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Quantum Teleportation with Photons

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Joint work with Chris Adami

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Results

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- I found a way to simplify an optical simulation of the quantum teleportation circuit using *timing qubits*.
- We are working to generalize this result to other quantum circuits.

Outline

Quantum Computing
- Quantum Bits and Logic Gates
- Quantum Circuits

Optical Physics
- Standard Optical Devices
- Implementing Quantum Gates with Optical Equipment

Quantum Teleportation
- Overview of Quantum Teleportation
- Implementing the Teleportation Circuit with Optical Equipment

- A *quantum computer* is a computer that utilizes properties from quantum mechanics to process information very quickly.

Classical Computer

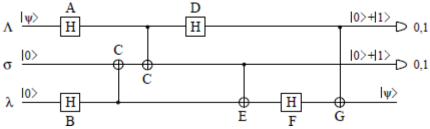
- Information is stored in a binary digit (*bit*), 0 or 1.
- Information is processed by logic gates (e.g., NOT).

Quantum Computer

- Information is stored in a quantum bit (*qubit*), $|0\rangle$ or $|1\rangle$.
- Information is processed by quantum gates (e.g., X).

- Why can information be processed faster?
  1. *Superposition:* A qubit can be both $|0\rangle$ and $|1\rangle$ at the same time.
  2. *Entanglement:* A quantum gate on one qubit affects another.

- A *quantum circuit* is simply a set of quantum gates acting on a set of (entangled) qubits.



- The *Hadamard gate*, H, produces a superposition:

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

- The *controlled-not gate*, CNOT, flips the second qubit conditional on the first qubit:

$$\text{CNOT}|00\rangle = |00\rangle, \qquad \text{CNOT}|01\rangle = |01\rangle$$

$$\text{CNOT}|10\rangle = |11\rangle, \qquad \text{CNOT}|11\rangle = |10\rangle$$

Optical Physics

Standard Optical Devices

- Optical physics (optics) consists of *optical devices* acting on particles of light (*photons*).
- Photons have a *polarization* and a *phase*, and beams of photons can be split and sent in different directions.

Beam Splitter

Acts on a beam of photons and splits them.

Phase Shifter

Acts on a single photon and rotates the phase by some angle.

Polarizing Rotator

Acts on a single photon and rotates the polarization.

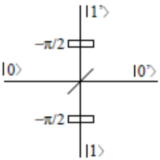
- These devices are represented schematically by the symbols:

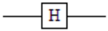
Optical Physics

Implementing Quantum Gates with Optical Equipment

- *Quantum gates can be implemented with optical equipment!*

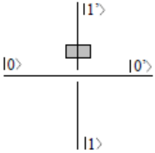
The Hadamard gate with optical equipment looks like:

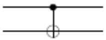




$H|0\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}, \qquad H|1\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$

The CNOT gate with optical equipment looks like:





$\text{CNOT}|00\rangle = |00\rangle, \qquad \text{CNOT}|01\rangle = |01\rangle$
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- By linking together optical devices implementing quantum gates, we can simulate a quantum circuit.

- Alice has two qubits: $|\psi\rangle$ and $|0\rangle$. She wants to send $|\psi\rangle$ to Bob, who has one qubit, $|0\rangle$.
- The qubit $|\psi\rangle$ is unknown, and Alice cannot duplicate it without destroying the state (*no-cloning theorem*). She can't measure $|\psi\rangle$ without destroying it either.

Alice

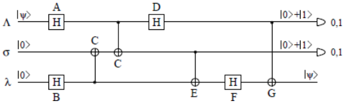
- Entangles $|\psi\rangle$ and $|0\rangle$.
- Performs a series of operations.
- Measures one of four possible outcomes (00, 01, 10, or 11) and sends it to Bob.

Bob

- Performs an operation T depending on Alice's measurement to get the original qubit $|\psi\rangle = T|0\rangle$.

- The qubit $|\psi\rangle$ teleports to Bob without either party knowing the actual state!

The Quantum Teleportation Circuit

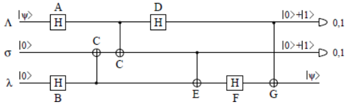


This is achieved with quantum gates acting on quantum bits.

Quantum Teleportation

Implementing the Teleportation Circuit with Optical Equipment

The Quantum Teleportation Circuit



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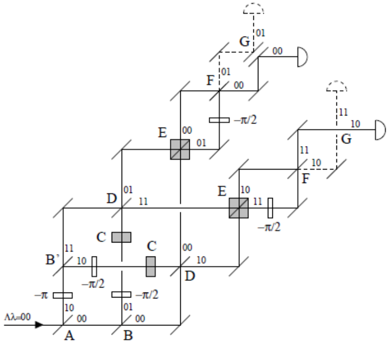
Optical Simulation of the Quantum Teleportation Circuit



This is achieved with optical devices acting on photons.

- Optical simulations of quantum circuits are good for a number of reasons:
    1. Inexpensive to implement.
    2. Photons have long coherence times and are easy to control.
    3. Any circuit can be simulated, in principle.
- The biggest downfall is the *exponential* increase in the number of optical devices needed.
- Timing qubits can simplify complexity by converting spatial information to temporal information.

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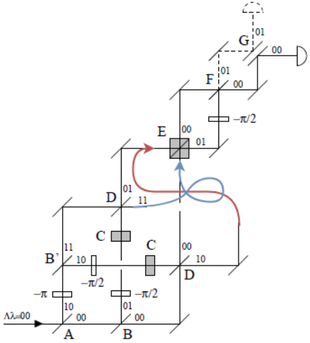
Simplified Optical Simulation of Quantum Teleportation via Timing Qubits



- The quantum teleportation circuit uses only three qubits and doesn't utilize the full potential of quantum computers.

Quantum Computers

Supercomputers of the Future

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- *Quantum supremacy*, which is achieved when a quantum computer performs a calculation no classical computer can, will be achieved with around 50 qubits.
- Near term quantum computers will be useful for optimization problems, quantum chemistry, and machine learning.
- Research in quantum information science is vital to advancing the science of high performance computing.

Thank you for your attention.
Questions?