College of Integrative Sciences and Arts
Arizona State University
Student Showcase

Optical Qubits and Logic Gates

Princess Colon & Dr. Michael Dugger
College of Integrative Sciences and Arts, Arizona State University, Polytechnic campus

Introduction

- Superposition: A quantum state that can take on multiple independent or contradicting aspects at the same time.
- Entanglement: When two or more quantum observables can be used to "infer" other observables.
- Quantum Computers distinguish themselves from classical computers by harnessing these two principal aspects of quantum systems.
- This distinction allows them to complete certain tasks with greater efficiency than classical computers.

Qubits

$$|\psi\rangle = cos(\theta/2)\,|0\rangle + e^{i\phi} sin(\theta/2)\,|1\rangle$$

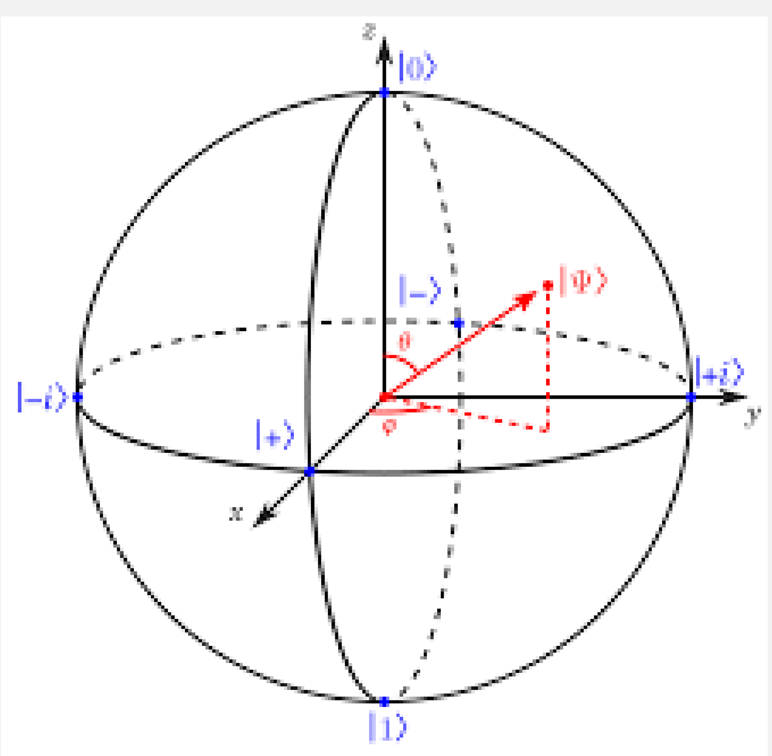

Fig. 1: Bloch Sphere

- Classical bits can represent 1's and 0's, Qubits are a superposition of state 1 and state 0 and the outcome is measured as a probability of one or the other.
- This superposition can be represented by a Bloch Sphere:
  - X – Axis (Hadamard Basis)

$$|+\rangle = (|0\rangle + |1\rangle)\frac{1}{\sqrt{2}} \qquad |-\rangle = (|0\rangle - |1\rangle)\frac{1}{\sqrt{2}}$$

  - Y-Axis (Phase Basis)

$$|+i\rangle = (|0\rangle + i\,|1\rangle)\frac{1}{\sqrt{2}} \qquad |-i\rangle = (|0\rangle - i\,|1\rangle)\frac{1}{\sqrt{2}}$$

  - Z-Axis (Computational Basis)

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

- A practical optical qubit can be based on a quantum system with only two distinct states [1].
  - Polarized Qubits (Horizontal $=|0\rangle$, Vertical $= |1\rangle$) - A single photon passes through QHQ waveplate combination to obtain desired polarization
  - Path Qubits (Upper $= |0\rangle$, Lower $= |1\rangle$) - A single photon passes through a Beam Splitter to create two paths. A phase shift can be introduced into one path. The beams can then be passed through another beam splitter to obtain any desired superposition.

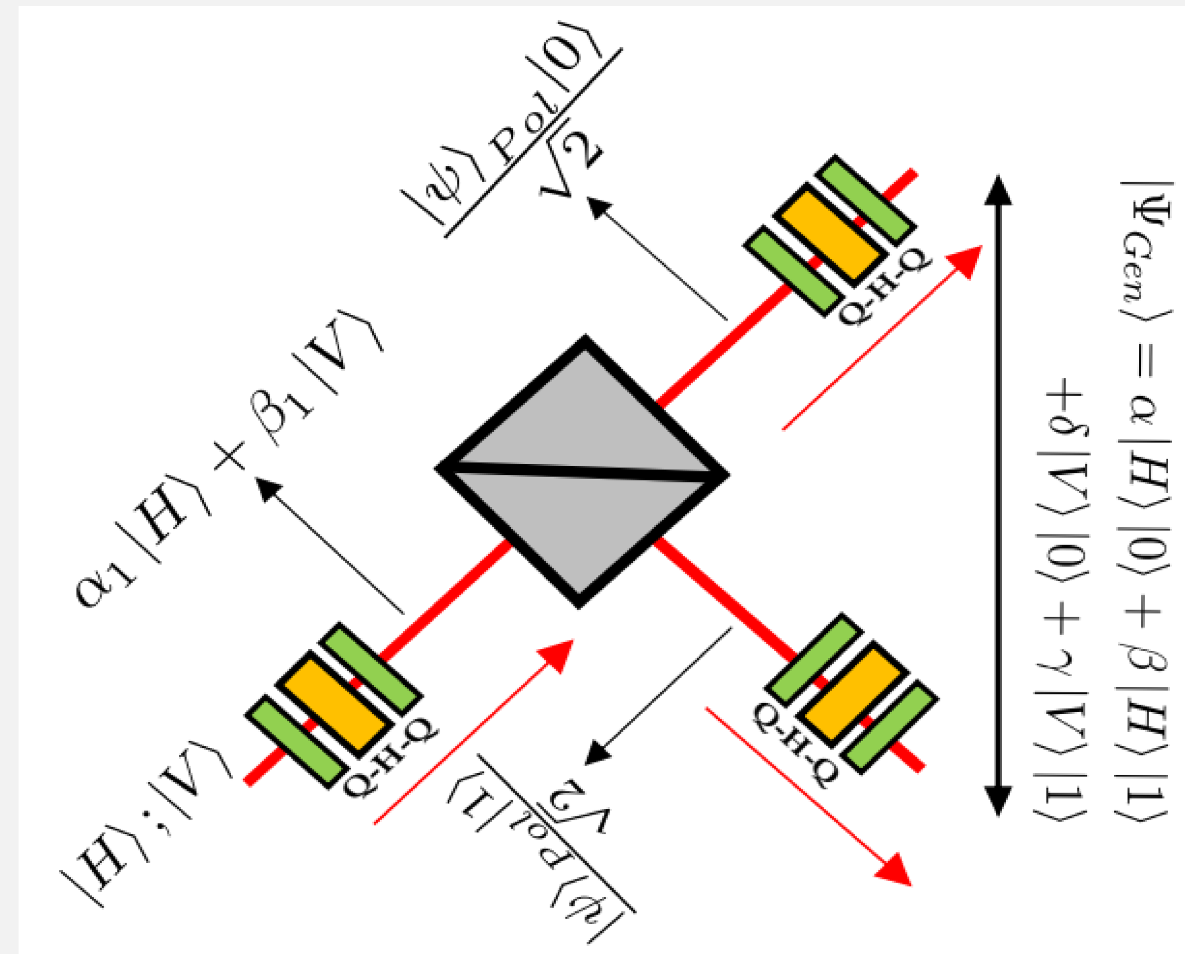

Fig. 2: Polarization and Path Qubit configuration [1]

- By introducing a phase shift in the path qubit with QHQ plates instead of the beam splitting method, we can effectively create a configuration which "overlays" a Path and a Polarized Qubit onto each other in such as way that allow for entanglement through the use of a Polarized Beam Splitter.

Logic Gates

- In classical computers, Logic Gates are mechanisms used to manipulate the bit based on its input state. In quantum computing, this idea also applies.
- Logic gates can be visualized as rotations of the described qubit about specific axes.
- In the implementation of optical qubits, these gates may be made with a specific combination of waveplates and beam splitters with differentiating configurations based on whether they affect a Path or Polarized Qubit.
- Pauli Gates
  - X : Analog to classical NOT Gate. Is a 180 degrees rotation about X-Axis.
  - Y : Combines NOT operation with a phase shift of +/- 90 degrees. Is a 180 degrees rotation about the Y-Axis
  - Z : Introduces a phase flip to wave function. Is a 180 degrees rotation about Z-Axis.
- Phase Gate: Introduces a phase shift of 90 degrees.
- Hadamard: Creates an equal superposition of both states. It is a combination of two rotations within a Bloch sphere, 90 degrees about the Y-Axis and 180 degrees about the X-Axis

Uses

The possible uses for quantum computers is limited by our imagination. The most common type of desired applications include

- Factoring of large numbers for the purpose of breaking encryptions
- Simulation of actual quantum systems
- Search algorithms

Example: Grover's Algorithm

- Grover's Algorithm is a theoretical unstructured search algorithm specific to quantum computers.
- In classical computers, a search algorithm is run by checking each entry inside a database individually and returning when the correct entry is found. If some number, *N*, represented the number of entries within the database, then the number of steps needed to find the correct entry. On average it would be $N/2$ steps.
- In Grover's Algorithm, through the means of superposition, the computer checks multiple entries at once. The average number of steps is in this case $\sqrt{2}$.
- The algorithm begins first with an equal superposition of all states using Hadamard gates.
- The superpositioned states are then entered into a black box concept referred to as an "oracle".
- An oracle in this algorithm carries the burden of identifying the solution but does not actually solve the problem.
- In this instance, its operations mark the solution by first inverting the amplitude of the associated wave function.
- The system is then put through something referred to as the "diffusion operator" which works to condition the signals(or qubits) so that the probability that the system returns the correct answer is near 1 and all other possibilities are 0.

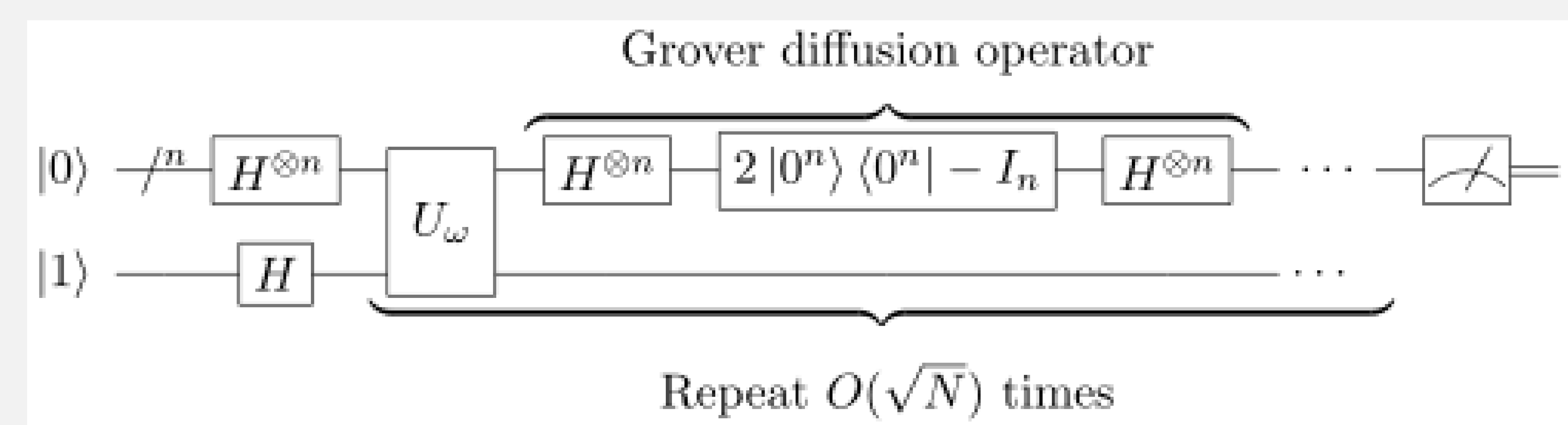

Fig. 3: Grover Algorithm Block Description [2]

Literature Cited & Acknowledgements

[1] Kanad S. et. al., Experimental realization of universal quantum gates and six-qubit state using photonic quantum walk, arXiv:2403.06665 (2023).
[2] A. Nikhade, "Grover's search algorithm: Simplified," Medium, https://towardsdatascience.com/grovers-search-algorithm-simplified-4d4266bae29e (accessed Oct. 28, 2024).