Bits to Qubits: An Overview of Quantum Computing

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Abstract—The advent of computers has significantly diminished the need for manual computation. As technology has evolved, it has led to the creation of classical computers with high performance, throughput, and memory capacity. Classical computers store data in binary format, using bits that can either be 0 or 1, typically represented by low and high voltage levels, respectively. While effective, this method sometimes demands considerable resources for certain computations. In contrast, quantum computers represent the cutting edge of computing technology. They utilize quantum bits or qubits, which exploit quantum mechanical phenomena like superposition and entanglement, allowing for more efficient problem-solving. This paper presents a simplified overview of the core concepts of quantum computing.

Keywords— Quantum, qubits, gates, superposition.

I. INTRODUCTION

Richard Feynman first introduced the concept of quantum computers in 1982, aiming to simulate complex physical systems [1]. Despite the rapid advancements in classical computers, which allow theoretical physicists to numerically analyze and compute fundamental properties of various states of matter [2], calculating real physical systems with a vast number of electrons remains a formidable challenge even for the most advanced classical computers. Classical computers process data using binary logic and store information as bits. While most efficient computers today rely on this binary logic to solve problems, some issues require immense computational time to resolve using classical methods. These challenges can be addressed through quantum computing, which leverages the principles of quantum physics and utilizes qubits as its fundamental units. Quantum computers are estimated to solve problems significantly faster than their classical computers [3]

Quantum computing involves the study of advancing computer technology, using principles of quantum theory and its quantum phenomena. Quantum phenomena, such as entanglement and quantum superposition, play a crucial role in processing data through computing. Quantum computers work on qubits or further superposition of qubits [4].

II. QUBIT AND SUPERPOSITION

In classical computing, information is encoded in bits, which can be either 0 (off/false) or 1 (on/true) at any moment, based on Boolean algebra principles. Quantum computing, on the other hand, utilizes quantum bits, or qubits. Unlike classical bits, a qubit can represent 0 and 1, or a quantum superposition of both states, expressed in ket notation as $|0>$ and $|1>$. A single qubit can thus exist in two potential states (0 or 1). When dealing with two qubits, there are four possible combinations: 00, 01, 10, and 11. For three qubits, the number of possible combinations rises to eight: 000, 001, 010, 011, 100, 101, 110, and 111 [4].

A single qubit can be represented as a unit vector within a two-dimensional complex vector space, commonly visualized using the Bloch sphere model. The state of a qubit is described by a linear combination of the basis states, denoted as $|0\rangle$ and $|1\rangle$. Which are the computational basis states. A qubit's state, denoted $|\psi\rangle$, can be written as [8]:

$$|\psi\rangle=\alpha|0\rangle+\beta|1\rangle \qquad \text{(i)}$$

Here, α and β are complex numbers, with the condition that $|\alpha|^2 + |\beta|^2 = 1$ to maintain normalization [5].

The state of two qubits can be represented as a complex vector in a four-dimensional complex vector space. For 2 qubits it is necessary to do the tensor product of each state of a single qubit to convert it into the 2 qubit state in vector space. The tensor product is nothing but the outer product matrix, in qubit it is the tensor product of each state which can be calculated as shown:

$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} \otimes \begin{pmatrix}\Upsilon\\ \delta\end{pmatrix} = \begin{pmatrix}\alpha\begin{pmatrix}\Upsilon\\ \delta\end{pmatrix}\\ \beta\begin{pmatrix}\Upsilon\\ \delta\end{pmatrix}\end{pmatrix} = \begin{pmatrix}\alpha\Upsilon\\ \alpha\delta\\ \beta\Upsilon\\ \beta\delta\end{pmatrix}$$

Fig. 1. General representation of tensor product for 2 qubits [8].

Two qubits converted it into the vector, as given below. We write vector as column matrix i.e. called as state vectors. This states that, if 'n' bits are given then the vector size is 2n. For 2 qubits four vector states are calculated as given:

Representation in vector space form State of 2 qubits

$$|0> = |00> = |0> \otimes |0> = \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}1\\0\\0\\0\end{pmatrix}$$

$$|1> = |01> = |0> \otimes |1> = \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\1\\0\\0\end{pmatrix}$$

$$|2> = |10> = |1> \otimes |0> = \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}0\\0\\1\\0\end{pmatrix}$$

$$|3> = |11> = |1> \otimes |1> = \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

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Fig. 2. Qubit in the form of a vector [7].

A general state of two qubits, with α0 and α1 are complex numbers for ∣ ψ 1⟩ state. β0 and β1 are complex numbers for ∣ ψ 2⟩ state. This can be represented as:

$$\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \qquad \text{from equation (i)}$$

$$|\psi\rangle = (\alpha_0\,|0\rangle + \alpha_1\,|1\rangle) \otimes (\beta_0|0\rangle + \beta_1|1\rangle)$$

$$|\psi\rangle = \alpha_0\beta_0\,|00\rangle + \alpha_0\beta_1\,|01\rangle + \alpha_1\beta_0\,|10\rangle + \alpha_1\beta_1|11\rangle$$

Where, α0β0, α0β1, α1β0 and α1β1 are complex numbers. Which represents the probability amplitudes of each possible combination of the states of the two qubits [5].

Qubits can represent multiple states simultaneously as shown, allowing quantum computers to perform calculations in parallel. In quantum computation final result is the qubit collapsing into either 0 or 1. However in supersession the qubit is simultaneously in 0 and 1 state. Upon measurement the qubit collapses one of this state according to some probability as shown in fig3. Suppose in polarization through glass, photon polarize horizontal as 0 qubits and vertical as 1 qubits and superposition is like photon at horizontal and vertical also, when we measure it we will get the actual value. Here, qubit collapses to 0 is of probability ||α2 || and 1 probability is ||β2 || [5] [12].

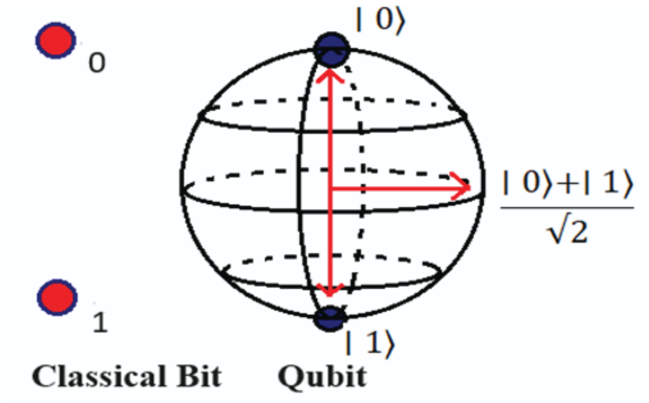

Fig. 3. Classical and qubit.

III. Gates

Quantum gates serve as the fundamental components of quantum circuits, similar to how classical logic gates function in classical computing. The representation of quantum gates involves their mathematical characterization. In classical computing, logic gates like AND, OR, and NOT manipulate binary bits. Quantum gates, on the other hand, operate on qubits to manage quantum information. They are essential for executing quantum algorithms and conducting quantum computations. Each quantum gate is depicted by a unitary matrix, which illustrates how the gate alters the quantum state of the qubits. This matrix must meet specific criteria, including reversibility and the preservation of quantum state normalization. Quantum gates enable a range of operations on qubits, such as:

A. *Pauli Gates:* These gates, including X, Y, and Z, perform rotations around the X, Y, and Z axes of the Bloch sphere, respectively. The X gate acts similarly to a NOT gate, flipping the state's such that $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ transforms into $|\psi\rangle = \alpha|1\rangle + \beta|0\rangle$ It rotates the qubit's state around the X-axis of the Bloch sphere as shown in Fig4.

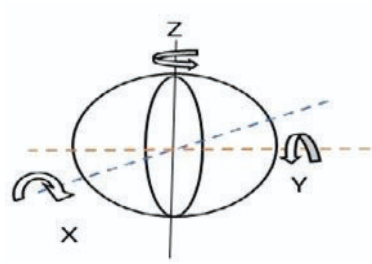

Fig. 4. Pauli gate rotation along axis.

B. *Hadamard Gate:* This gate facilitates the creation of superposition by converting a basis state into a superposition state and vice versa.

C. *Controlled Gates:* These gates operate on two or more qubits where the action depends on the state of one or more control qubits. Examples include the Controlled NOT (CNOT) gate. In CNOT gate one is controlled bit and another is target bit. If control bit is 1 then it flips the target bit as given below:

D. *Phase Gates:* These gates introduce a phase shift to the quantum state. Examples are the S gate and the T gate, which modify the phase of the qubit's state.

E. *Swap Gate*: This gate exchanges the states of two qubits.

TABLE I. CNOT OPRATION

Control_bit	**Target_bit**		**Control_bit**	**Target_bit**
0	0	⟶	0	0
0	1	⟶	0	1
1	0	⟶	1	1
1	1	⟶	1	0

I. Entanglement

The most n-qubit states cannot be described as a combination of n single-qubit states, even though they can be expressed as a mix of the basic states of the n-qubit system. Those specific states that cannot be decomposed into a tensor product of n single-qubit states are referred to as entangled states. Entanglement can be understood as a unique type of superposition involving multiple qubits. In superposition, a qubit exists in a combination of basis states (|0⟩ and |1⟩ for a single qubit). Entanglement extends this idea to multiple qubits, creating states that can't be separated into individual qubit states. Consider a composite quantum system described by a vector space V. This space can be decomposed into the tensor product of smaller vector spaces, each representing a single qubit: V=V0⊗V1⊗⋯⊗Vn−1. A state ∣ ψ ⟩ in this composite system is separable (or unentangled) with respect to this decomposition if it can be written as: ∣ ψ ⟩= ∣ v0⟩⊗ ∣ v1⟩⊗⋯⊗ ∣ vn−1⟩ where ∣ vi⟩ belongs to the vector space Vi. This means that the state of the entire system is just a simple combination of the states of individual qubits. If the state ∣ ψ ⟩ cannot be written in this separable form, it is considered entangled with respect to the given decomposition [10]. Let's take the Bell states as an example, which are also known as EPR pairs, named after an article authored by Einstein, Podolsky, and Rosen in 1935[11].

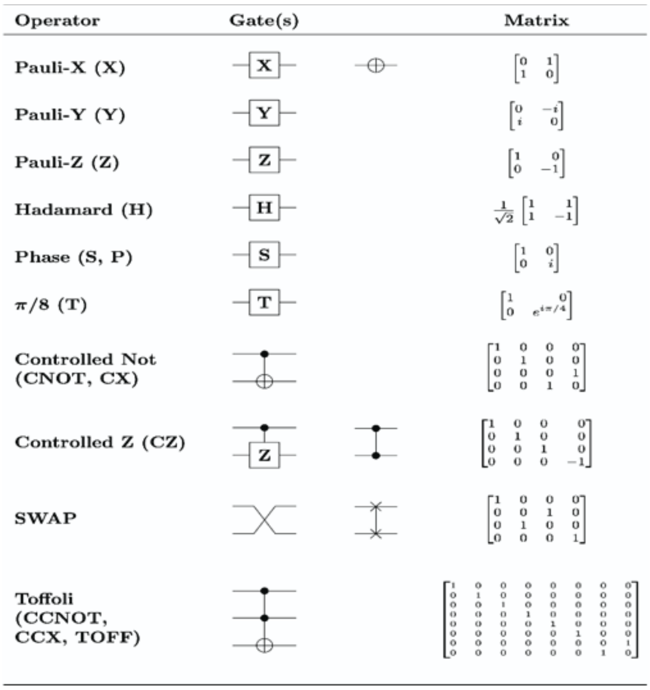

Fig. 5. Gates representation [9].

$$|\phi+\rangle = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle) \quad (1)$$

$$|\phi -\rangle = \frac{1}{\sqrt{2}}(|00\rangle-|11\rangle) \quad (2)$$

$$|\psi +\rangle = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle) \quad (3)$$

$$|\psi -\rangle = \frac{1}{\sqrt{2}}(|00\rangle-|11\rangle) \quad (4)$$

These represent four maximally entangled 2-qubit states. The Bell states cannot be decomposed, as it is impossible to find coefficients a0, a1, b0, b1 such that [10]:

$$(a_0|0\rangle+b_0|1\rangle) \otimes (a_1|0\rangle+b_1|1\rangle) = |\phi\rangle \quad (5)$$

$$(a_0|0\rangle+b_0|1\rangle) \otimes (a_1|0\rangle+b_1|1\rangle) = |\psi\rangle \quad (6)$$

To better understand the entanglement concept, let us consider for example Bell state $|\psi+\rangle$ in this state both electrons either at excited state and in ground state. If we express states in superposition basis it can be written as:

$$\frac{1}{\sqrt{2}}(|{+}{+}\rangle + |{-}{-}\rangle)$$

Can be evaluated as:

$$|\psi +\rangle = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$$

$$= \frac{1}{\sqrt{2}}\left[\left(\frac{1}{\sqrt{2}}\middle|+\right\rangle + \frac{1}{\sqrt{2}}|-\rangle) \otimes (\frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle)\right]_{1^{st} \text{ and } 2^{nd} \text{ qubit at ground state}} +$$

$$\frac{1}{\sqrt{2}}\left[\left(\frac{1}{\sqrt{2}}\middle|+\right\rangle - \frac{1}{\sqrt{2}}|-\rangle) \otimes (\frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle)\right]_{1^{st} \text{ and } 2^{nd} \text{ qubit at excited state}}$$

$$= \frac{1}{\sqrt{2}}\left[\left(\frac{1}{2}\middle|++\right\rangle + \frac{1}{2}|\pm\rangle + \frac{1}{2}|\mp\rangle + \frac{1}{2}|++\rangle)\right] + \frac{1}{\sqrt{2}}\left[\frac{1}{2}|++\rangle - \frac{1}{2}|\pm\rangle - \frac{1}{2}|\mp\rangle + \frac{1}{2}|--\rangle)\right]$$

$$= \frac{1}{\sqrt{2}}\left[\left(\frac{1}{2}\middle|++\right\rangle + \frac{1}{2}|++\rangle + \frac{1}{2}|--\rangle + \frac{1}{2}|--\rangle)\right]$$

$$= \frac{1}{\sqrt{2}}[(|++\rangle + |--\rangle)]$$

$$= \left[\frac{1}{\sqrt{2}}|++\rangle + \frac{1}{\sqrt{2}}|--\rangle\right].$$

This shows that an entangled state in a particular basis stays entangled even if we change it to a different basis. This state of 2 qubits are entangled with each other so it is not possible to separate each state of single qubit and state of one qubit changes the state of second qubit.

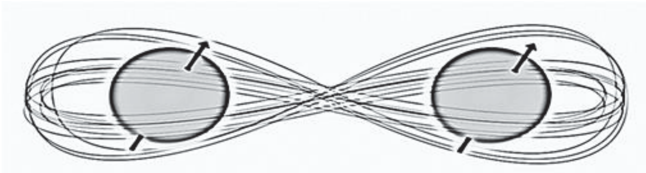

Fig. 6. Illustration of quantum entanglement, where the spin of one particle can affect the spin of another particle [11].

Quantum entanglement led Einstein and his colleagues to the EPR paradox: measuring one qubit instantly changes the state of the second qubit, no matter how far apart they are. This seems to suggest that information is being sent faster than light, which would break the rules of Relativity. However, this paradox is not real because entanglement doesn't actually allow information to be transmitted faster than light [10].

II. TELEPORTATION

The main idea is to teleport the characteristics of an unknown quantum state $|\psi\rangle$ from Alice's lab to Bob's lab without sending the state itself. For a pure qubit, the state can be written as $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$, where α and β are complex numbers satisfying $|\alpha|2+|\beta|2=1$. If the sender, Alice, knows the quantum state $|\psi\rangle$, meaning she knows the values of α and β, she can simply send these values to Bob. Bob can then use this information to prepare the state $|\psi\rangle$ on his end by transforming a default state using his local operations. However, practical challenges arise, such as creating universal gates, determining the necessary quantum circuit depth, and ensuring the fidelity of the reconstructed state. Despite these challenges, from a communications engineering perspective, this task can, in principle, be accomplished with classical communication resources [9], [10].

In the more general case, where Alice does not know the quantum state $|\psi\rangle$, this task cannot be done using only classical communication. Quantum measurement would alter the original state, and the no-cloning theorem prevents Alice from making multiple copies of $|\psi\rangle$ to measure α and β. In other words, quantum mechanics doesn't allow a qubit to be copied or measured without altering it. So, while a photon can carry a qubit and be transmitted directly to a remote location, if the photon is lost or corrupted, the original quantum information is destroyed. This makes direct transmission of qubits via photons impractical.

Fortunately, Quantum Teleportation provides a valuable method for transmitting qubits without physically moving the particle or breaking quantum mechanical rules. As shown in Fig. 6, using local operations and an EPR pair shared between the sender and receiver, quantum teleportation enables the "transmission" of an unknown quantum state. This process involves the destruction of both the original qubit and the EPR pair member at the source due to measurement, but it successfully transfers the quantum information to the destination. The original qubit is recreated at the destination once the measurement results from the source (which are 2 classical bits) are received via a classical link. This link has a finite delay and follows the speed of light, such as in an optical fiber [10].

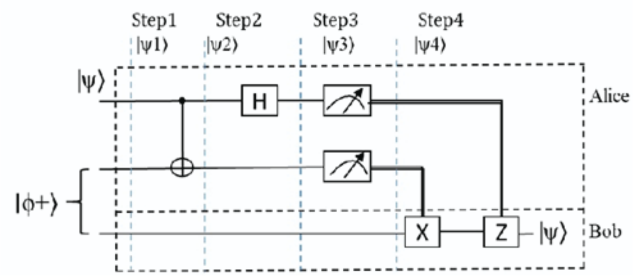

Fig. 7. Quantum Teleportation Circuit [10].

A. *Alice's and Bob's Experiment:*

Overall, the teleportation process in Fig 7 starts with the state $|\psi\rangle$ to be teleported and an EPR pair shared between Alice and Bob. Any of the four Bell states $|\phi\rangle$ or $|\psi\rangle$ can be used for quantum teleportation from equation 1. As long as Alice and Bob agree on the state before using a classical link with some delay. For simplicity, let's assume Alice and Bob share the state $|\phi+\rangle = 1/\sqrt{2}\,(|00\rangle + |11\rangle)$, as shown in Fig 7. The initial combined state $|\psi 1\rangle$ is: $|\psi 1\rangle = |\psi\rangle \otimes |\phi+\rangle$ which simplifies to:

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\,(\alpha|0\rangle \otimes (|00\rangle + |11\rangle) + \beta|1\rangle \otimes (|00\rangle + |11\rangle)).$$

Following the convention that the first two qubits belong to Alice and the third qubit belongs to Bob, this becomes:

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\,(\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle)$$

1) In step 1: ***Applying the CNOT Gate Alice applies a CNOT gate to her pair of qubits. The CNOT gate flips the second qubit if the first qubit is*** $|1\rangle$***. This changes the state to:***

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\,(\alpha|000\rangle + \alpha|011\rangle + \beta\,|110\rangle + \beta\,|101\rangle)$$

2) In step 2: Applying the H Gate Next, Alice applies a Hadamard (H) gate to her first qubit. The H gate creates a superposition, mapping $|0\rangle$ to $(|0\rangle + |1\rangle)/(\sqrt{2})$ and $|1\rangle$ to $(|0\rangle - |1\rangle)/(\sqrt{2})$. Applying Hadamard gate to the first (left most bit) qubit in our state gives:

$$|\psi_3\rangle = \frac{1}{\sqrt{2}}\left(\left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)\alpha|00\rangle + \left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)\alpha|11\rangle + \left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right)\beta\,|10\rangle + \left(\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right)\beta\,|01\rangle\right)$$

$$|\psi_3\rangle = \frac{1}{2}\,(\alpha|000\rangle + \alpha\,|100\rangle + \alpha\,(|011\rangle + \alpha\,|111\rangle + \beta\,(|010\rangle - \beta\,|110\rangle + \beta\,|001\rangle - \beta\,|101\rangle)$$

Taking Alice's two leftmost bit common in α and β form so final state after applying the is:

$$|\psi_3\rangle = \frac{1}{2}\,(|00\rangle \otimes (\alpha|0\rangle + \beta|1\rangle) + |01\rangle \otimes (\alpha|1\rangle + \beta|0\rangle) + |10\rangle \otimes (\alpha|0\rangle - \beta|1\rangle) + |11\rangle \otimes (\alpha|1\rangle - \beta|0\rangle)\,) \qquad (7)$$

In step 3, Alice measures the pair of qubits on her side, as shown in Fig. 7. Regardless of the specific values of α and β, Alice has a 25% chance of observing each of the four possible outcomes: $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$. This measurement immediately determines the state of Bob's qubit, no matter how far apart Alice and Bob are, which is because of entanglement between the qubits. However, Bob can only restore the original qubit $|\psi\rangle$ after receiving the two classical bits that tell him the results of Alice's measurement. This classical information must be transmitted at or below the speed of light [10].

In step 4. There are four possible outcomes based on the state of Alice's two qubits as shown in the equation 7. If Alice's qubits are in the state $|00\rangle$, Bob's qubit will be in the state $\alpha\,|0\rangle + \beta\,|1\rangle$, which is the same as the original quantum state $|\psi\rangle$. Therefore, if Alice measures her qubits and gets $|00\rangle$, she can tell Bob this result, and Bob can recover the original quantum state $|\psi\rangle$ from his qubit without needing any further quantum operations. At this point, we say the original quantum state $|\psi\rangle$ has been teleported to Bob [10].

Alternatively, if Alice's qubits are in the state $|10\rangle$, Bob's qubit will be in the state $\alpha\,|0\rangle - \beta\,|1\rangle$. When Alice measures her qubits and gets $|10\rangle$, she tells Bob this result through a classical link as given in equation 7. Bob can then recover the original quantum state $|\psi\rangle$ by applying the Z gate to his qubit, which changes $|1\rangle$ to $-|1\rangle$ and leaves $|0\rangle$ unchanged. This process is shown in Fig. 7. At this step, we say the original quantum state $|\psi\rangle$ has been teleported to Bob. Similarly, if Alice's measurement results are $|01\rangle$ or $|11\rangle$, Bob can recover the original state $|\psi\rangle$ by applying the X gate (which swaps $|0\rangle$ and $|1\rangle$) or the X gate followed by the Z gate to his qubit [10].

III. Programing In Quantum Computing

Quantum computing is revolutionizing the field of computation by leveraging the principles of quantum mechanics. Unlike classical computing, which relies on bits as the smallest unit of data, quantum computing uses qubits, which can exist in multiple states simultaneously thanks to superposition. This unique property, along with entanglement, allows quantum computers to process complex calculations more efficiently. To start programming in quantum computing, you need to set up a suitable development environment as given:

First, install Anaconda Navigator, which is a user-friendly interface for managing packages and environments for scientific computing with Python. Once Anaconda Navigator is installed, create a new Python environment to ensure that your projects have all the necessary dependencies without conflicting with other projects. Open Anaconda Prompt, give command with your environment name

```
conda create -n <name_env>
```

With your new environment active, you need to install the necessary quantum computing libraries. Open a terminal or Anaconda prompt and activate your environment using the command:

```
conda activate <name_env>
```

Then, install the required packages using the following command:

```
pip install qiskit==1.1.10 qiskit-aer==0.14.2 cython==0.29.21 jupyter
```

To execute your quantum programs on IBM's quantum computers, you need to install the qiskit_ibm_runtime package and set up your IBM Quantum Experience account. Install the IBM runtime package using the command:

```
pip install qiskit-ibm-runtime==0.25.0
```

Next, to use IBM's quantum simulators and hardware, you need an API token from IBM Quantum Experience. Sign up or log in to the IBM Quantum Experience, go to your account settings, and generate a new API token. Copy the token and save it securely. Configure Qiskit to use your IBM token. With your environment set up, open jupyter notebook to write code in the same environment by:

```
jupyter notebook
```

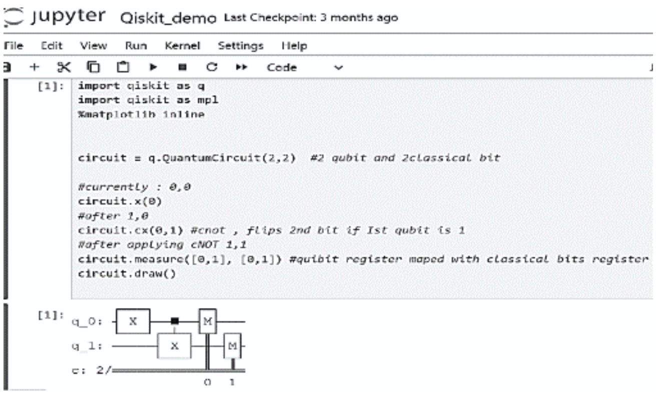

Fig. 8. Circuit designed using qiskit.

Fig 8 presents a basic example of constructing a simple quantum circuit. This circuit utilizes two qubits and two classical bits, created with QuantumCircuit(2, 2). An X gate is applied to the first qubit (circuit.x(0)), altering its state from $|0\rangle$ to $|1\rangle$. Subsequently, a CNOT gate (circuit.cx (0, 1)) is used to flip the second qubit if the first qubit is in the $|1\rangle$ state, resulting in both qubits being set to $|1\rangle$.

The final step involves measuring the qubits and mapping their states to the classical bits (circuit.measure([0, 1], [0, 1])). The circuit can be visualized with circuit.draw(), which displays a clear sequence of the quantum operations and measurements. This example demonstrates the essential procedures for designing quantum circuits using Qiskit and provides a foundation for developing more intricate quantum algorithms.

IV. Conclusion

This paper offers an in-depth exploration of quantum computing, tracing its development from Richard Feynman's groundbreaking proposal in 1982 to the latest advancements and applications. It examines the core principles of quantum mechanics that form the basis of quantum computing, including superposition and entanglement, and demonstrates how these principles allow quantum computers to surpass classical computers in certain problem areas. The paper also addresses the mathematical representation of qubits and quantum gates, and explains the crucial concept of entanglement, illustrating how these components integrate to create quantum circuits. Additionally, it covers the practical aspects of quantum programming, detailing the tools and procedures required to design quantum algorithms using Qiskit and IBM's quantum simulators. Overall, this paper highlights the transformative impact of quantum computing and provides a thorough understanding of both its theoretical foundations and practical implementations.

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