



Quantum Computing Transforming Science and Society with Applications Challenges and Future Pathways

Ratul Nath

Sabre, Navigator Building, ITPB, #7, Whitefield Main Road, Bangalore, India, 560066

Email: ratul.n@gmail.com

Received: 19 August 2025

Revised: 28 August 2025

Accepted: 29 August 2025

Published online: 2 September 2025

Article ID: SR01017

Citation: Nath, R. (2025). Quantum Computing Transforming Science and Society with Applications Challenges and Future Pathways. *Scientia Review*, 1(3), 9-11

Abstract

Quantum Computing (QC) represents a paradigm shift from classical computing by leveraging the principles of quantum mechanics superposition, entanglement and tunneling. Unlike conventional bits that exist in binary states (0 or 1), qubits exist in multiple states simultaneously, enabling exponential computational advantages for specific problem classes. The foundations of quantum computing are explored along with its applications in cryptography, optimization, healthcare and material science, while addressing technical and ethical challenges and examining regulatory and policy efforts and its future is envisioned as a transformative force for science, society and global innovation.

Keywords: Quantum, Cryptography, Optimization, Healthcare, Sustainability

Introduction

Computing has underpinned scientific discovery and economic growth for decades, yet many problems such as simulating molecules, solving optimization puzzles or breaking encryption remain intractable even for today's most powerful supercomputers. Richard Feynman, in the 1980s, envisioned a machine based on quantum mechanics capable of solving such problems. Since then, rapid advances have moved QC from theory to experimental reality, with demonstrations of 'quantum supremacy' by Google in 2019 and ongoing efforts by IBM, Microsoft and governments worldwide. The unique advantage of QC lies in qubits, which can exist in superposition and become entangled, enabling exponential computational possibilities. While still early, QC has the potential to disrupt fields ranging from cybersecurity to climate modeling.

Core Concepts in Quantum Computing

Quantum computing differs fundamentally from classical computing because it is built on qubits rather than bits. While classical bits can only be 0 or 1, qubits can represent 0, 1 or even a

quantum superposition of both, allowing them to exist in multiple states at once. This property, called superposition, makes it possible for

quantum computers to perform parallel computations, much like a spinning coin that shows both heads and tails at the same time. Another remarkable feature is entanglement, where qubits become deeply correlated and remain linked no matter how far apart they are similar to a pair of dice that always show related outcomes even when rolled in different places. To harness these properties, quantum gates and circuits are used to manipulate qubits, functioning in ways that parallel logic gates in classical computing but with far greater complexity. Together, these principles enable quantum algorithms such as Shor's for factoring and Grover's for searching, which demonstrate exponential and quadratic speedups, revealing the transformative potential of quantum computation.

Applications of Quantum Computing

Quantum computing is expected to have a profound impact across multiple fields. In cryptography and cybersecurity, Shor's algorithm poses a direct threat to widely used encryption methods like RSA and ECC, prompting initiatives such as NIST's development of post-quantum cryptography to secure future communications. In optimization,

quantum systems can tackle complex challenges in supply chains, logistics and finance with companies like Volkswagen already piloting quantum solutions to improve traffic flow in cities such as Lisbon and Beijing. Drug discovery and healthcare stand to benefit as well, since quantum simulations could dramatically shorten the timelines required for developing new medicines. In material science and energy, quantum computing is being applied to the design of superconductors, advanced batteries

and catalysts, with ExxonMobil exploring its potential for energy research. Artificial intelligence is another area where quantum machine learning promises to accelerate the training of deep models and hybrid AI-quantum algorithms are beginning to emerge. Finally, quantum computing could play a critical role in addressing climate and sustainability challenges, from enhancing atmospheric simulations and carbon capture strategies to optimizing the design of sustainable crops.

Benefits and Opportunities

Domain	Quantum Impact
Cryptography	Breaks classical encryption; drives need for post-quantum security
Optimization	Faster logistics, traffic flow and industrial scheduling
Healthcare	Accelerates drug discovery, protein folding, personalized medicine
Material Science	Enables new superconductors, energy materials, clean catalysts
AI Integration	Faster training and inference of machine learning models
Climate & Sustainability	Complex climate modeling, energy optimization, soil and crop simulations

Challenges and Risks

- **Decoherence:** Qubits are extremely fragile and tend to lose information very quickly.
- **Error Correction:** Achieving stable computation requires thousands of physical qubits just to create one reliable logical qubit.
- **Scalability:** Today's quantum systems have fewer than 2,000 qubits, while millions may be necessary for fully universal quantum computing.
- **Hardware Challenges:** Maintaining qubits demands ultra-cold cryogenic environments and highly complex fabrication techniques.
- **Software Fragmentation:** The ecosystem is split across multiple programming platforms such as Qiskit, Cirq and Braket, making development less standardized.
- **Security Risks:** Quantum computing could break existing global encryption standards, posing serious national security threats.
- **Economic Divide:** Access is currently limited to large technology companies and governments, leaving smaller nations and organizations at risk of exclusion.

- **Ethical Concerns:** The technology could fuel cyberwarfare, deepen digital inequality and raise significant societal challenges.

Regulatory and Policy Considerations

The USA's National Quantum Initiative Act (2018), the EU's €1B Quantum Flagship program, India's ₹8000 crore National Mission on Quantum Technologies and China's rapid QC expansion represent major government commitments. NIST has also initiated standards for Post-Quantum Cryptography (2024). Stronger global collaboration is required to balance innovation with ethical safeguards

Future Directions

The future of quantum computing is being shaped by several promising directions. Quantum cloud services, offered by platforms such as IBM Q, Google Quantum AI and Amazon Braket are making this technology accessible to researchers and developers worldwide. Hybrid systems that combine classical high-performance computing with quantum processors are emerging as practical solutions for tackling real-world challenges. At the same time, progress toward fault-tolerant quantum computing, where error-corrected qubits enable scalable and universal machines, represents a crucial milestone. Beyond computing itself, the concept of a quantum internet built on

entanglement promises ultra-secure communication networks, while quantum sensors are poised to deliver breakthroughs in areas such as high-precision navigation and underground resource detection. Looking further ahead, cross-disciplinary fusion of quantum computing with fields like artificial intelligence, blockchain, genomics and material science could open entirely new frontiers of innovation and discovery.

Conclusion

Quantum Computing is not a replacement for classical systems but a complementary tool

unlocking solutions once deemed impossible. Its applications in cryptography, drug discovery, material science, AI and climate studies signal a new technological revolution. However, scalability, accessibility and ethics remain formidable barriers. QC stands at an inflection point: policies, investments and collaborations made today will decide whether it becomes a tool for global good or a driver of digital inequality.