© SEP 2025 | IRE Journals | Volume 9 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I3-1710662-7753

The Future of Quantum Computing

YAASH SAHNAN

Abstract- Quantum Computing often described as one of the most exciting frontiers of modern science—a field that does not just push the boundaries of technology but also reshapes how we think about solving problems. Unlike classical computers, which process information in simple 0s and 1s, quantum mechanics, allowing a single qubit to explore multiple possibilities at the same time. This gives them the potential to perform calculations that would take even today's most powerful supercomputers thousands of years. In recent years, progress has been rapid, with breakthroughs in hardware, algorithms and applications that range from developing new medicines to strengthening artificial intelligence and tackling climate change. Yet, enormous challenges remain, such as stabilizing fragile qubits, reducing error rates, and making these systems accessible beyond a handful of elite labs. This paper explores both the promises and the pitfalls of quantum computing, offering a closer look at how it could reshape industries, global security and even the pace of human innovation in the decades ahead.

Index Terms- Artificial Intelligence, Supercomputers, Qubits, climate change and Quantum Computing.

I. INTRODUCTION

The story of computing is in many ways the story of Human Curiosity. From the abacus to the very first mechanical calculators-from the room sized mainframes to the smartphones in our pockets, every generation has found new ways to make machines think faster and smarter. For decades, classical computers—built on the logic of 0s and 1s, they have powered revolutions in communication, medicine, science and industry. Yet as the problems we hope to solve become more complex, such as modelling global climate change, decoding the mysteries of the human brain or designing life-saving drugs. Even the fastest supercomputers start to show their limits.

Quantum computing enters this story not as an incremental upgrade, but as a dramatic shift in how we imagine computing itself. Instead of bits, quantum computers use qubits which can hold many states at once thanks to the strange rules of quantum mechanics. With principles like superposition and entanglement, they can explore solutions in parallel, tackling problems that would overwhelm even the most advanced classical machines.

But quantum computing is not just about faster calculations. It holds the promise of transforming entire It holds the promise of transforming entire industries, pharmaceutical companies could simulate molecules at the atomic level to design new medicines, banks could optimize financial models in real time and scientists could create more accurate models of the Earth's climate. At the same time, it raises new questions:

What happens to our current systems of digital security? When quantum machines can break today's encryption? Who will control the technology and how will it shape global power?

This paper takes a deep look into the world of quantum computing, not just the science behind it but also the possibilities, the challenges and the very human stakes of a future where our computers may think in ways that feel almost alien to us.

II. RESREARCH ELABORATIONS

A. Principles of Quantum Computing

At the heart of quantum computing lie three fundamental principles of quantum mechanics:

1. Superposition: While a classical bit can exist in only one state (0 or 1) at a time, a quantum bit or qubit can exist in a combination of both states simultaneously. This enables quantum computers to process an enormous number of possibilities in parallel. For example: 20 qubits can represent over a million different states at once.

2. Entanglement: Entangled qubits are strongly correlated meaning the state of one qubit instantly affects the state of another even if they are separated by large distances. Entanglement allows quantum systems to achieve exponentially greater computational power and enables new forms of secure communication.
3. Quantum Interference: Quantum algorithms exploit interference patterns to amplify correct solutions and cancel out incorrect ones guiding computations toward the right answer with high probability.

Together these properties give quantum computers capabilities that classical systems fundamentally lack. Problems such as factoring large numbers, simulating quantum systems and solving complex optimization challenges become tractable with quantum resources.

B. Current Developments in Quantum Computing

1) Hardware Platforms

Several competing approaches exist to build quantum computers:

- Superconducting Qubit: Used by companies such as Google and IBM these rely on circuits cooled near absolute zero to achieve quantum behaviour. They are among the most advanced and scalable designs.
- Trapped Ions: Employed by IonQ and Honeywell, this method uses individual ions suspended in electromagnetic fields manipulated by lasers. They offer high accuracy and long coherence times.
- Photonic Systems: Quantum Systems based on photons (particles of light) are being developed for high-speed quantum communication and computing.
- Topological Qubits: Still largely experimental these aim reduce error rates by encoding information in the "braiding" of quasiparticles.

2) Software and Algorithms:

Quantum computing requires a new class of algorithms many of which have been developed in theory:

- Shor's Algorithm (1994): Efficiently factors large numbers threatening classical cryptography systems.
- Grover's Algorithm (1996): Provides a quadratic speedup for unstructured search problems.
- Quantum Machine Learning Algorithms: Designed to accelerate AI models by performing faster optimization and pattern recognition.

3) Quantum Supremacy:

In 2019, Google announced that its 53-qubit quantum computer "Sycamore" had performed a computation in 200 seconds that would take the world's fastest supercomputer thousands of years. While this milestone called quantum supremacy was controversial, it highlighted the accelerating pace of quantum progress.

C. Applications of Quantum Computing

1) Cryptography and Cybersecurity

One of the most discussed applications of quantum computing is its ability to break widely used cryptographic systems. Public-key encryption methods such as RSA and ECC rely on the difficulty of factoring large numbers or solving discrete logarithms, tasks that quantum computers can perform efficiently with Shor's Algorithm. This has profound implications for global cybersecrity potentially rendering current systems obsolete.

At the same time, quantum technologies also provide new opportunities for secure communication. Quantum Key Distribution (QKD) allows two parties to share encryption keys in a way that is fundamentally secure against eavesdropping. Countries such as china have already launched quantum satellites to test QKD at global scales.

3) Artificial Intelligence and Machine Learning

AI and machine learning involve optimization over massive datasets a task where quantum computers excel. Quantum enhanced machine learning models can improve natural language processing, image recognition and predictive analytics. Start-ups and Corporations are exploring how hybrid classical-quantum systems could create breakthroughs in AI efficiency.

4) Climate Modelling and Sustainability

Climate change presents one of the most complex challenges facing humanity. Accurate modelling of atmospheric, oceanic and ecological systems requires computational power beyond classical capabilities. Quantum simulations could enhance the accuracy of climate predictions optimize renewable energy grids and design sustainable materials.

5) Finance and Logistics
Quantum computing can solve optimization problems in portfolio management, risk analysis and supply chain logistics. Banks such as JP Morgan Chase and Volkswagen are investing heavily in quantum research to gain competitive advantages in finance and transportation.

D. Challenges and Limitations
Despite impressive progress quantum computing is still in its infancy and faces several challenges:

1. Dechorence and Noise: Qubits are highly fragile and lose their quantum state when interacting with the environment. This limits the time available for computations.
2. Error Correction: Quantum error correcting codes require multiple physical qubits to create one reliable logical qubit, dramatically increasing hardware requirements.
3. Scalability: Building systems with thousands or millions of qubits remains a monumental engineering challenge,
4. Cost and Complexity: Quantum computers require highly specialized environments such as cryogenic cooling and vacuum chambers making them expensive to operate.
5. Algorithm Development: While few breakthrough algorithms exist many real-world applications still lack effective quantum solutions.

E. Ethical, Economic and Geopolitical Implications.
Quantum computing is not only a scientific and technological challenge but also a societal one.

- Ethics and Privacy: If quantum computers break current encryption methods sensitive data from governments, corporations and individuals could be exposed. This raises questions about data privacy and the responsibility of those who control quantum technologies.
- Economic Disruption: Industries such as cybersecurity, pharmaceuticals and finance may face massive disruption as quantum technologies mature. Early adopters will gain sufficient advantages while others risk obsolescence.
- Geopolitical Competition: The race for quantum supremacy has become a new arena for global competition similar to the space race of the 20th century. Countries such as the United States, China and the members of the European Union are investing heavily to secure leadership. Control over quantum technology could determine economic and military dominance in the coming decades.

III. RESULTS OR FINDINGS

The study of quantum computing reveals both extraordinary opportunities and formidable challenges. Current developments indicate that while fully scalable quantum computers are still years away, practical applications in optimization, cryptography and simulation are already emerging.

Finding show that quantum computing will likely evolve through a hybrid phase where quantum processors complement classical supercomputers rather than replace them entirely, Industries that rely heavily on optimization and simulation, finance, pharmaceuticals, materials science will see earliest benefits.

Furthermore, the research highlights that global investment accelerating. Over 20 countries now have national quantum initiatives and venture capital funding for quantum start-ups has surged past billions of dollars. These findings suggest that within the nest two decades, quantum computing will move from research labs into mainstream use.

CONCLUSION

Quantum computing is more than just a new chapter in the history of technology, it is like a beginning of an entirely new book. By harnessing the strange and powerful rules of quantum mechanics, we are learning to approach problems that once seemed impossible. From simulating molecules that could unlock new medicines to building smarter artificial intelligence and protecting our planet through better climate models the possibilities stretch far beyond what today's computers can achieve.

© SEP 2025 | IRE Journals | Volume 9 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I3-1710662-7753

But this future will not come without challenges. Fragile qubits, error-prone systems and enormous costs remind us that the road ahead is still long. There are also human questions to answer: How do we secure our digital world once current encryption can be broken? How do we ensure that quantum technologies are shared fairly instead of widening the gap between powerful nations and the rest of the world?

The story of quantum computing is still being written. It is a story not only of physics and engineering but also of people, scientists pushing the boundaries of knowledge, industries reimaging their future and societies grappling with the impact of a tool that could change everything. If humanity can meet both the scientific and ethical challenges ahead, quantum computing will simply make our machines smarter. It will expand what we, as humans are capable of imagining and achieving.

APPENDIX

A. Classical V/s Quantum Computers

Feature	Classical Computer	Quantum Computer
Basic Unit	Bit (0 or 1)	Qubit (0, 1 or both at once)
Processing	Sequential (one calculation at a time)	Parallel (many possibilities at once)
Speed	Very fast, but limited by Moore's law	Exponentially faster for certain problems
Security	Relies on encryption (RSA, ECC)	Can break current encryption, but enables quantum-safe cryptography
Examples	Laptops, Supercomputers	Google Sycamore, IBM Eagle, IonQ trapped-ION systems

B. Timeline of Key Milestones in Quantum Computing

- 1980s: Richard Feynman and David Deutsch propose the concept of quantum computers.
- 1994: Peter Shor develops Shor's Algorithm for factoring numbers efficiently.
- 1996: Lov Grover introduces Grover's Algorithm for faster database search.
- 2001: IBM and Stanford demonstrate a 7-qubit quantum computer.
- 2019: Google's Sycamore achieves "quantum supremacy"
- 20021: IBM announces a 127-qubit processor, Eagle.
- 2023: China claims progress toward a quantum advantage in certain tasks.
- Future Goal: Build faut-tolerent quantum computers with thousands and millions of stable qubits.

C. Statistics on Quantum Computing Progress

1. Qubit Count (As of 2024)
   - IBM Eagle Processor: 127 qubits
   - IBM Osprey: 433 qubits
   - Google Sycamore: 53 qubits (Quantum Supremacy demo)
   - IonQ trapped-ion system: 32 qubits (high fidelity)
2. Market Growth:
   - The Global quantum computing market was valued at 866 million USD in 2023.
   - It is expected to reach USD 4.4 billion by 2028 with a compound annual growth rate (CAGR) of over 38 percent.
3. Investment Trends:
   - The U.S. National Quantum Initiative Act (2018) pledged over USD 1.2 billion in funding.
   - China invested more than USD 10 billion in its national quantum program
   - Venture capital in investments in quantum start-ups exceeded 2 billion USD by 2023.
4. Industry Adoption:
   - Pharmaceuticals: Pfizer and Roche are testing quantum simulations for drug discovery.
   - Finance: JPMorgan Chase is developing quantum algorithms for risk modelling.
   - Automotive: Volkswagen and Daimler use quantum computing for traffic optimization and battery design.

Acknowledgement

The author acknowledges the guidance of mentors and the whole broader scientific community whose research formed the foundation of this paper.

REFERENCES

[1] Arute, F.et al. "Quantum Supremacy using a programmable superconducting processor" Nature, 574, 505-510, 2019
[2] Preskill, J. "Quantum Computing in the NISQ era and beyond." Quantum, 2, 79, 2018.
[3] Nielsen, M.A. & Chuang, I.L. Quantum Computation and Quantum Information. Cambridge University Press, 2010.
[4] Paper by Gambetta, J.M. Chow, J.M & Steffen on "Building logical quibits in a superconducting quantum computing system." 2017.
[5] Shor, P.W. "Algorithms for quantum computation: Discrete logarithms and factoring." Proceedings 35th Annual Symposium of Foundations of Computer Science, 1994.
[6] Grover, L.K. "A fast quantum mechanical algorithm for database search." Proceedings of the 28th Annual ACM Symposium on Theory of Computing. 1996.
[7] IBM Research. "The Future of Quantum Computing." [Online]. Available: https://research.ibm.com
[8] National Quantum Initiative Act. U.S. Government, 2018.