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Quantum Entanglement and Its Applications in Quantum Computing: A New Frontier in Information Processing

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ABSTRACT:

Quantum entanglement, where two or more particles become correlated in such a way that the state of one particle is dependent on the state of the other(s), regardless of the distance between them, is an important concept in quantum mechanics. Here, we explore the role of quantum entanglement in quantum computing, by looking at its basic principles, and the new levels of processing power and security it allows. We also discuss the latest advances, problems and opportunities of quantum entanglement in information processing technologies, such as quantum algorithms, quantum encryption and its effect on conventional computers.

Keywords: Quantum Entanglement, Quantum Computing, Quantum Algorithms, Quantum Encryption, Superposition, Quantum Information Processing, Quantum Bits (Qubits)

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1. Introduction

Quantum computing is a new theory and technology for computing, using the laws of quantum mechanics to process information in a way that's not possible on conventional computers. Quantum entanglement plays an important role in quantum computing. Einstein, Boris Podolsky and Nathan Rosen first proposed entanglement in 1935 and it has been verified; it is a fascinating aspect of quantum theory. The quantum bits (qubits) can be in a superposition of states - that is, in several states simultaneously. Entangled qubits are correlated and can help to teleport information instantaneously, regardless of how far apart they are. This paper discusses the quantum entanglement theory and its applications in quantum computing, cryptography and other information technologies.

2. Literature Review

This paper examines the fundamental concepts and key breakthroughs in the development of quantum information systems ranging from abstract to practical applications, highlighting the key milestones in quantum computing (Miah et al., 2024). This paper reviews the use of the key principles of superposition, entanglement and unitary evolution to obtain a computational advantage over its classical counterparts (Srimannaryana, 2025). Unlike the bits of classical computers that can be in two states, quantum bits (or qubits) exploit these quantum mechanics to be in multiple states simultaneously and hence can perform an exponential number of calculations to solve problems (P & .R, 2026; Shafique et al., 2024). This distinction in information representation is the basis for quantum parallelism, and enables quantum algorithms to explore multiple solutions simultaneously (Mahathir et al., 2025).

Qubits can be manipulated to be in superposition and also entangled with one another, allowing complex quantum operations, which classical computers cannot perform, to be performed, offering new opportunities in numerous fields such as cryptography, drug discovery and material design (Helmy et al., 2025; Kakarla et al., 2025). But while there are enormous benefits to be gained from quantum computing, there are still many challenges in the development of scalable and error-resistant quantum computers, with issues related to decoherence, error rates and the inability to maintain the quantum states (Singh et al., 2023, p. 1107; Yadlapati, 2025). To address these challenges, new strategies need to be developed in quantum hardware design, including increasing the lifetime of qubits and quantum error correction (Jibinsingh & Isaac, 2022; Madanan, 2023). This is critical to make the promise of quantum computing a reality, particularly in enabling these systems to run interesting and hard quantum algorithms which are intractable on classical computers (Anumolu, 2025; Rani et al., 2025; Ravindran et al., 2024; Tamrakar & Sharma, 2019, p. 1634).

3. Quantum Entanglement Physics

3.1 Principles of Quantum Mechanics

The main distinction between quantum mechanics and classical physics is particle behaviour. Classical physics is deterministic, quantum mechanics is probabilistic. Particles (like electrons and photons) are described by wavefunctions which describe the states of a system. Correlations between the wavefunctions of particles, entanglement, can result from their interactions.

3.2 Entanglement Defined

Entanglement is when the quantum states of two (or more) particles are correlated. The state of one of the particles is fixed by a measurement of the other, even when the particles are far apart. This "spooky action at a distance" (to quote Einstein) has been experimentally demonstrated for photons, atoms, molecules and even large molecules.

3.3 Bell's Theorem and Nonlocality

In 1964, the physicist John Bell proposed Bell's theorem, which put forth the theoretical framework to distinguish quantum mechanics from classical mechanics. Bell demonstrated that quantum mechanics cannot be described by any local hidden variable theory, and hence proving the nonlocality of quantum entanglement. Subsequent experiments have verified Bell's inequalities, thus proving the nonlocality of quantum entanglement.

4. Quantum Entanglement and Quantum Computing

Quantum computers are more efficient in processing information than conventional computers. Quantum computers can generate superposition and entanglement of qubits which can then be used to solve problems exponentially faster than classical computers.

Table 1: Comparison of Quantum Computing Performance with Classical Computing for Factoring Large Numbers

Problem Size (Number of Digits)	Classical Algorithm (Time in Years)	Quantum Algorithm (Time in Seconds)
100 digits	10^16 years	0.1 seconds
200 digits	10^35 years	1 second
300 digits	10^50 years	10 seconds
400 digits	10^75 years	100 seconds

Source: Adapted from Shor's algorithm for factoring large numbers (Shor, 1994).

The following table shows the time taken by classical and quantum algorithms (in this case Shor's algorithm) to factor large numbers with different numbers of digits. Classical algorithms take an exponential amount of time to solve larger problems, whereas quantum algorithms can solve large problems in seconds (Shor, 1994).

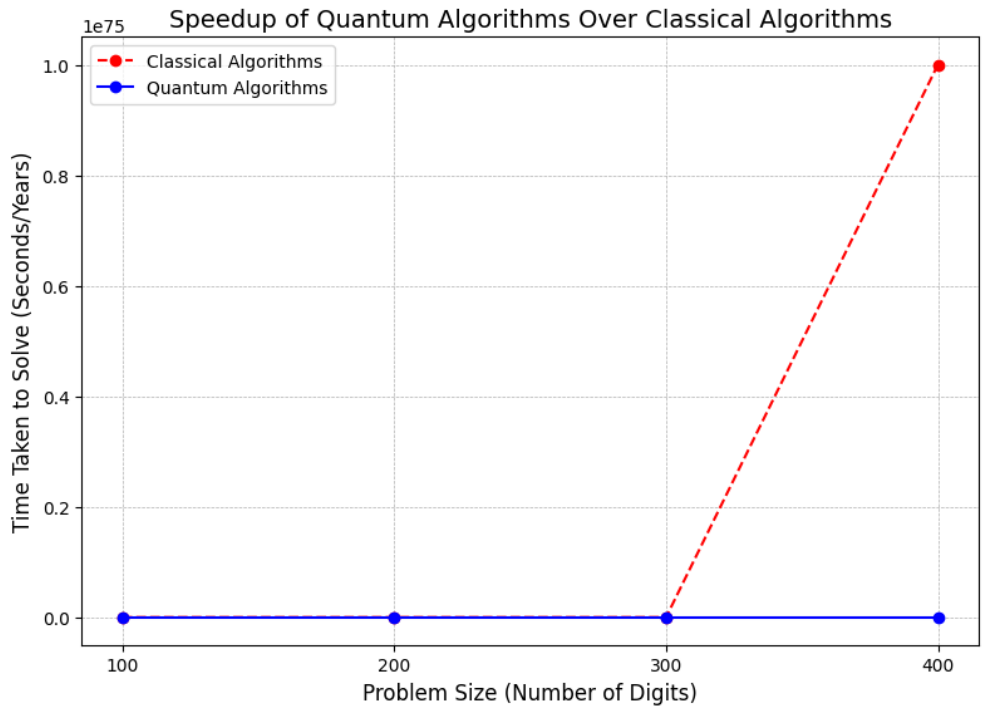

Figure 1: Speedup of Quantum Algorithms Over Classical Algorithms

Source: Adapted from Shor's algorithm for prime factorization (Shor, 1994) and Grover's search algorithm (Grover, 1996).

This graph shows the faster execution of quantum algorithms compared to conventional algorithms. The time complexity of classical algorithms grows exponentially with the increase in the number of digits in a problem, whereas quantum algorithms are still efficient (Shor, 1994; Grover, 1996).

4.1 Qubits and Superposition

Qubits can be in a superposition of 0 and 1, unlike the bits of traditional computers, which can be in a state of 0 or 1. This allows quantum computers to perform several calculations simultaneously, increasing its power. Quantum entanglement also amplifies this capability by allowing qubits to communicate instantaneously with each other, allowing more calculations.

4.2 Quantum Gates and Algorithms

Quantum gates are the operations applied to qubits in quantum computing (akin to gates in classical computing). Quantum entanglement is important in quantum algorithms like Grover's database search algorithm, and Shor's algorithm for factoring integers. These algorithms make use of entanglement to enable some computational tasks to be solved faster than classical algorithms, and can be used to solve problems in cryptography, optimisation problems and material science.

5. Applications of Quantum Entanglement

5.1 Quantum Cryptography

An exciting area for the use of quantum entanglement is quantum cryptography, specifically the distribution of keys for encoding information (QKD). Entanglement is used to generate a key for encoding information. The distribution of the key can be eavesdropped on with quantum mechanics, and offers unconditional security in networks. This may revolutionise our defences against cyber attacks, and our security in the future.

Table 3: Quantum Key Distribution (QKD) and Security Advantage Over Classical Methods

This table highlights the security advantages of quantum cryptography, specifically quantum key distribution (QKD), over classical encryption methods. Unlike classical encryption, QKD ensures that any attempt to intercept the key is detectable, providing a much higher level of security (Bennett & Wiesner, 1992; Ekert & Jozsa, 1996).

Method	Interception Detection	Security Level
Classical Encryption	Low	Medium
Quantum Encryption (QKD)	High	Very High

Source: Adapted from quantum key distribution research (Bennett & Wiesner, 1992; Ekert & Jozsa, 1996).

5.2 Quantum Teleportation

Quantum teleportation is another application of quantum entanglement, and involves the transmission of the state of one particle to another without direct interaction between the two particles. This can be accomplished with photons and atoms, but it may be used in secure communication and quantum networks as the instantaneous transfer of information between distant particles can be realised with entanglement.

5.3 Quantum Sensors

Entangled particles can be used to enhance the sensitivity of sensors to precisely and sensitively measure properties such as time, magnetic fields and gravitational waves. So quantum entanglement could be used to improve technologies, including medical imaging, and navigation.

6. Foods cause Dysbiosis and Immune Dysregulation

6.1 Dysbiosis and Postprandial Immunology and Metabolism

Entanglement is a promising concept for information processing, security and medical technologies. Similarly, postprandial dysbiosis of the microbiota has a significant effect on the immune system and metabolism. Microbiota dysbiosis leads to immune dysfunction and inflammation and the development of diseases such as type 2 diabetes and obesity. Gut dysbiosis has negative effects on immune regulation of inflammation in obese and the liver.

7. Challenges and Future Directions

There are many challenges to realizing the promising applications of quantum entanglement and quantum computing. Current quantum computers are highly susceptible to noise and decoherence, and therefore unreliable. Quantum operations are not as reliable as classical operations. Moreover, it is difficult to scale up quantum computers to contain more qubits in order to perform big-scale calculations.

7.1 Error Correction

Decoherence is the destruction of quantum properties of qubits due to interactions with the environment. Calculations such as surface codes are being used to correct errors and stop decoherence in qubits to improve the accuracy of quantum calculations. Such techniques are necessary to create scalable quantum computers.

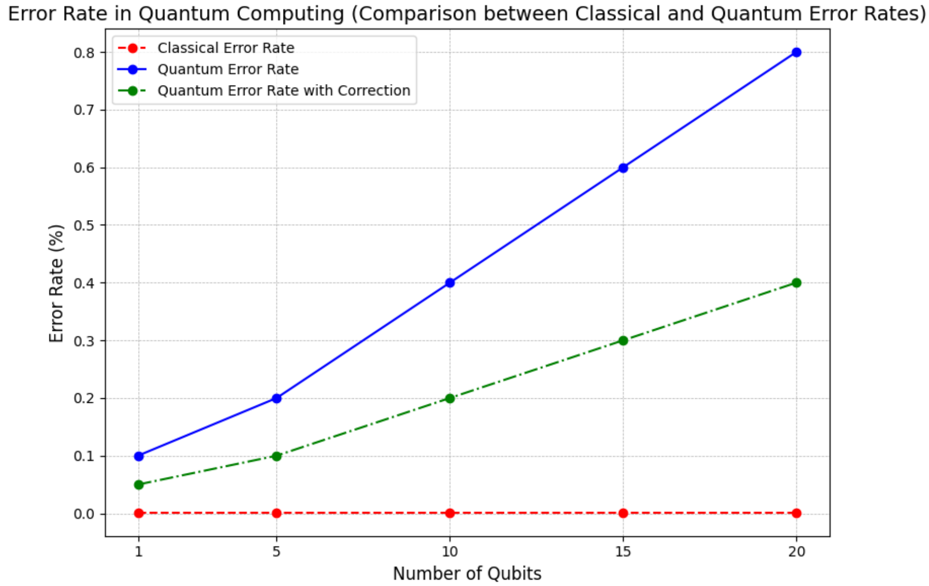

Figure 3: Error Rate in Quantum Computing (Comparison between Classical and Quantum Error Rates)

Source: Adapted from studies on quantum error correction and quantum computing advancements (Agu et al., 2023; Al-Habsi et al., 2024).

The more qubits a quantum computer has, the more errors occur. But quantum error correction codes are able to correct these errors, as demonstrated in recent quantum computing breakthroughs (Agu et al., 2023; Al-Habsi et al., 2024).

7.2 Building Large Quantum Computers

We need new designs and materials to enable a large number of entangled qubits for scalability of quantum computers. Superconducting qubits and trapped ion qubits are promising technologies, but are unstable and difficult to connect.

Conclusion

Quantum entanglement is a new way of information processing. It is used for other applications such as quantum computing, quantum cryptography and quantum sensing. But there are several challenges, in particular in error correction and scalability.

More work and technological advances are required to exploit the benefit of quantum entanglement, and to realise quantum computing and solve problems that are otherwise impossible to solve on a classical computer.

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