**Practical-7**

**Quantum Computing: An Introduction and Experimentation with IBM Quantum's "Hello World"**

Quantum computing represents a significant shift in computational paradigms, leveraging principles of quantum mechanics to process information in ways that classical computers cannot. Unlike classical bits, which are binary and represent either a 0 or a 1, quantum computers use quantum bits, or qubits, which can exist in a state of 0, 1, or any quantum superposition of these states. This characteristic enables quantum computers to perform complex calculations more efficiently than their classical counterparts.

**Advantages:**

1. **Parallelism:** Qubits can represent multiple states simultaneously, allowing quantum computers to process a vast number of possibilities at once, leading to significant speedups in certain computations.
2. **Exponential Growth:** The computational power of a quantum system grows exponentially with the addition of each qubit, enabling the solving of problems that are currently infeasible for classical computers.
3. **Enhanced Security:** Quantum cryptography promises theoretically unbreakable communication channels, leveraging the principles of quantum mechanics to detect any eavesdropping attempts.

**Disadvantages:**

1. **Decoherence:** Qubits are highly sensitive to environmental factors, and maintaining their quantum state (coherence) is challenging, leading to potential errors in computation.
2. **Error Correction:** Developing effective quantum error correction methods is complex due to the nature of quantum information, which cannot be copied or measured without disturbance.
3. **Resource Intensive:** Quantum computers require extremely low temperatures and isolated environments to function correctly, making them expensive and challenging to maintain.

**Cost of Accessing IBM Quantum Systems**

IBM offers various plans for accessing their quantum computing resources:

* **Open Plan:** Free access to utility-scale quantum computers for up to 10 minutes of runtime per month, suitable for learning and exploration purposes.
* **Pay-As-You-Go:** Starting at $96 USD per minute, this plan allows flexible access, billed per second of usage via IBM Cloud, ideal for research projects and business model testing.
* **Premium Plan:** Equivalent to $48 USD per minute, this subscription-based plan provides reserved capacity, offering up to 1,600 minutes per Quantum Allocation Unit (QAU) every 28 days, tailored for strategic quantum roadmap execution and large-scale algorithm development.
* **Dedicated Service:** Pricing is available upon request for access to an entirely dedicated quantum system, serviced and maintained by IBM Quantum, best suited for organizations requiring high control over resources and data.

**Experimentation with IBM Quantum's "Hello World"**

To gain practical experience with quantum computing, we engaged in the "Hello World" experiment provided by IBM Quantum. This exercise involves creating and executing a simple quantum program using Qiskit, IBM's open-source quantum computing framework.

**Steps Undertaken:**

1. **Problem Mapping:** We began by translating the problem into a quantum-native format, constructing a quantum circuit that generates a Bell state—a fundamental quantum state where two qubits are entangled.
2. **Circuit Optimization:** The constructed circuit was optimized to reduce errors and improve execution efficiency.
3. **Execution:** Utilizing IBM's quantum primitive functions, the circuit was executed on a quantum processing unit (QPU).
4. **Result Analysis:** The output was analyzed to interpret the results and understand the behavior of the quantum system.

A **Bell state** is a fundamental concept in quantum computing, representing a pair of qubits that are maximally entangled. This entanglement creates a strong correlation between the qubits, such that the state of one qubit is directly related to the state of the other, regardless of the distance separating them. Bell states are essential in quantum information science, underpinning protocols like quantum teleportation and superdense coding.

**Understanding Qubits and Superposition**

Before delving into Bell states, it's important to grasp the basics of qubits:

* **Qubit:** The fundamental unit of quantum information, analogous to a classical bit. Unlike a bit, which can be either 0 or 1, a qubit can exist in a state of 0, 1, or any quantum superposition of these states. This means a qubit can represent both 0 and 1 simultaneously, a property that enables quantum computers to process a vast number of possibilities at once.

**What Are Bell States?**

Bell states are specific quantum states of two qubits that exhibit maximal entanglement. There are four such states, commonly denoted as:

1. \*\*Φ⁺ (Phi Plus):\*\* ∣Φ+⟩=12(∣00⟩+∣11⟩)|\Phi^+\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) In this state, both qubits are in a superposition where they are simultaneously 00 and 11. Measuring one qubit collapses the state, instantaneously determining the state of the other qubit.
2. \*\*Φ⁻ (Phi Minus):\*\* ∣Φ−⟩=12(∣00⟩−∣11⟩)|\Phi^-\rangle = \frac{1}{\sqrt{2}} (|00\rangle - |11\rangle) Similar to Φ⁺ but with a phase difference, affecting the interference patterns observed during measurements.
3. \*\*Ψ⁺ (Psi Plus):\*\* ∣Ψ+⟩=12(∣01⟩+∣10⟩)|\Psi^+\rangle = \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle) Here, the qubits are in a superposition of being in states 01 and 10, meaning if one qubit is measured as 0, the other will be 1, and vice versa.
4. \*\*Ψ⁻ (Psi Minus):\*\* ∣Ψ−⟩=12(∣01⟩−∣10⟩)|\Psi^-\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle) This state also involves a superposition of 01 and 10 but includes a phase difference.

These states are named after physicist John Bell, who explored the fundamental aspects of quantum entanglement.

**Creating a Bell State: The Quantum Circuit**

To generate a Bell state, a simple quantum circuit involving two qubits and two quantum gates is used:

1. **Hadamard Gate (H):**
   * Applied to the first qubit, the Hadamard gate creates a superposition state. If the qubit starts in the state |0⟩, applying the Hadamard gate transforms it into: H∣0⟩=12(∣0⟩+∣1⟩)H|0\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) This means the qubit is now in an equal probability of being in state 0 or 1.
2. **Controlled-NOT Gate (CNOT):**
   * This gate operates on two qubits: a control qubit and a target qubit. It flips the state of the target qubit (from 0 to 1 or from 1 to 0) if and only if the control qubit is in the state |1⟩.

The process to create a Bell state (specifically Φ⁺) is as follows:

* **Initialize the Qubits:** Both qubits start in the state |0⟩.
* **Apply Hadamard Gate to Qubit 1:** This creates a superposition:H∣0⟩=12(∣0⟩+∣1⟩)H|0\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)
* **Apply CNOT Gate with Qubit 1 as Control and Qubit 2 as Target:** The CNOT gate entangles the qubits, resulting in the state: ∣Φ+⟩=12(∣00⟩+∣11⟩)|\Phi^+\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)

This means both qubits are now entangled in such a way that measuring one qubit will instantaneously determine the state of the other, regardless of the distance between them.

**Significance of Bell States**

Bell states are crucial in quantum computing and quantum information theory because they exemplify the non-classical correlations possible in quantum systems. They serve as the foundation for various quantum protocols:

* **Quantum Teleportation:** Utilizes entangled pairs to transmit quantum information between parties without physically sending the qubits themselves.
* **Superdense Coding:** Allows the transmission of two classical bits of information using only one qubit, by leveraging the properties of entangled states.

**Challenges Faced:**

* **Understanding Quantum Concepts:** Grasping the principles of quantum mechanics and their application in quantum computing required a steep learning curve.
* **Resource Constraints:** Limited free access time necessitated efficient use of resources and careful planning of experiments.
* **Error Rates:** Managing and mitigating errors inherent in quantum computations due to decoherence and other quantum noise presented significant challenges.

Through this experiment, we gained valuable insights into the practical aspects of quantum computing, including circuit design, execution, and result interpretation. The experience highlighted both the immense potential of quantum computing and the current limitations that researchers and practitioners must navigate.







