

Applications of Quantum Computing: A Review of Current and Emerging Use Cases

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Abstract:

Quantum computing is emerging as a transformative paradigm across various fields, from drug discovery to secure communications. This paper surveys current and potential applications of quantum computing, particularly focusing on chemistry, optimization, cryptography, finance, and remote sensing. We discuss the state of the art, existing hardware and software approaches, and future research challenges. The review highlights the role of quantum algorithms in outperforming classical methods in specific problem domains.

Keywords: Quantum Computing, Qubit, Cryptography, Optimization, Quantum Machine Learning, Quantum Chemistry, QAOA, Shor's Algorithm, QKD

I. Introduction:

Quantum computing harnesses principles such as superposition and entanglement to solve computational problems previously intractable by classical computers [1]. Quantum bits (qubits) allow exponential scaling of state space, unlocking significant gains in optimization, molecular simulation, and machine learning. This paper provides a comprehensive overview of quantum computing applications and outlines their transformative potential across scientific and industrial domains.

II. Applications in Chemistry and Materials Science:

Quantum simulation allows for highly accurate modelling of atomic and molecular interactions enabling innovation in pharmaceuticals and material design.

A. Molecular Simulation and Drug Discovery: The Variational Quantum Eigen solver (VQE) has demonstrated success in simulating the ground-state energy of small molecules [2]. Companies such as IBM and Google have used VQE to simulate systems like lithium hydride and beryllium hydride [3]. These developments are vital for drug discovery, where predicting binding affinity and reaction pathways is computationally intensive.

B. Green Chemistry and Materials: Quantum computing aids in identifying efficient catalysts for industrial processes such as nitrogen fixation and CO₂ sequestration [4]. Researchers have begun using quantum techniques to study new materials for batteries, photovoltaics, and biodegradable plastics.

III. Optimization and Machine Learning:

Optimization problems in scheduling, logistics, and finance benefit greatly from quantum enhancements.

A. Combinatorial Optimization: The Quantum Approximate Optimization Algorithm (QAOA) and Quantum Annealing are effective for solving NP-hard problems [5]. Applications include traffic optimization, warehouse logistics, and network design.

B. Quantum Machine Learning (QML): Quantum classifiers and kernel methods accelerate pattern recognition in high-dimensional datasets. Use cases include satellite image classification, financial fraud detection, and protein structure prediction [6].

IV. Cryptography and Cybersecurity:

Quantum computing has dual implications for digital security: enabling new cryptographic methods while breaking current ones.

A. Threat from Shor's Algorithm: Shor's algorithm can factor large integers in polynomial time on a fault-tolerant quantum computer, threatening RSA and ECC encryption schemes [7].

B. Quantum Key Distribution (QKD): QKD enables unbreakable encryption by detecting eavesdropping using quantum properties. It is being tested in national defence and banking sectors across Europe and Asia [8].

C. Post-Quantum Cryptography (PQC): NIST is finalizing new encryption standards to resist quantum attacks [9]. These algorithms are being adopted globally across government and finance.

V. Financial Applications:

The financial industry stands to benefit from quantum computing through enhanced modelling, faster simulations, and more secure communications.

A. Portfolio Optimization: Quantum algorithms can find optimal asset distributions by evaluating complex, multi-constraint objective functions [10].

B. Derivatives Pricing and Risk Modelling: Quantum Monte Carlo methods accelerate computation of option prices and risk exposure metrics, especially under stochastic volatility models.

C. Fraud Detection and Blockchain: Quantum machine learning techniques improve real-time fraud detection. Quantum-safe cryptographic protocols are also being developed to future-proof blockchain infrastructures [11].

VI. Space, Remote Sensing, and Communication:

Quantum computing enables new capabilities in space mission planning, data compression, and secure inter-satellite communication.

A. Earth Observation: QML is used to classify hyperspectral imagery from Earth-observing satellites, assisting in climate monitoring, crop yield prediction, and natural disaster assessment [12].

B. Quantum Communication Networks: Satellite-based quantum networks are being developed in China and Europe to enable entangled communication links across continents [13].

VII. Software Engineering and Cloud Platforms: Cloud-based quantum services democratize access to quantum hardware. Platforms like IBM Q, Amazon Bracket, and Microsoft Azure Quantum support development of quantum applications [14].

The emerging discipline of Quantum Software Engineering (QSE) focuses on standardizing best practices, lifecycle models, debugging tools, and hybrid algorithm development [15].

VIII. Challenges and Future Directions:

Challenge	Description
Hardware limitations	Current systems are noisy and limited in scale.

Error correction	Requires thousands of physical qubits per logical qubit.
Algorithm development	Few quantum algorithms outperform classical ones yet.
Workforce & education	Skills gap in quantum programming and systems engineering.
Ethical implications	Equity, access, and misuse of quantum power remain concerns.

Governments worldwide are investing heavily to mitigate these barriers, including the UK's £2.5 billion quantum strategy and India's National Quantum Mission [16].

Conclusion:

Quantum computing is transitioning from theoretical promise to real-world application. Its unique capabilities in optimization, simulation, and security are reshaping disciplines as diverse as drug discovery, finance, and aerospace. Continued advances in hardware, algorithms, and ecosystem maturity will define its trajectory in the coming decade.

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