Module 4: Elements of Quantum Computing

(Physics for Computer Engineering Stream – 22PHYS12/22)

1. Introduction to quantum computers

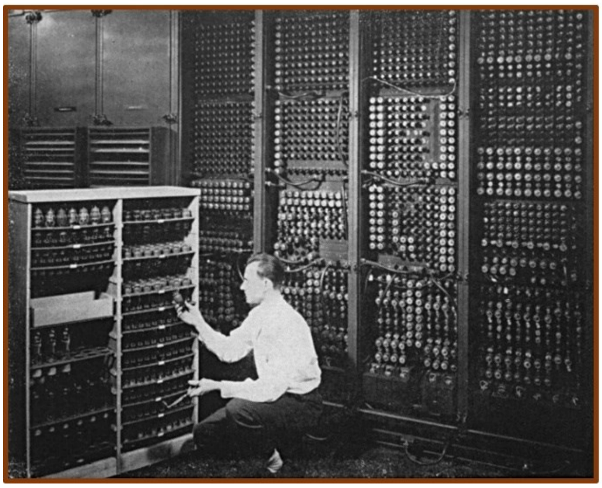
Background: The computer today is made by introducing several tiny transistors embedded on silicon chips. We call these computers 'classical computers' throughout the discussion. Examples of classical computers are Desktop computer, laptop, Tab, mobile, smart watch, etc. Tiny transistors act as switches depicting the states 0 and 1. These discrete states are called bits which are readable by the classical computer. Physically, state '1' on a bit depicts a developed/high voltage *(a 'bit' refers here as an abstract physical segment on which 0 or 1 is assigned)* in a capacitor in combination with transistors on a chip (Ex - RAM - random access memory). A detailed discussion on physical processes about the memory and processing units in a classical computer was given in module 1. On the other hand, state '0' represents declined/low voltage in a capacitor in combination with transistors on a chip. All types of calculations are made easy for computers by converting information (numbers, characters etc.) into binary digit system. All arithmetic operations are carried out by the computers only when the numbers are represented in binary digits as 0 and 1. The simple addition operation on 3 and 4 is 7. However, this is an impossible task for a computer unless they are fed in the form of binary digits. Therefore, our job is to convert it into the required binary form and feed it. The binary forms of 3 and 4 are 11 and 100 respectively. The addition of them made by the computer is 111. The "111" binary digit is again reformed to decimal as "7" which is readable by a human. Increasing a greater number of such bits on a processor chip speeds up the computation.

As technology developed over the decades the transistors fabricated on an integrated chip within a certain area are being doubled, and price is halved every two years. This law was the extrapolation of the observation made on the development of chip technology predicted by Gordon Moore (one of the co-founders of Intel Company). This is popularly known as **Moor's Law**. Today, there can be 1.2 trillion transistors printed over 21 x 21 square cm. Such a big number enhanced the speed of a processor by a significant magnitude which in turn squeezed the individual transistor to nano dimension. This has made a single transistor to attain such a smaller size where roughly 100 electrons are participating in switching action. Such miniaturization of the size of an individual transistor makes switching of state 1 to 0 and vice-versa more difficult. This is because the quantum mechanical effects will start playing a major role by not allowing electrons and atoms to behave as they were expected to be before the size of a transistor was made smaller. This is a result of trapping electrons and atoms within a small, confined nano area. Because of the quantum principles like quantum superposition, energy discreteness, quantum tunneling, quantum interference etc., it is impossible for a transistor to create a resistive path permanently when the state of a bit must be written as 0 or conductive path for the state 1. As a result, resistive path may conduct electricity inevitably through quantum tunneling effect. Such restriction has significantly hindered the further development of microprocessor fabrication technology and showed the red flag. Physicists across the globe experienced the limitation of lowering the size of a transistor by such quantum mechanical effects. However, this limitation turned the whole picture upside down and became a milestone for the inception of an entirely new computational method which is called "Quantum Computation". They decided to exploit the same limitation as foundation to open an entirely new area of computation which is even greater than the earlier "Classical Computation."

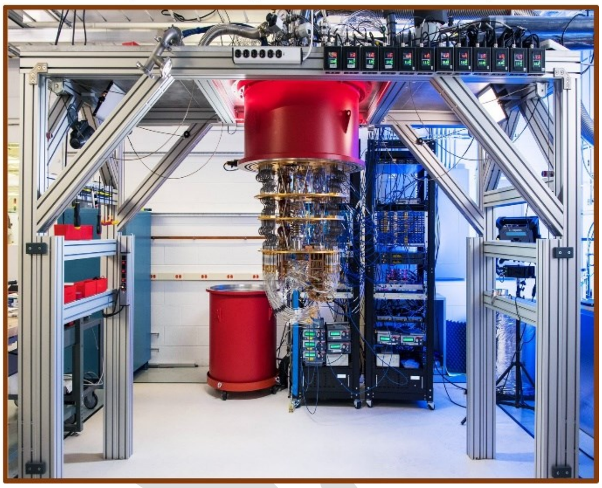
Quantum computers are not the replacement of classical computers with which we are working today, they are not even the upgradation of the super computers which are being used to solve critical problems, but they are fundamentally different in their basic principles of operations. They work on the principles of quantum physics such as wave-particle duality, quantum superposition, quantum entanglement, quantum Interference, quantum tunneling, Heisenberg's uncertainty principle, etc. These principles enable the quantum computer to drastically boost computational power among all other computers ever built.

A typical quantum computer would resemble the classical computer in its earlier development time (middle of 19th century). The complexity and size of quantum computers' hardware are enormous.

Development stage of Classical Computer



Development stage of Quantum Computer



Quantum computer is a device which manipulates qubits for computation. Quantum computation is the process of manipulating qubits in a quantum computer. Qubits are quantum binary digits who would work under the principles of quantum mechanics like quantum superposition, quantum entanglement, quantum interference, etc.

2. Differences between classical and quantum computers

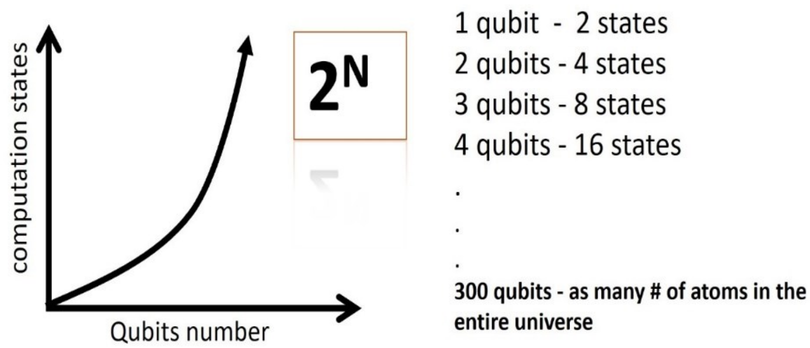
Classical computers	Vs Quantum computers
Transistors and capacitors are the building blocks	Quantum particles/system
Fast but many steps - so ultimately slower	Slow but single step - so ultimately faster
Parallel computing : **NO** (Multiprocessors are required for the same)	Parallel computing : **YES** (Single processor is enough for parallel computation)
Reversible computation is not possible	Reversible computation is possible
Entropy increases as a result of erasing of inputs Landauer's law :The entropy of the system increases by kT $ln\,2$ times	Entropy remines the same for an isolated System. No erasing of inputs.
Doubling growth of power when a bit is added using **2N** N – number bits	Exponential growth of power when a qubit is added using $\mathbf{2^N}$ N – number Qubits

2.1 Exponential growth of Power of computation in a quantum computer (for AI &ML)

Consider a qubit with $|0\rangle$ and $|1\rangle$ as its computational states. For qubits these two states are available for computation at the same time. If there are two such qubits are there, then there would be 4 states available at the same time. The vital aspect is the growth of the number of states available for computation after the addition of every single qubit. Because, after adding a qubit, the total number of states doubles. This would follow the exponential trend as shown in the above figure. Because, if there are N qubits, then there would be 2^N states available at the same time.

$$|W\rangle = \alpha_1|w_1\rangle + \alpha_2|w_2\rangle + \alpha_3|w_3\rangle + \ldots + \alpha_N|w_N\rangle$$

Here, $\alpha_1, \alpha_2, \alpha_3 --- \alpha_N$ are the coefficients of the computational basis states $|w_1\rangle, |w_2\rangle$, ----, $|w_n\rangle$ respectively.



If there are 300 qubits in a quantum computer, then the number of available computational basis states can represent the total number of atoms in the entire universe. Such exponential power of growth of number of computation states is unique for quantum computer in making it more powerful than classical computers. **Note:** Even though the same trend is observed in the classical computers case, not all the states are available for computation at the same time.

Artificial intelligence and deep learning: Exponential growth in the power of quantum computers has the potential to bring several advantages to the fields of Artificial Intelligence (AI) and deep learning.

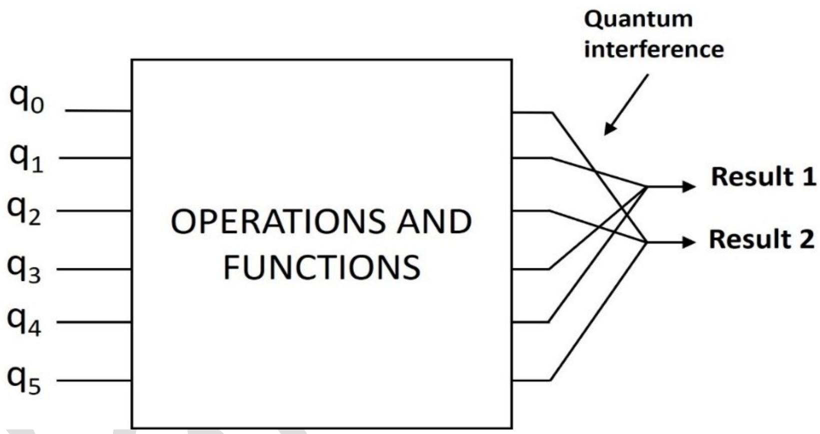
1. **Speeding Up Computations:** Quantum computers have the ability to solve certain types of problems much faster than classical computers due to their unique properties, such as superposition and entanglement. This speedup could significantly accelerate complex calculations involved in training deep learning models, which often require a large number of iterations.
2. **Optimization Problems:** Many AI tasks involve optimization, such as finding the optimal parameters for a neural network. Quantum computers could potentially provide more efficient solutions to these optimization problems, leading to faster and more accurate model training.
3. **Parallelism:** Quantum computers can perform multiple calculations simultaneously through superposition, enabling parallelism that could be advantageous for tasks like matrix operations and certain types of data processing commonly encountered in AI and deep learning.
4. **Handling Large Datasets:** Quantum computers might be able to process and analyze large datasets more efficiently than classical computers, which could be beneficial for training and inference tasks in AI.
5. **New Algorithms:** Quantum computing could lead to the development of new algorithms specifically designed for quantum hardware. These algorithms might uncover novel ways to approach AI and deep learning problems, potentially yielding better solutions or insights.

6. **Solving Complex Equations:** Quantum computers have the potential to solve complex differential equations and linear algebra problems, which are foundational in many AI and deep learning applications. This capability could enhance the development of advanced models and techniques.

7. **Simulation and Quantum Machine Learning:** Quantum computers might be used to simulate quantum systems more accurately, which could have applications in fields like materials science and drug discovery. This, in turn, could impact AI and deep learning research by providing more accurate data for training and validation.

2.2 Parallel computation in a quantum computer

Quantum computers would work under the principle of quantum mechanical rules such as quantum superposition, quantum entanglement, quantum interference, etc. Because of such powerful rules, quantum computers can perform parallel computation. Particularly the quantum interference would vanish few of the unwanted states and arrive at multiple results obtained from multiple processing at the same time using a single quantum processor as can be seen in the below figure. Such parallel computation is impossible in classical computers to perform using a single processor. Therefore, parallel computation feature of quantum computer has made it more powerful than any other classical computers. Because the process of quantum computers would play multi processors role during computation.



Artificial intelligence and deep learning: The parallel nature of quantum computers offers several potential advantages for solving problems in the fields of Artificial Intelligence (AI) and deep learning. While practical implementations are still in the early stages, the parallelism inherent in quantum computing could bring significant benefits to these domains:

1. **Speedup in Model Training:** Quantum computers can perform multiple computations simultaneously through superposition, allowing them to explore different solutions in parallel. This property could significantly speed up the training of complex deep learning models, which often involves iterative optimization processes.
2. **Enhanced Optimization:** Many AI and deep learning tasks involve optimization problems, such as finding the optimal parameters for a neural network. Quantum computers can explore multiple potential solutions simultaneously, potentially leading to more efficient and effective optimization processes.
3. **Large-scale Data Processing:** Quantum computers can process and manipulate large amounts of data in parallel, which is advantageous for tasks like data preprocessing, feature extraction, and other data-centric operations common in AI and deep learning.

4. **Matrix Operations:** Quantum computers are naturally suited for performing linear algebra operations, which are fundamental to many AI and deep learning algorithms. The ability to handle matrix operations in parallel could lead to faster and more efficient computations.
5. **Reduced Training Time:** Quantum computers could accelerate the training time of AI models by simultaneously exploring different parts of the parameter space. This could lead to quicker convergence and faster model deployment.
6. **Dimensionality Reduction:** Quantum computers might enable more efficient dimensionality reduction techniques, helping to streamline data representation and processing in complex AI systems.
7. **Exploration of Hyperparameters:** Hyperparameter tuning is a critical aspect of deep learning model optimization. Quantum computers could potentially explore different combinations of hyperparameters in parallel, leading to faster identification of optimal configurations.
8. **Solving Complex Equations:** Quantum computers excel at solving complex equations, which are often encountered in AI and deep learning. This capability could be particularly useful for advanced modeling and simulations.
9. **Quantum Machine Learning:** Quantum computers can be used to develop novel quantum machine learning algorithms that leverage their parallelism for improved performance on certain tasks.

2.3. Reversible computation in a quantum computer

In quantum computers, every input will have a corresponding output. Therefore, no single input is erased. The truth table of a linear algebra of quantum computation would have N number of outputs column for N number of inputs columns as can be seen in the below figure.

Truth table of a quantum logic gates							
Input 1	Input 2	Input 3	Input 4	Output 1	Output 2	Output 3	Output 4
q0	q1	q2	q3	Y1	Y2	Y3	Y4

Therefore, all the inputs can be recovered by tracking the outputs by performing reverse operation. This is how computation is made reversible.

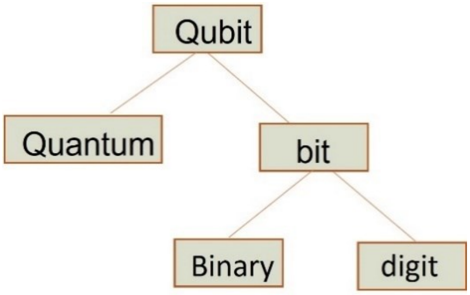
Since no inputs are erased in a computation process in a quantum computer its entropy will remain the same. In the case of classical computers, thousands of inputs will be erased in computational processes which would increase the entropy.

Artificial intelligence and deep learning: The reversible nature of quantum computers offers several potential advantages for applications in Artificial Intelligence (AI) and deep learning. Reversibility refers to the ability of quantum operations to be easily undone, allowing for precise control over computation steps. While the practical implementation of these advantages is still a subject of ongoing research, the reversible nature of quantum computing could bring significant benefits to these fields:

1. **Energy Efficiency:** Reversible computation is inherently more energy-efficient compared to irreversible computation. In AI and deep learning, where large-scale computations are common, quantum computers' reversible operations could help reduce energy consumption and computational costs.
2. **Algorithm Optimization:** Quantum computers' reversibility could lead to more efficient and optimized algorithms for AI and deep learning tasks. By leveraging the ability to backtrack and undo operations, researchers could develop algorithms with improved convergence and fewer redundant calculations.
3. **Error Correction:** Reversible operations are crucial for error correction techniques in quantum computing. Applying these techniques effectively could lead to enhanced stability and accuracy in quantum computations, which is particularly important for complex AI and deep learning tasks.
4. **Quantum Circuits and Gates:** Quantum gates, the fundamental building blocks of quantum circuits, are inherently reversible. This property can lead to the development of more compact and efficient quantum circuits for performing operations required by AI and deep learning algorithms.
5. **Training and Inference:** Reversible quantum operations could have applications in the training and inference phases of deep learning. They might lead to more efficient and accurate optimization methods and data processing steps.
6. **Quantum Data Representation:** The reversible nature of quantum computing can influence how data is represented and manipulated in quantum machine learning algorithms. This could potentially lead to more compact and information-rich data representations.
7. **Memory Management:** Reversible computing could impact memory management and storage techniques, enabling more efficient use of resources in AI and deep learning applications.
8. **Simulation and Analysis:** Quantum computers' ability to reverse operations could be valuable for simulations and analysis of complex systems, such as simulating molecular interactions for drug discovery or analyzing large-scale neural networks.
9. **Hybrid Quantum-Classical Approaches:** Reversible quantum operations can be integrated with classical computing methods, enabling the development of hybrid algorithms that take advantage of both reversible quantum steps and classical processing for AI and deep learning tasks.

3. Qubits

Qubit is the acronym for quantum binary digits. This is the building block of quantum computers who will be manipulated for computation. These qubits are made from quantum particles like electrons, protons, molecules, quantum trapped systems etc.



Popular types of qubits

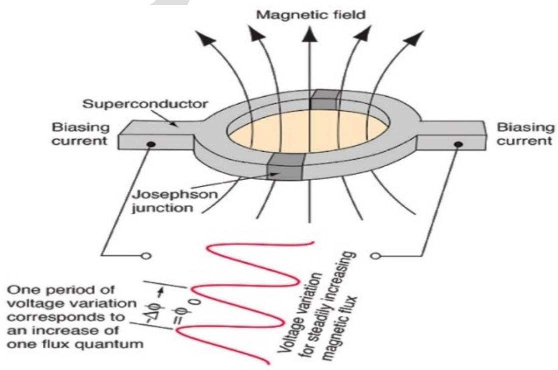
SQUID qubits
Photon qubits (Optical cavity or Microwave cavity)
NMR Qubits
Ion trap (Nuclear or Electron or Spin) qubits

Examples of types of qubits

Spin based qubits; atomic nuclei, spin of electrons, spin trapped ions. charge based qubits electron charge in materials like Au, GaAs, quantum dots, etc. Cavity based qubits optical cavity qubits, Microwave cavity qubits.

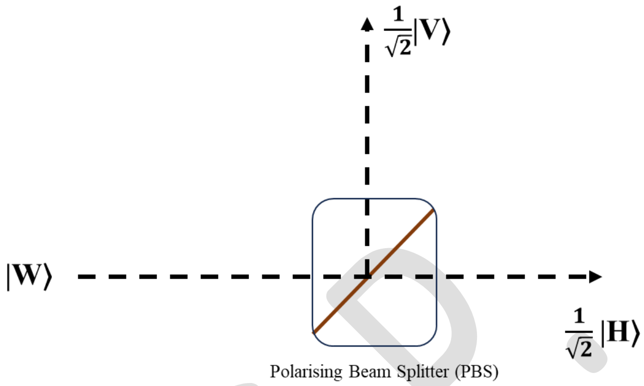
3.1 SQUID based qubits.

SQUID refers to Superconducting quantum interferometer device. This device is sensitive to tiny amount of magnetic field. With such sensitivity people have used it to process quantum data. This consists of a ring with two Josephson junctions. Each Josephson jenction is made by introducing a thin insulating material in between two superconducting segments as shown in the figure which acts as an imposible barrier for Cooper pair to be hopping across. Cooper pairs can tunnel through it from one superconductor to the other one if a suitable magnetic field is applied to the ring perpendicular to its plan. Because of the same, there will be change in current density in the coil at the two Josephsen junctions when the ring is carrying supercurrent in it. Direction of presence of current will be considered as the paramter for representing two distintive states $|0\rangle$ and $|1\rangle$ in SQUID based quantum computers as an example. If there is current in clockwise direction it is considered as $|0\rangle$ state and otherway arround for the $|1\rangle$ state. Current in both the direction at the same time is nothing but superposition state for the qubit. In the same way all other features required for computation will be achieved.



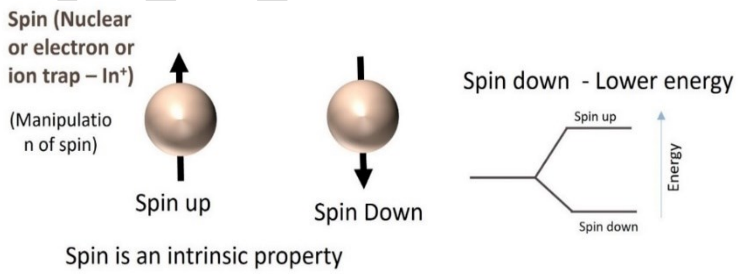
3.2 Photon qubits (Optical cavity or Microwave cavity)

Encoding of quantum information in photons-based qubits is through their polarization properties. Polarization refers to the orientation of the electric field vector associated with a photon's electromagnetic wave. Polarization can be represented using various bases, such as the horizontal $|H\rangle$ and vertical $|V\rangle$ basis to represent $|0\rangle$ and $|1\rangle$ respectively, the diagonal basis for super position states. Here, the quantum superposition is defined by the ability of a photon to exist in horizontal and vertical polarization states simultaneously as shown in the figure. Quantum entanglement will be achieved when two or more photons become correlated in such a way that the state of one photon is dependent on the state of another, even when they are separated by large distances. When such photonics-based qubits are measured their superposition state collapses into either $|0\rangle$ or $|1\rangle$ with a certain probability. This measurement process is a crucial step in extracting information from quantum systems for computation.



3.3 NMR based qubits

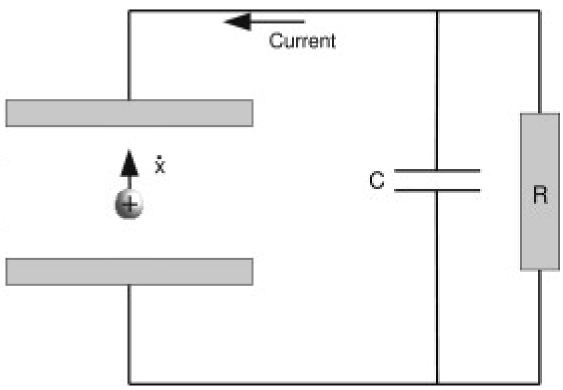
In nuclear magnetic resonance (NMR) based quantum computing, superposition and entanglement are achieved using the properties of nuclear spins within molecules placed in a strong external magnetic field. Superposition: Manipulation of nuclear spins of certain atoms within a molecule is used for computation. Such nucleus with spins can act like tiny magnets aligning themselves parallel or antiparallel to the direction of the applied external magnetic field. These two directions will be used as two distinctive states to represent $|0\rangle$ and $|1\rangle$. Suitable radiofrequency (RF) pulse with the specific frequency and pulse duration, nuclear spins will be manipulated from their initial state into a superposition state. This is simply aligning them parallel and antiparallel at the same time. Quantum entangled state will be achieved when multiple qubits are aligned to the same magnetic field with suitable combination of frequencies.



3.4 Ion trapped qubits

In ion trap quantum computing, superposition is achieved by manipulating the internal energy levels of trapped ions using laser pulses and electromagnetic fields. Ion trap qubits are typically based on the electronic states of ions, such as trapped ions in suitable elements.

The first step is to trap individual ions using electromagnetic fields in a vacuum chamber. The ions are typically held in place using a combination of radiofrequency (RF) and static electric fields. Cooling techniques, such as laser cooling, are then applied to bring the ions' motion to the ground state,



reducing their thermal motion and interaction with the environment. The ground state and an excited state of the ion can often be used as the two basis states of your qubit. The two states could be represented as |0⟩ (ground state) and |1⟩ (excited state). If the ion is at ground state, the qubit is at |0⟩ state. Once the trapped ion is taken to higher energy, it gives electron for conduction which is considered as |1⟩ state. The ion is at ground and excited states at the same state will make the quantum superposition of the qubit.

4. Representation of qubits and their operations

Types of representations of qubits in quantum computing

Dirac bracket notation, Bloch sphere, and Matrix representation

4.1 Dirac bracket notation

Dirac bracket notation, also known as Dirac notation or bra-ket notation, is a mathematical notation used in quantum mechanics to describe and manipulate quantum states, vectors, and operators. It was introduced by physicist Paul Dirac as a concise and powerful way to represent quantum concepts.

In Dirac notation, a quantum state is represented as a ket vector |ψ⟩, and its corresponding dual vector (also known as a bra) is ⟨ψ|. The ket vector |ψ⟩ represents a column vector in a complex vector space, while the bra vector ⟨ψ| represents a row vector in the same space. Together, they form a bra-ket pair, and their inner product (also known as a scalar product or bracket) ⟨ψ|ϕ⟩ represents the amplitude of transitioning from state |ψ⟩ to state |ϕ⟩.

Here's a breakdown of the notation and its components:

Ket vector (|ψ⟩): This represents a quantum state. It's a column vector in a complex vector space. The vector can have components in various bases, depending on the choice of representation.

Bra vector (⟨ψ|): The dual vector to the ket vector. It's a row vector in the same complex vector space. The bra vector is used to represent the complex conjugate of the corresponding ket vector.

Inner product (⟨ψ|ϕ⟩): The inner product of two states (bra and ket) gives a complex number that represents the amplitude of transitioning from state |ψ⟩ to state |ϕ⟩.

Mathematically, this is the dot product of the bra vector ⟨ψ| and the ket vector |ϕ⟩. Dirac notation makes many quantum mechanical operations more intuitive.

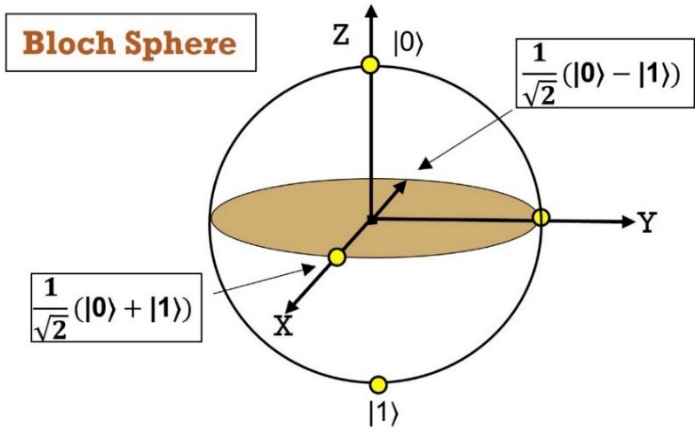
For example Normalization qubits: A state |ψ⟩ is normalized if ⟨ψ|ψ⟩ = 1. This ensures that the probability of finding the system in state |ψ⟩ is 1.

Operators: Operators, such as observables and transformations, are represented by matrices. Acting an operator on a state |ψ⟩ is written as the product of the operator and the ket vector: A|ψ⟩.

Measurement: The probability of measuring a quantum state |ψ⟩ in a basis represented by the ket vectors |a⟩ is given by $|\langle a|\psi\rangle|^2$.

Superposition: A state can exist in a linear combination of other states. For example, |ψ⟩ = α|0⟩ + β|1⟩ represents a qubit in a superposition of |0⟩ and |1⟩ states. In the context of quantum computing, Dirac notation is used to represent quantum states, gates, and operations, making it a concise and elegant way to describe and manipulate quantum information. It simplifies calculations and allows for easy visualization of quantum concepts.

4.2 Bloch sphere



The Bloch sphere is a geometric representation that provides a visual way to understand and represent the state of a qubit in quantum computing. It is a sphere with a qubit's pure states represented as points on the surface, and mixed states represented within the sphere. The Bloch sphere is a useful tool to visualize qubit states and quantum operations. Here's how qubits are represented on the Bloch sphere:

Physical Representation: Imagine a sphere where the north pole (the top) represents the state $|0\rangle$ and the south pole (the bottom) represents the state $|1\rangle$. The equator of the sphere represents a superposition of $|0\rangle$ and $|1\rangle$ states.

Pure States on the Surface: The surface of the sphere represents all possible pure states of a qubit. Any point on the surface corresponds to a unique state of the qubit. For example, the state $(|0\rangle + |1\rangle) / \sqrt{2}$ would be represented on the equator of the sphere.

Bloch Vector: To represent a qubit state on the Bloch sphere, you use a Bloch vector. The Bloch vector is a three-dimensional vector that points from the center of the sphere to the corresponding point on the surface. It is defined as:

$$\vec{r} = \begin{bmatrix} \langle\sigma_x\rangle \\ \langle\sigma_y\rangle \\ \langle\sigma_z\rangle \end{bmatrix}$$

where $\langle\sigma_x\rangle\langle\sigma_y\rangle\langle\sigma_z\rangle$ are the expected values of the Pauli operators X, Y, and Z for the qubit state.

The states $|0\rangle$ is represented by the point at the north pole of the Bloch sphere (r = [0,0,1]).

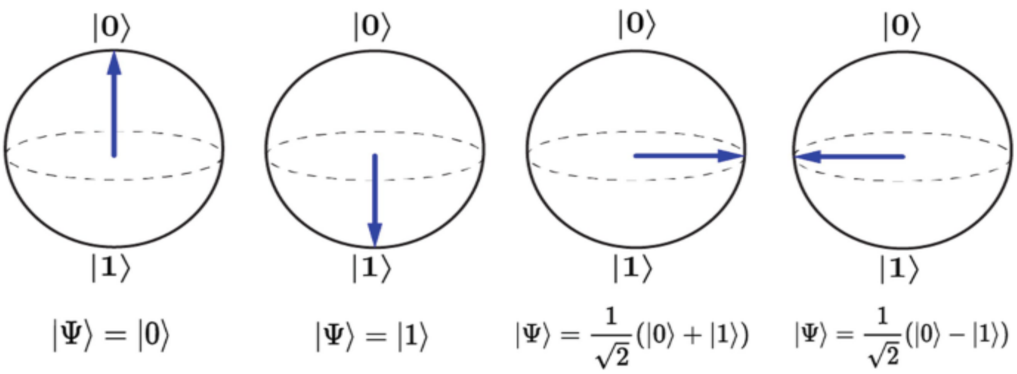
The state $|1\rangle$ is represented by the point at the south pole of the Bloch sphere (r = [0,0,-1]).

Superpositions like are represented on the equator of the sphere.

Phases and amplitudes of the superposition states are represented by the azimuthal angle (ϕ) and polar angle (θ) on the sphere, respectively.

Quantum Operations: Quantum gates and operations can be visualized as rotations on the Bloch sphere. Applying a gate to a qubit corresponds to rotating the Bloch vector by a certain angle around a specific axis.

In summary, the Bloch sphere provides an intuitive way to visualize and understand the behavior of qubits in quantum computing. It helps in grasping concepts like superposition, phases, and quantum operations, making it a valuable tool for both beginners and experienced practitioners in the field.



4.3 Matrix representation

Qubits can be represented using matrix methods through a formalism known as the matrix representation of quantum states and operations. In this formalism, qubit states are represented as column vectors, and quantum operations (gates) are represented as matrices that act on these vectors. This approach is widely used in quantum computing and quantum mechanics to perform calculations and analyze qubit behavior.

Qubit States: Qubit states are typically represented as two-component column vectors using the Dirac notation. The basis states |0⟩ and |1⟩ are represented as:

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

A general qubit state |ψ⟩ can be written as a linear combination of basis states:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Here α and βare complex probability amplitudes.

Quantum gates are represented as unitary matrices that act on qubit states. A gate's action on a qubit state |ψ⟩ can be computed by matrix-vector multiplication. For example, the Pauli-X gate (bit-flip gate) is represented by the following matrix:

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

To apply the Pauli-X gate to a qubit state |ψ⟩, you multiply the X matrix with the state vector:

$$X|\psi\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \beta \\ \alpha \end{bmatrix}$$

Similarly, other quantum gates are represented using their corresponding matrices, such as the Pauli-Y gate, Pauli-Z gate, Hadamard gate, and more.

Quantum circuits are constructed using sequences of quantum gates. Each gate in a quantum circuit corresponds to a matrix multiplication applied to the state vector. The entire circuit's operation is the product of the individual gate matrices. For example, if you have a circuit with two qubits and apply gates U and V to them, the combined operation of the circuit can be represented by the tensor product of the gate matrices U and V.

Matrix methods provide a powerful way to analyze and compute the behavior of qubits in quantum systems. They facilitate calculations involving quantum gates, transformations, and measurements, making them an essential tool in quantum computing and quantum mechanics.

5. Principles for Quantum Computers ; Heisenberg's uncertainty principle, Quantum tunneling, Quantum superposition and Quantum entanglement.

Heisenberg's uncertainty principle:

The Heisenberg Uncertainty Principle is a fundamental concept in quantum mechanics that states that there is an inherent limit to the precision with which certain pairs of complementary properties, such as a particle's position and momentum, can be simultaneously known. Specifically, the more accurately one property is measured, the less accurately the other can be determined. This principle arises from the wave-like nature of particles and sets a fundamental bound on the predictability and measurement precision of quantum systems.

Quantum tunneling: Quantum tunneling is a fundamental quantum mechanical phenomenon in which particles have a finite probability of crossing or passing through energy barriers that would be classically impassable due to their insufficient energy. This phenomenon occurs due to the wave-like nature of particles at the quantum scale and is a result of the uncertainty principle. In essence, quantum tunneling allows particles to "leak" through barriers and explore regions that would be classically forbidden, leading to a unique and counterintuitive behavior in the realm of quantum physics.

Quantum superposition:

Quantum superposition is a fundamental principle of quantum mechanics whereby a quantum system can exist in a linear combination or mixture of multiple distinct states simultaneously. This state of superposition is not the same as a classical mixture; rather, it reflects the intrinsic uncertainty and wave-like behavior of quantum particles. As a consequence, until measured or observed, the system's properties are described by the combined probabilities of the various states, allowing for the coexistence of multiple possibilities and outcomes.

Quantum entanglement:

Quantum entanglement is a profound phenomenon in quantum mechanics where two or more particles become correlated in such a way that the properties of one particle instantaneously influence the properties of another, regardless of the distance between them. These particles are said to be "entangled" and share an interconnected state that cannot be described independently. Entanglement defies classical intuition and highlights the non-local, interconnected nature of quantum systems, playing a crucial role in various quantum phenomena and technologies, including quantum computing and cryptography.

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