Simulated Design of Quantum Networks

Senior design team sddec23-17

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Problem Statement & Design Context

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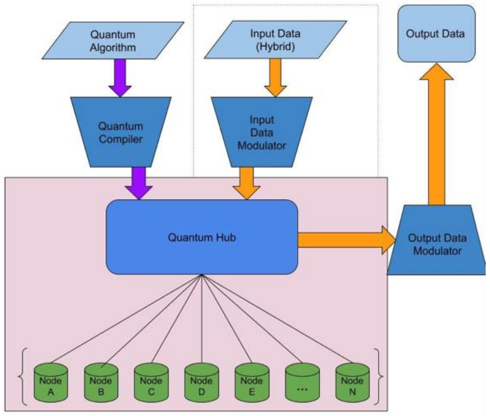
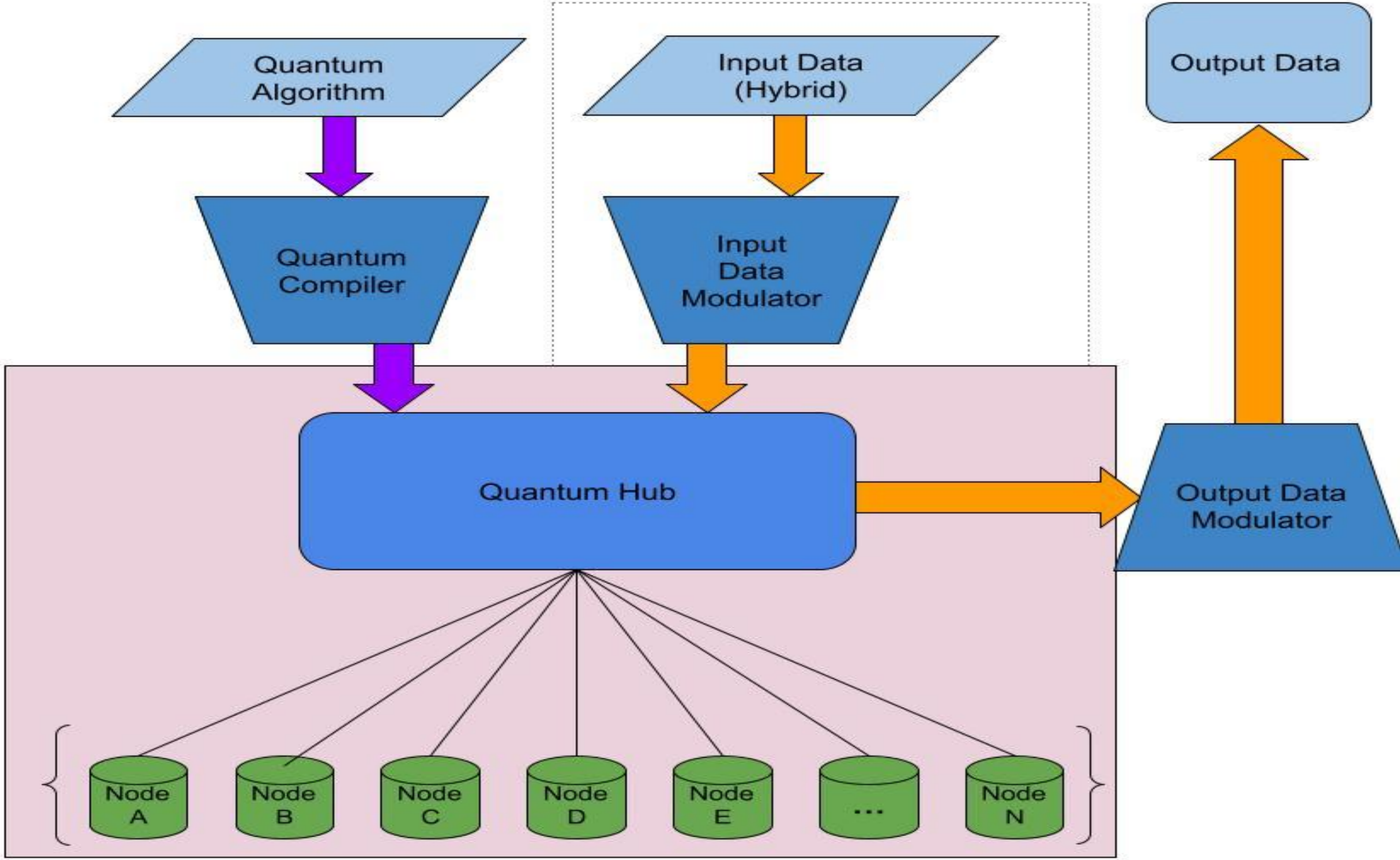
- Client: Dr. Durga
  - Doing intensive research regarding quantum computers.
  - Major interest : Quantum computation and Quantum information theory
    - Working making Ion traps to hold Q-bits. Also research in future of quantum computing clusters.
- Needs:
  - Design a modular quantum network simulation to communicate with quantum cluster computers. These computers will have both classical and quantum components.





Quantum Algorithm
Input Data (Hybrid)
Output Data
Quantum Compiler
Input Data Modulator
Quantum Hub
Output Data Modulator
Node A
Node B
Node C
Node D
Node E
...
Node N

Engineering Standards and Protocols

IEEE 802.3 Ethernet: This standard defines the physical and data linky layers of wired Ethernet networks. These networks are going to be critical to set up as they will be used in conjunction with our quantum network we are creating and provide a good baseline network that we can build off of.

IETF RFC 2544: **Methodology for measuring the performance of network devices:** This standard from the Internet Engineering Task Force describes standards on how network devices are monitored and how their performance is tracked. Once our network is running, we will need to test the speed and reliability using these standards to ensure that it is a viable option compared to standard internet.

IEEE P7130: **Standard for Quantum Computing Definitions:** These standards provide standards on how quantum computing framework functions are described and what terminology is used. This is important because if we are to communicate with our advisor, we will need to use the proper terms so that he can understand and implement our design.

IEEE P802.1Q-2021: **Bridges and Bridged Networks, Amendment 28: Quantum Key Distribution Protocol:** This amendment to IEEE 802..1Q defines the Quantum Key Distribution (QKD) protocol which is used to secure network traffic over a quantum network. This is important because if we want the traffic on our network to be secure therefore we will need to implement QKD.

Functionality and Engineering Requirements

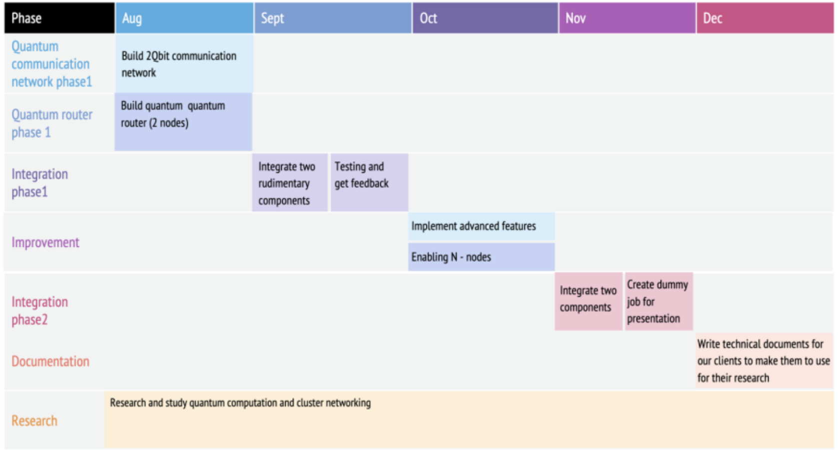
- Modular design
- Capable of hosting large number of nodes (factor of 10)
- Statistical analysis output

Project Explanation

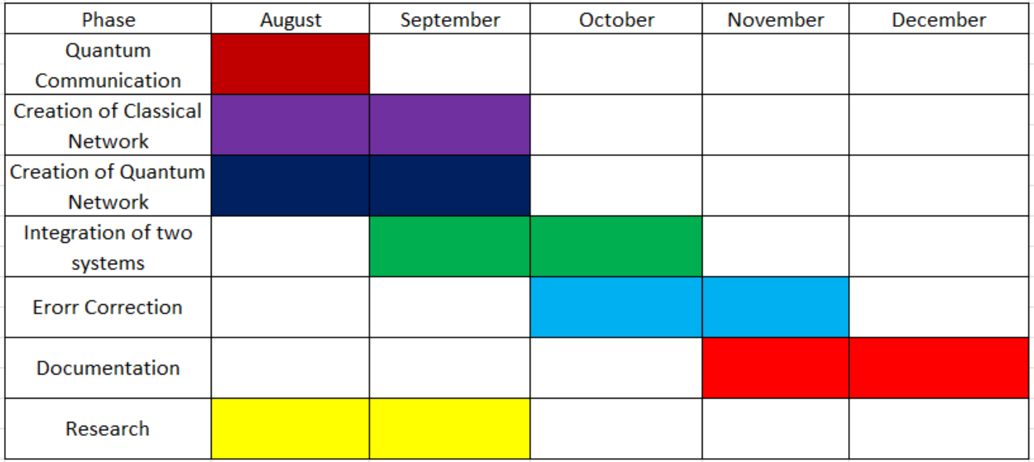
Project Timeline & Roles

Benjamin A. - Classical network development
Steven T. - Classical network development
Ohik K. - Quantum circuit designing
Derrick W. - Code development & integration

Quantum network for quantum cluster computing Project Timeline



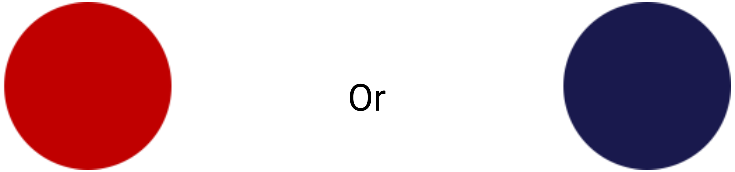
Revised Timeline



Quantum components: What is Quantum Computing

Classical Computers (Digital Computers)

Bits



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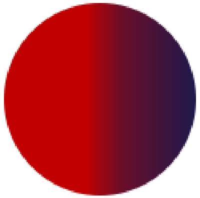
Quantum Computers ~ Analog computer

Qbits

$$a|0> \;\; +b|1>$$

0



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Quantum components: Why does the superposition matter?

How many numbers are need to describe 2 bits versus 2 Qbits

Classical Computers

2 bits -> 00, 01, 10, and 11 *(only 2 numbers enough)*

Quantum Computers

$$a|00>, \quad b(|01>+|10>), \quad c(|01>-|10>), \quad d|11>$$

(we need 4 numbers)

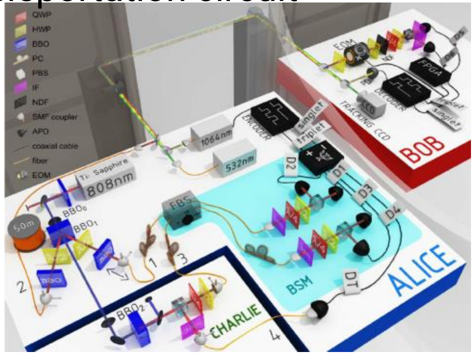
N Qbits -> 2^N Bits

2^{300} = Number of particles in Universe

Quantum components: Quantum circuits we made

Implemented by parts

Quantum Teleportation circuit



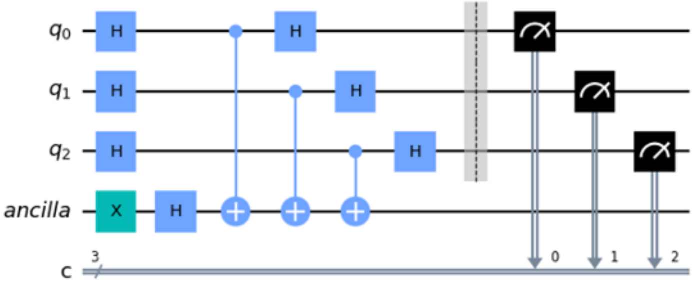
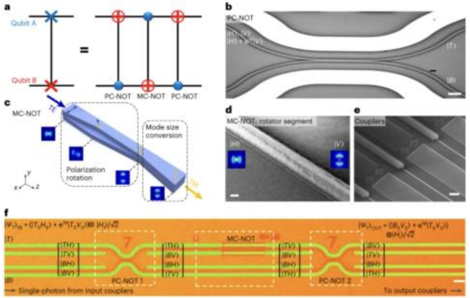


Image Source: Experimental quantum teleportation over a high-loss free-space channel, OCIS codes: (270.5565) Quantum communications; (270.5585) Quantum information and processing.

Quantum Entanglement verification *- Implemented as extra functionality.*



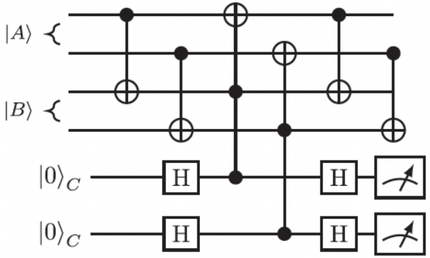


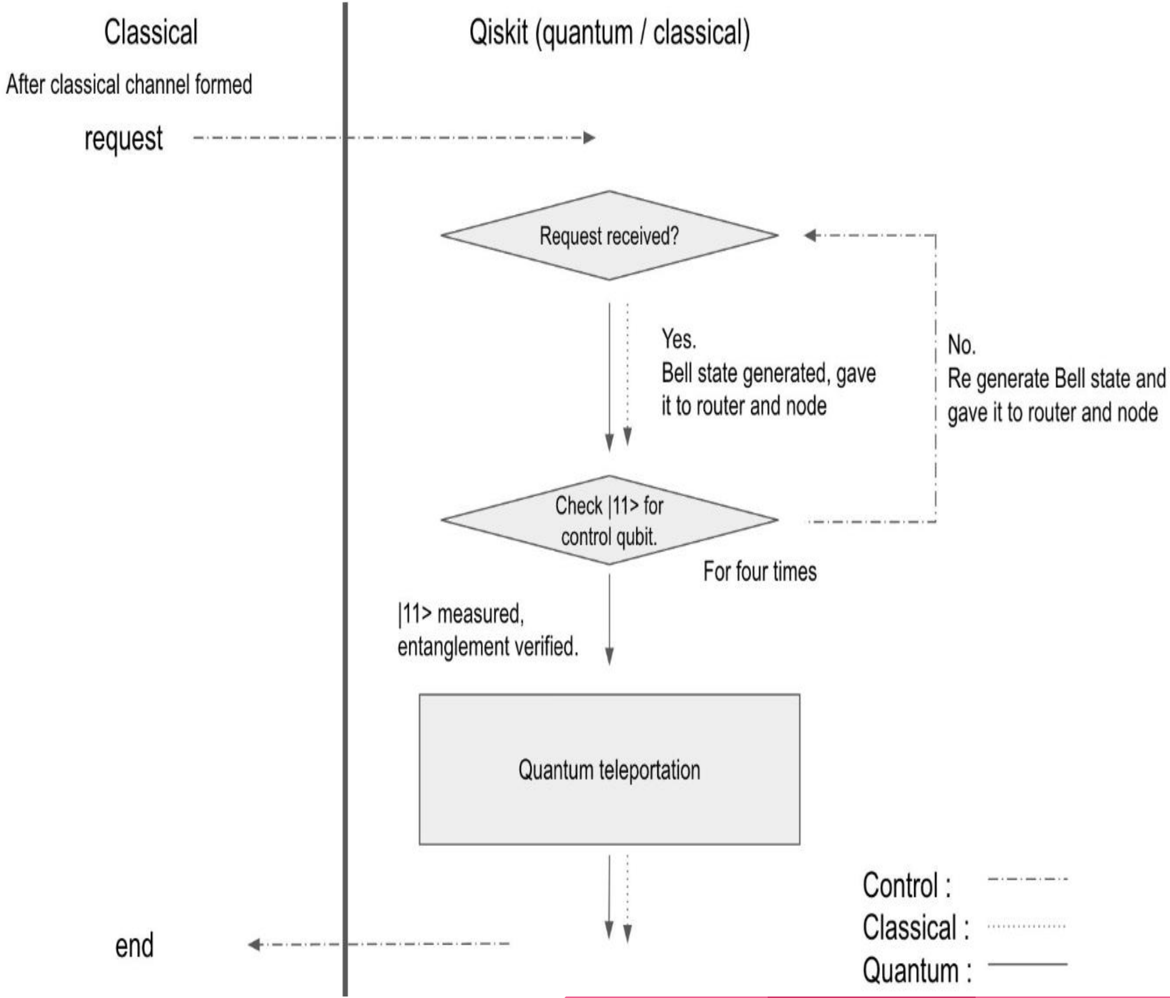
Image Source: https://doi.org/10.1038/s41566-023-012240x
https://doi.org/10.1088/2058-9565/abe458

Communication Between Quantum and Classical

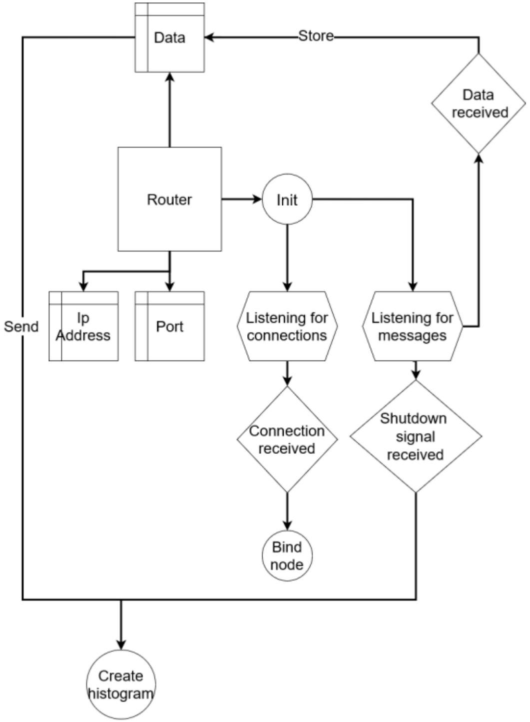
- Way to integrate already proven technology
- Process that allows for files to be communicated correctly and timely
- Much smaller needs than Quantum communication

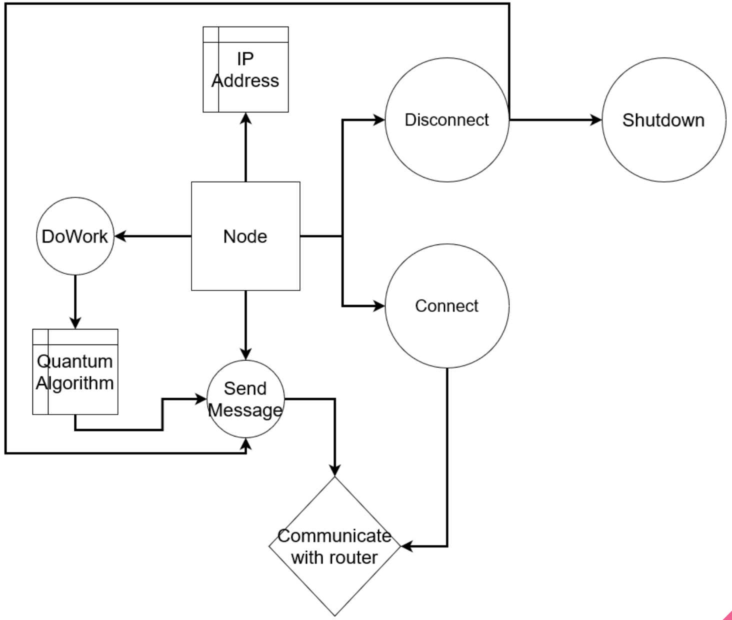
Overall Flow Control

- How they work together
- Quasi 3 way handshake
- Start and receive



Overall Flow Control - continued





Proving Functionality

Classical components:

Sockets allow for quick and correct communication that can be tweaked easily

Quantum components:

Implementing debug mode for following quantum operation.

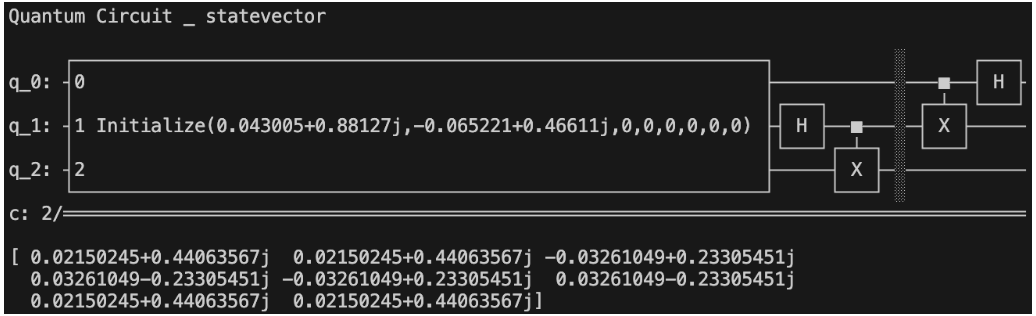
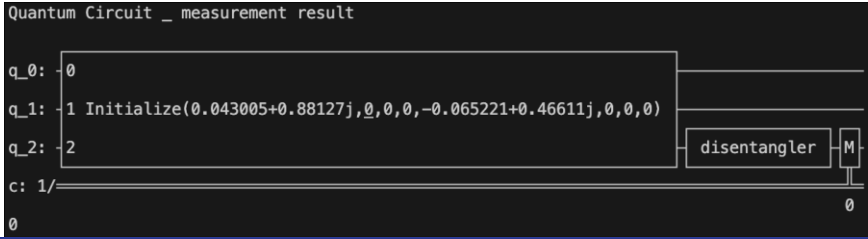


Figure: Generate random qubit from |0> state and check quantum operation

```
Statevector([ 0.0430049 +0.88127134j,  0.        +0.j        ,
             -0.        +0.j        ,  0.        +0.j        ,
             -0.06522099+0.46610902j,  0.        +0.j        ,
              0.        +0.j        ,  0.        +0.j        ],
            dims=(2, 2, 2))
```



Later improvements on this work

Because of our modular design and making our system robust, there can easily be improvements later on when new developments in quantum information systems are made

Risk and Risk Management / Mitigation

- Implementation Issues
  - Network and router design could just not work
    - Thoroughly checked with advisor and experts

- Creation of classical network
  - Issues concerning detection and design
    - Through research, keeping our advisor updated

- Merging of classical network and quantum network
  - Issues when combining and scheduling router swaps
    - We based our project on most fundamental quantum mechanics

Testing

Unit Testing

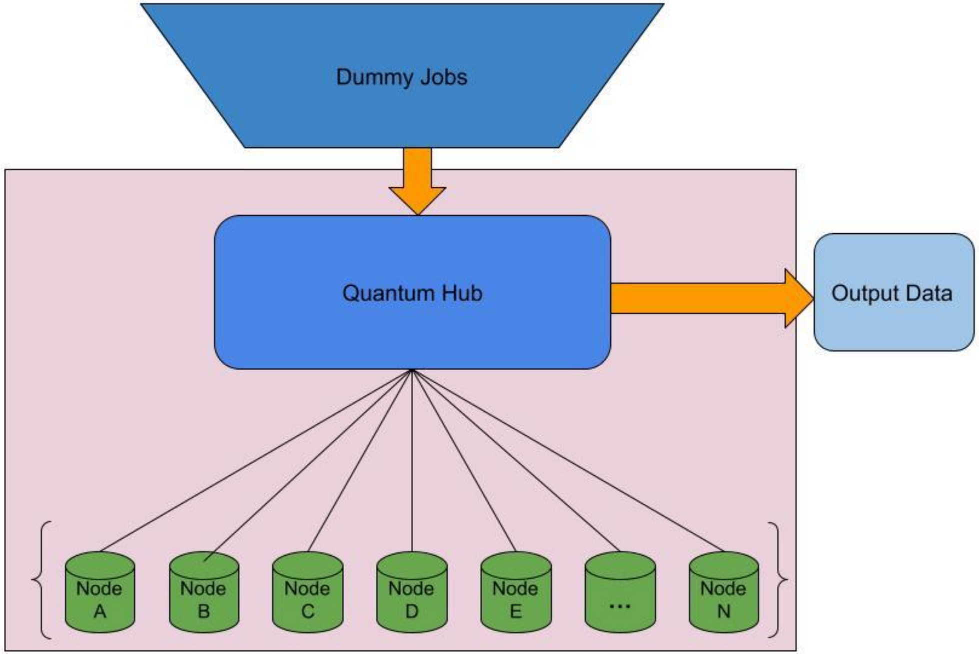
- Classical Network
  - Can the switch distribute tasks without error?
  - Can the nodes send error signals back to the router?
  - Can the router do the correct statistical analysis on the information?
  - Can the router schedule jobs optimally?

- Quantum Network
  - Can the router and node establish entanglement?
  - Can the switch and the nodes swap information accurately?
  - Can the switch and the nodes swap information quickly?

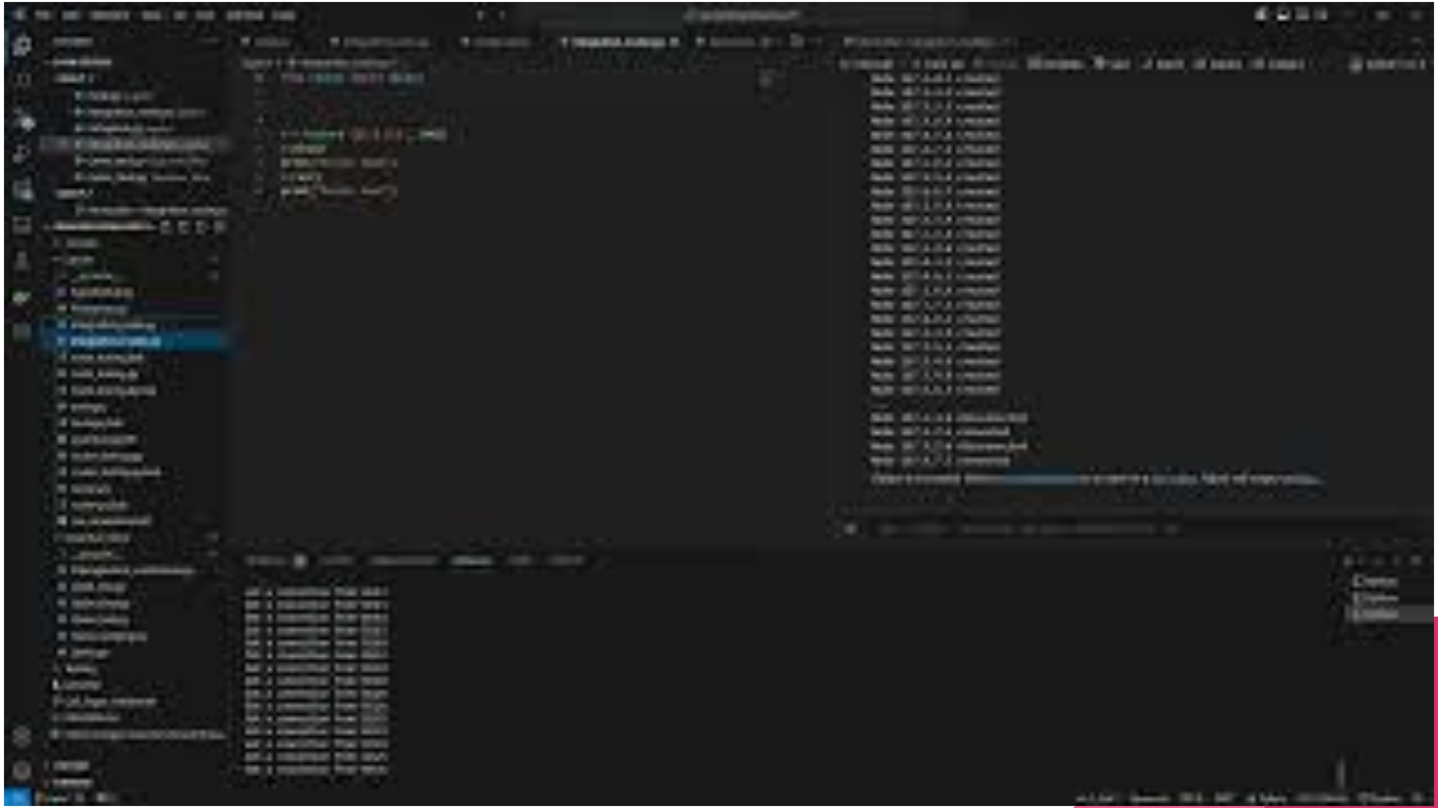
Acceptance and Regression Testing

Goals For testing:

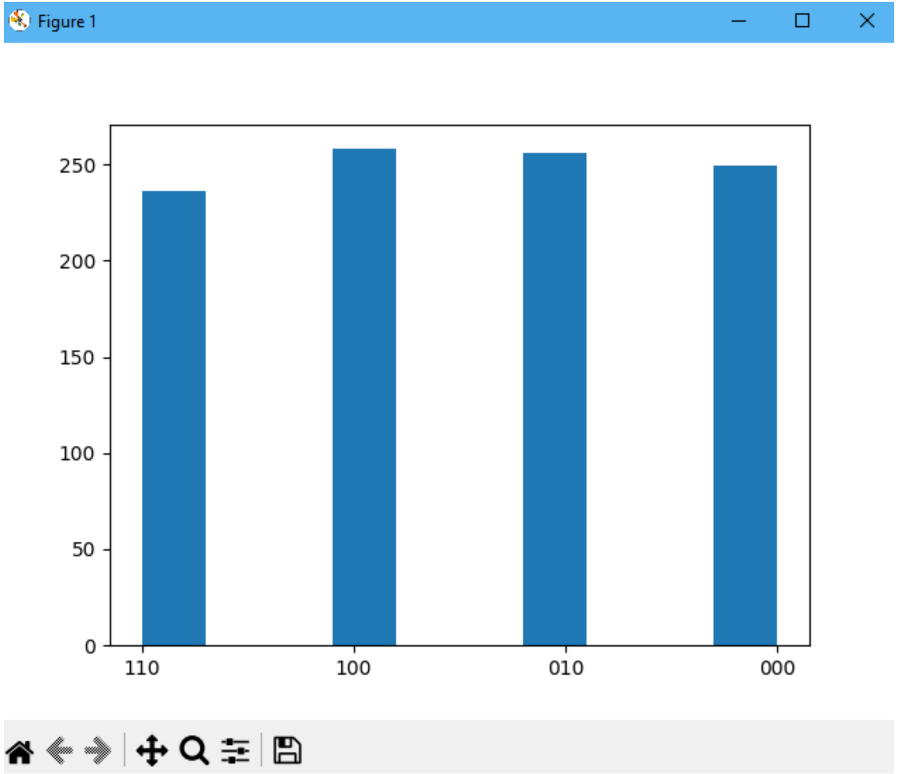
- The router can communicate with nodes
- We can create as many nodes as our client needs
- The router can output desired data after analysis



Live Demo



Live Demo - results



Difference from 491 to 492

- New timeline, less focus on research, more on development
- Different understandings of our project and its place in QIS
- Preventing scope creep
- Found new limitations in a needed software (qiskit)
- Development of documentation for later uses

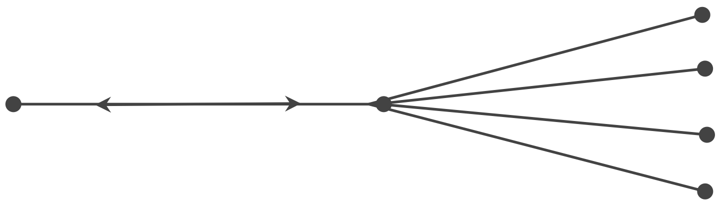
Thank you

Supplement materials

Quantum 1 - Quantum computing

Classic computer - logic gate, Boolean operation

Quantum computer - quantum gate , *Matrix* operation $U^\dagger U = I$



Probability of being one answer

Operator	Gate(s)		Matrix
Pauli-X (X)	X		$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T		$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}$
Controlled Z (CZ)	Z		$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&-1\end{bmatrix}$
SWAP			$\begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$

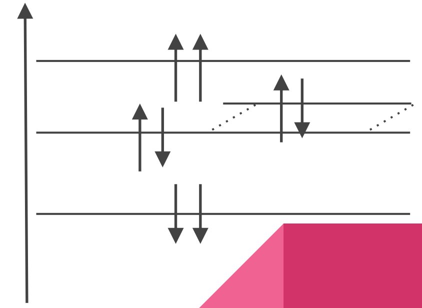
CNOT $$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}\begin{bmatrix}a'\\b'\\c'\\d'\end{bmatrix}=\begin{bmatrix}a'\\b'\\d'\\c'\end{bmatrix}$$

$$a' = a'|00> \quad ...$$

$$a|00>, \quad b(|01>+|10>), \quad c(|01>-|10>), \quad d|11>$$

Controlled by probability!

Energy level



Quantum 2 - information

Nature is analog -> we can't describe analog nature perfectly using digital system.

we can if we use analog system.(without concerning many problems)

It turns out that the nature is quantum.

And we can describe quantum nature perfectly using quantum system. No entailed problems in there.

We can deal with measured quantum data.

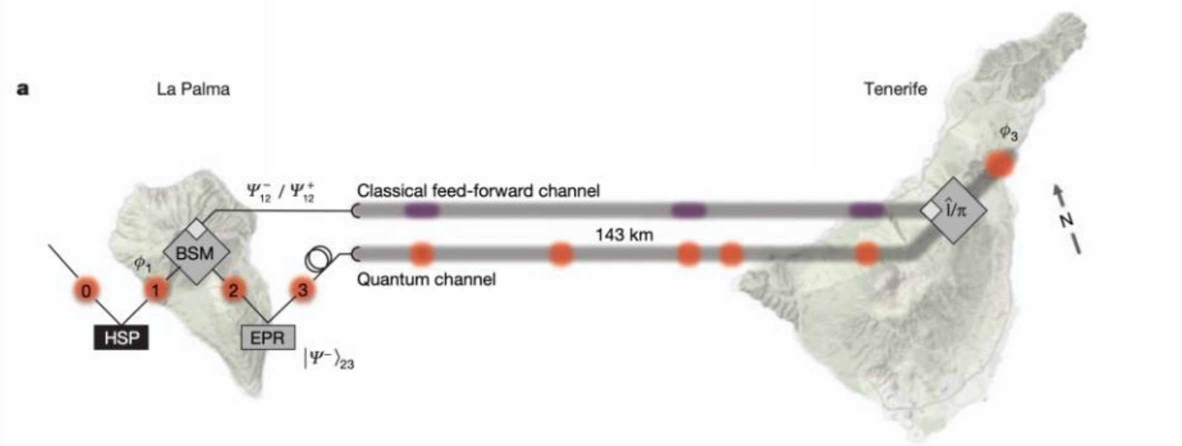
Superposition and Entanglement

Superposition

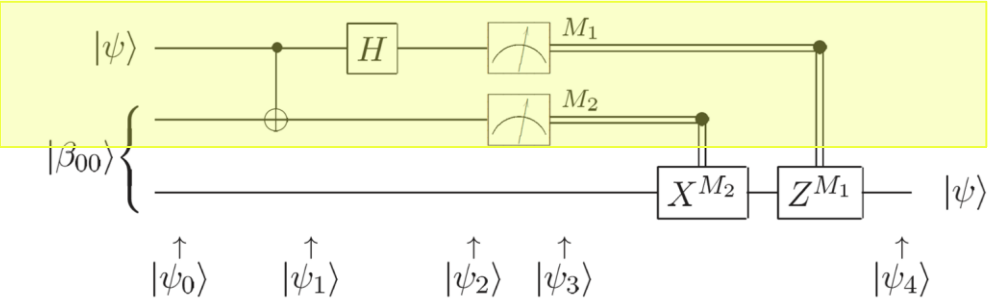
Denser information -> Solving complex problems

Entanglement

Quantum teleportation



1 Qbit teleportation by *Charles H. Bennett*



$$|\psi_0\rangle = |\psi\rangle|\beta_{00}\rangle$$

$$= \frac{1}{\sqrt{2}}\left[\alpha|0\rangle(|00\rangle + |11\rangle) + \beta|1\rangle(|00\rangle + |11\rangle)\right]$$

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\left[\alpha|0\rangle(|00\rangle + |11\rangle) + \beta|1\rangle(|10\rangle + |01\rangle)\right].$$

$$|\psi_2\rangle = \frac{1}{2}\Big[|00\rangle\left(\alpha|0\rangle + \beta|1\rangle\right) + |01\rangle\left(\alpha|1\rangle + \beta|0\rangle\right) + |10\rangle\left(\alpha|0\rangle - \beta|1\rangle\right) + |11\rangle\left(\alpha|1\rangle - \beta|0\rangle\right)\Big]$$

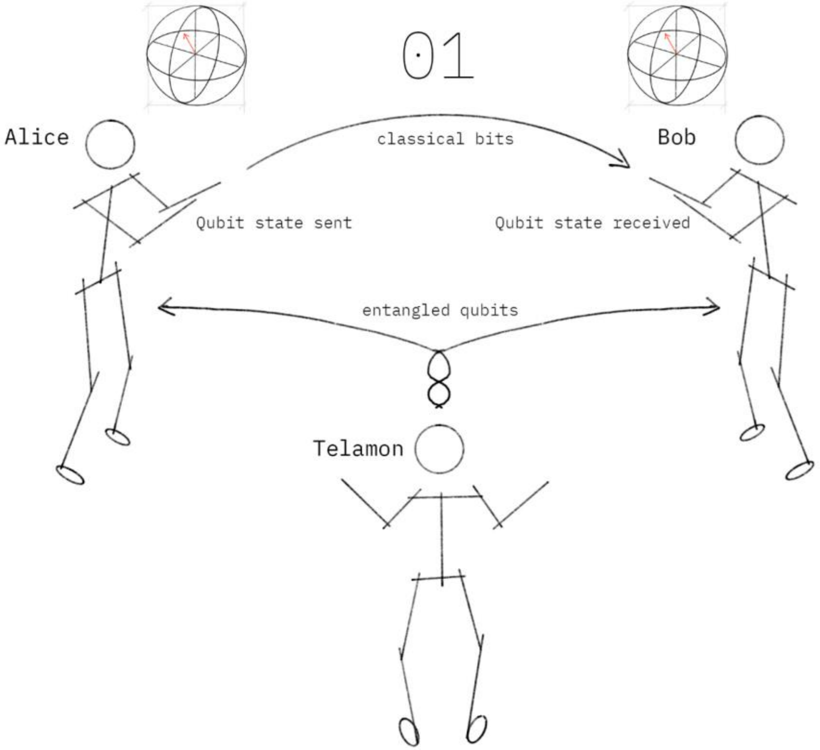
$$00 \longmapsto |\psi_3(00)\rangle \equiv \left[\alpha|0\rangle + \beta|1\rangle\right]$$

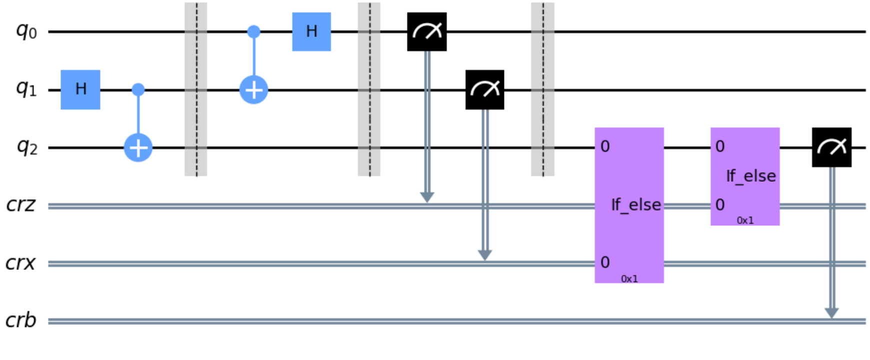
$$01 \longmapsto |\psi_3(01)\rangle \equiv \left[\alpha|1\rangle + \beta|0\rangle\right]$$

$$10 \longmapsto |\psi_3(10)\rangle \equiv \left[\alpha|0\rangle - \beta|1\rangle\right]$$

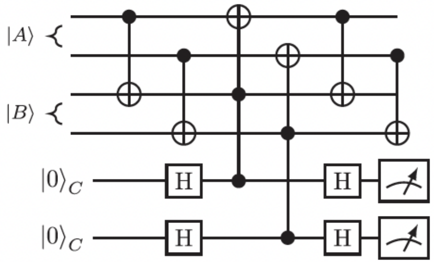
$$11 \longmapsto |\psi_3(11)\rangle \equiv \left[\alpha|1\rangle - \beta|0\rangle\right]$$

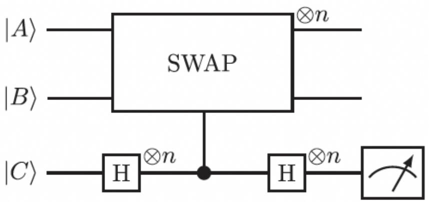
1 Qbit transportation simulation circuit





Quantum verification protocol





Anticipated result when two quantum information entangled.

$$P(|00\rangle_C) = \frac{3}{4},$$

$$P(|01\rangle_C) = 0,$$

$$P(|10\rangle_C) = 0,$$

$$P(|11\rangle_C) = \frac{1}{4}.$$

Gate operation result after two H gate.

$$|\Psi\rangle = \frac{1}{2}[(|\phi\rangle_A|\psi\rangle_B + |\psi\rangle_A|\phi\rangle_B)|0\rangle_C + (|\phi\rangle_A|\psi\rangle_B - |\psi\rangle_A|\phi\rangle_B)|1\rangle_C].$$

Gate operation result after two H gate.

$$\begin{aligned}|\Psi\rangle = \frac{1}{4}\sum_{ijrs}|ij\rangle_A|rs\rangle_B\,[&(A_{ij}B_{rs} + A_{is}B_{rj} + A_{rj}B_{is} + A_{rs}B_{ij})|00\rangle_C,\\ &+ (A_{ij}B_{rs} - A_{is}B_{rj} + A_{rj}B_{is} - A_{rs}B_{ij})|01\rangle_C,\\ &+ (A_{ij}B_{rs} + A_{is}B_{rj} - A_{rj}B_{is} - A_{rs}B_{ij})|10\rangle_C,\\ &+ (A_{ij}B_{rs} - A_{is}B_{rj} - A_{rj}B_{is} + A_{rs}B_{ij})|11\rangle_C\,].\end{aligned}$$