pythonbased toolkit for simulating, programming, and running quantum circuits on various backends, including real quantum hardware.

Cirq: Created by Google, Cirq provides a flexible framework for constructing and manipulating quantum circuits, supporting diverse hardware platforms and optimization techniques.

Scaffold: Developed by Microsoft, Scaffold focuses on highlevel functional programming for quantum algorithms, aiming to enhance readability and maintainability.

Other notable languages: Quipper, Strawberry Fields, PennyLane, OpenQASM.

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2. Variational Algorithms:

Moving beyond pre-defined algorithms, variational approaches use classical optimizers to tune parameters within quantum circuits, enabling efficient solutions for specific problems where exact algorithms haven't been discovered.

Example: The Variational Quantum Eigensolver (VQE) finds ground states of complex molecules by iteratively optimizing a quantum circuit representing the Hamiltonian, demonstrating potential for drug discovery and materials science.

3. Quantum Machine Learning (QML):

Lets explore leveraging quantum resources to enhance machine learning models. Quantum algorithms can improve tasks like classification, feature learning, and data generation, potentially surpassing classical approaches in specific domains.

Example: Quantum Generative Adversarial Networks (QGANs) can generate synthetic data with higher fidelity than classical GANs, offering benefits for training and augmenting datasets in areas like medical imaging.

4. Hybrid Quantum-Classical Algorithms:

Bridging the gap between classical and quantum computing, hybrid algorithms utilize both frameworks together. Classical computations handle heavy lifting and prepare inputs, while quantum subroutines tackle specific tasks where they demonstrate significant speedups.

Example: Variational Quantum Approximate Optimization Algorithm (VQAA) addresses combinatorial optimization problems by combining classical search algorithms with quantum subroutines to evaluate potential solutions, offering practical advantages over purely classical approaches.

5. Future Directions:

- Development of high-level abstraction tools to simplify quantum programming and make it accessible to a wider audience.
- Exploration of domain-specific languages tailored to specific application areas in chemistry, materials science, and finance.
- Integration of quantum software with classical machine learning frameworks for seamless interoperability and enhanced problem-solving capabilities.

VII. Quantum Computing's Reach: Surveying Potential Applications across Diverse Fields

1. Cryptography:

- Challenge: Current encryption methods rely on factoring large numbers, which quantum algorithms like Shor's could break.
- Progress: Quantum-resistant cryptography research is underway, focusing on post-quantum algorithms and lattice-based cryptography.
- Future: Developing and standardizing quantumresistant algorithms is crucial to ensure secure communication in a quantum future.

2. Optimization:

- Challenge: Many real-world problems, like logistics and finance, involve complex optimization, often intractable for classical computers.
- Progress: Quantum algorithms like VQE and QAOA show promise for tackling specific optimization problems.
- Future: Refining algorithms and integrating them with classical solvers could lead to significant efficiency gains in optimization tasks.

3. Drug Discovery:

- Challenge: Simulating complex molecules for drug design is computationally demanding.
- Progress: Quantum algorithms like VQE demonstrate potential for faster and more accurate molecular simulations.
- Future: Integrating quantum simulations with drug discovery pipelines could accelerate the development of new drugs and therapies.

4. Artificial Intelligence:

- Challenge: Classical AI struggles with certain tasks like natural language processing and complex pattern recognition.

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- Progress: QML research explores using quantum resources to enhance specific AI tasks like image recognition and data generation.
- Future: Developing hybrid quantum-classical AI algorithms could lead to breakthroughs in areas like machine learning and artificial general intelligence.

5. Materials Science:

- Challenge: Designing new materials with desired properties can be time-consuming and expensive.
- Progress: Quantum simulations can predict material properties with higher accuracy, aiding in material discovery.
- Future: Refining simulation capabilities could accelerate the development of novel materials for applications like energy storage and superconductivity.

6. Finance:

- Challenge: Financial modeling and risk assessment often involve complex calculations with incomplete information.
- Progress: Quantum algorithms are being explored for portfolio optimization and fraud detection.
- Future: Quantum-powered financial models could lead to more accurate predictions and efficient risk management strategies.

VIII. Quantum Key Distribution: Securing Communication in the Quantum Age

Imagine sending messages with unbreakable locks, impervious even to the most advanced code-breakers. Quantum Key Distribution (QKD) promises this very idea, using the weird laws of quantum mechanics to generate and distribute cryptographic keys that are provably secure against any eavesdropper, even those wielding quantum computers.

How it works:

1. Quantum particles (photons or entangled qubits) are transmitted between two parties (Alice and Bob) through a secure channel.
2. These particles carry random information encoded in their quantum states (polarization, phase, etc.).
3. Alice and Bob measure the particles in different bases, extracting their own secret keys from the measured values.
4. They publicly compare a portion of their keys to ensure no eavesdropper tampered with the transmission.
5. Any attempt to intercept or modify the particles would introduce errors, detectable by Alice and Bob, rendering the key unusable and alerting them to a potential attack.

Implications for secure communication:

- Unbreakable security: QKD offers provable security based on the laws of physics, unlike classical cryptography vulnerable to advancements in computing power.
- Future-proof: QKD is immune to attacks from potential quantum computers, safeguarding communication in the quantum era.
- High-security applications: QKD is ideal for protecting sensitive data in sectors like finance, healthcare, and government communications.

Challenges and limitations:

- Distance limitations: Current QKD systems have limited transmission range, requiring secure relay stations for long-distance communication.
- Cost and complexity: Setting up and maintaining QKD infrastructure is currently expensive and technically demanding.
- Integration with existing networks: Seamless integration of QKD with existing classical communication networks remains a challenge.

Role of quantum computing in quantum networks:

While QKD provides secure key distribution, quantum computing can further enhance quantum networks:

- Quantum repeaters: These devices, relying on entanglement and quantum error correction, could amplify weak quantum signals, extending the reach of QKD over larger distances.

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- Network management: Quantum algorithms could optimize network resource allocation and routing, ensuring efficient communication flow.
- Quantum cryptography protocols: Novel protocols leveraging quantum resources could offer advanced security features beyond current QKD capabilities.

IX. Quantum Supremacy: Conquering the Mountain, But Are We at the Peak?

The Concept:

Quantum supremacy refers to the hypothetical moment when a quantum computer demonstrates the ability to solve a problem probably impossible for any classical computer, no matter how large or powerful, within a reasonable timeframe. This achievement would mark a significant milestone, showcasing the unique computational power of quantum machines.

Notable Experiments:

- Google's Sycamore (2019): This experiment claimed quantum supremacy by generating random numbers with specific statistical properties that would take a classical computer years to produce.
- IBM's Quantum System One (2020): This experiment tackled a different problem, using a larger quantum processor to demonstrate faster sampling of specific circuits compared to simulations.
- Honeywell's H1 (2023): This experiment focused on demonstrating longer coherence times (information retention) in trapped-ion qubits, potentially leading to more error-resistant quantum processors.

Significance for Practical Applications:

While achieving quantum supremacy is a significant feat, it's not the same as building a practically useful quantum computer. The problems tackled in these experiments, though demonstrably hard for classical computers, don't have immediate real-world applications.

However, surpassing classical capabilities marks a crucial step. It showcases the potential of quantum computers to tackle problems beyond current computing limits, paving the way for future breakthroughs in areas like:

- Drug discovery: Simulating complex molecules for more efficient drug design.
- Materials science: Discovering new materials with desired properties by simulating their behavior at the atomic level.
- Financial modeling: More accurate and efficient risk assessment and portfolio optimization.
- Cryptography: Breaking current encryption methods and developing new, quantum-resistant algorithms.

Challenges and Future Prospects:

Achieving practical applications requires overcoming significant challenges:

- Scalability: Building large, error-resistant quantum processors with thousands or millions of qubits remains a hurdle.
- Error correction: Quantum computations are prone to errors, and effective error correction methods are still under development.
- Algorithm development: Designing algorithms that truly leverage the unique strengths of quantum computers for real-world problems is crucial.

Despite these challenges, the field of quantum computing is rapidly progressing. Continued research and development are addressing these hurdles, and the future holds promise for realizing the true potential of quantum supremacy in solving complex problems with real-world impact.

Acknowledgment

We would like to express our sincere gratitude for the opportunity to delve into the captivating world of quantum computing. This journey wouldn't have been possible without the dedication of several individuals and resources.

First and foremost, we acknowledge the remarkable researchers and pioneers whose groundbreaking work has paved the way for this revolutionary technology. Their unwavering pursuit of pushing scientific boundaries continues to inspire exploration and innovation in the field.

We are also grateful for the wealth of knowledge gleaned from reputable sources and publications on quantum computing. These resources provided invaluable insights and helped us shape a comprehensive understanding of this complex subject.

Finally, a special thanks to Mr. Vasudev Shahpur. Their guidance, feedback, and shared resources proved instrumental throughout this exploration.

This collaborative venture into the realm of quantum computing has been a stimulating and enriching experience. By acknowledging the contributions of those who came before and those who continue to shape this field, we can pave the

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way for a future where quantum computing unlocks its full potential and revolutionizes various aspects of our world.

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