Entanglement Swapping

Group 12

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Qubits

What exactly are qubits?

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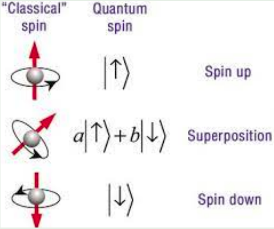
- It is the quantum version of the classic binary bit physically realized with a two-state device.
- Qubit is the superposition of both the bits simultaneously.A qubit is a two-state (or two-level) quantum-mechanical system.

Examples

spin of electron where spin can be up and down at the same time.



Qubits

How many bits are in a qubit?

- Each qubit consist of two bits 0 and 1.

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- In general n qubits can have $2^n possiblestates$.

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- These vectors are usually denoted as $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} and |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.
- They are written in the conventional Dirac—or "bra–ket"—notation; the $|0\rangle and |1\rangle, pronounced" ket0" and" ket1", respectively$.

Qubits

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- Qubit basis states can also be combined to form product basis states.
- A set of qubits taken together is called a quantum register.

4-D reperentation of 2 quantum bits.

four-dimensional linear vector space spanned by the following product basis states: $|00\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, |01\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, |10\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, and|11\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}.$

- n qubits are represented by a superposition state vector in $2^n dimensionalHilbertspace.$

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Quantum entanglement

Quantum technologies are based on several engineering applications of the different quantum principles: superposition (quantum computing), entanglement (networking, quantum key distribution), illumination (quantum radar) and so on.

Examples

Consider a case where you are given 2 small boxes, one containing burger and one containing hot dog. When you open one box, and see that it contains burger, you directly infer that the other box contains a hot dog. This means that the burger and hot dog are entangled in a certain way.

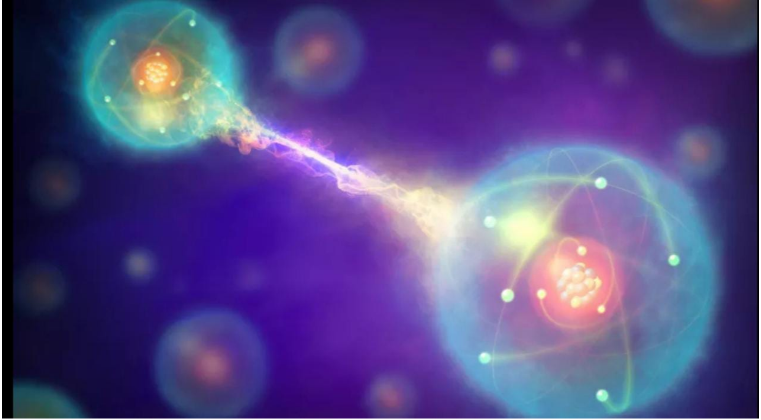

Figure: An image of a entanglement

Quantum entanglement

Quantum entanglement can be referred to as some sort of correlation that exists between two particles in quantum realm. When two particles, such as a pair of photons or electrons, become entangled, they remain connected even when separated by vast distances.

So observations of one of the particles can automatically provide information about the other entangled particles, regardless of the distance between them. And any action to one of these particles will invariably impact the others in the entangled system.

Remark

When two or more particles link up in a certain way, no matter how far apart they are in space, their states remain linked. That means they share a common, unified quantum state.

Quantum entanglement - History

The first physicist to use the word "entanglement" was Erwin Schrödinger, one of the founders of quantum mechanics. He described entanglement as the most essential aspect of quantum mechanics, saying its existence is a complete departure from classical lines of thought.

Creating Quantum entanglement

There are many ways to entangle particles. One method is to cool the particles and place them close enough together so that their quantum states (representing the uncertainty in the position) overlap, making it impossible to distinguish one particle from the other. Another way is to rely on some subatomic process, like nuclear decay, that automatically produces entangled particles. According to NASA, it's also possible to create entangled pairs of photons, or particles of light, by either splitting a single photon and generating a pair of photons in the process, or by mixing pairs of photons in a fiber-optic cable.

Uses of quantum entanglement

Perhaps the most widely used application of quantum entanglement is in cryptography. According to Caltech Magazine, in this scenario, a sender and a receiver build a secure communication link that includes pairs of entangled particles.
The sender and receiver use the entangled particles to generate private keys, known only to them, that they can use to encode their messages. If someone intercepts the signal and attempts to read the private keys, the entanglement breaks, because measuring an entangled particle changes its state. That means the sender and receiver will know that their communications have been compromised.

Uses of quantum entanglement

Another application of entanglement is quantum computing, in which large numbers of particles are entangled, thereby allowing them to work in concert to solve some large, complex problems.
For example, a quantum computer with just 10 qubits (quantum bits) can represent the same amount of memory as $2^10 traditionalbits$.

Quantum Entanglement teleportation

Contrary to the usual use of the word "teleport," quantum teleportation does not involve the movement or translation of particles themselves. Instead, in quantum teleportation, information about one quantum state is transported great distances and replicated somewhere else.

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Types of Entanglement

Quantum Entanglement comes in two types:

- Bipartite Entanglement

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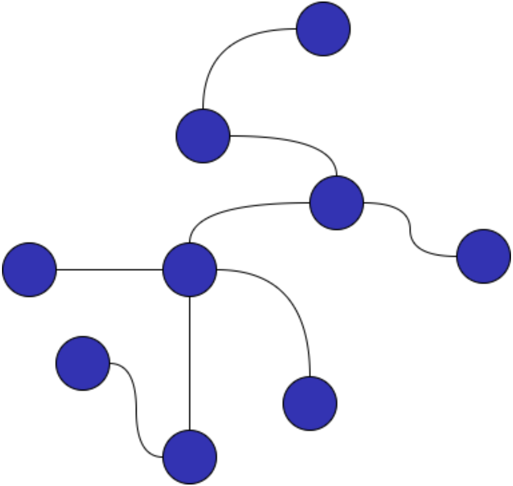
- Bipartite Entanglement
- Multipartite Entanglement

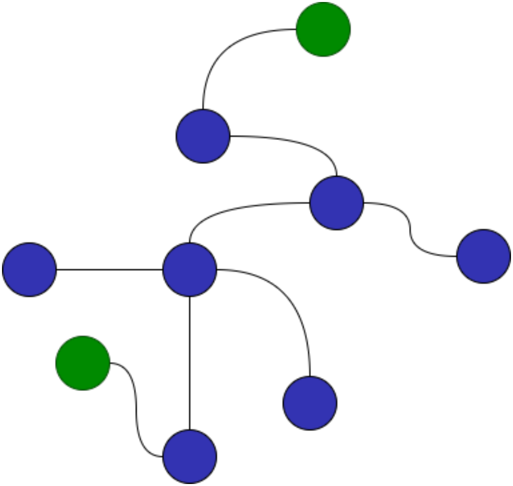
Bipartite Entanglement

Consider a quantum network:



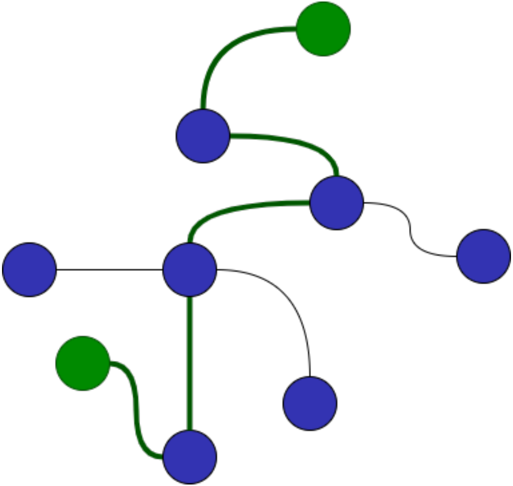
Bipartite Entanglement

Suppose a method of quantum communication must be established between the highlighted nodes.



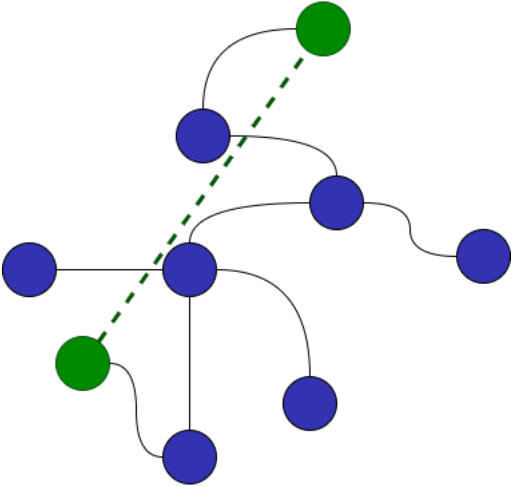
Bipartite Entanglement

Entanglement swapping is conducted using the highlighted physical links



Bipartite Entanglement

And like that, The two nodes can share an entangled pair.



Challenges with QKD

With quantum communication comes the need for secure transfer of information.

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Encryption of messages entails the need for Quantum Key Distribution (QKD).

Challenges with QKD

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- Only then can the network ensure a fully correlated key.

Challenges with QKD

Secure entanglement-based QKD assumes maximally entangled states because:

- Only then can the network ensure a fully correlated key.
- Eavesdroppers can find information about the key otherwise.

Metrics for entanglement quality

To ensure a maximally entangled state a measure of the level of entanglement is required.

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This can be done by using the following function:

$$\psi - \text{Reference State}, \ \rho - \text{Actual State}$$

$$F(\rho, \psi) = \psi \rho \psi$$

Metrics for entanglement quality

Consider, though, an orthogonal state.

$$\rho = \phi^{-}\phi^{-}$$

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Consider, though, an orthogonal state.

$$\rho = \phi^- \phi^-$$

$$\begin{aligned} F(\rho, \phi^+) &= \phi^+ \rho \phi^+ \\ &= \phi^+ \phi^- \phi^- \phi^+ \\ &= 0 \end{aligned}$$

Even though, the state is entangled and can be used to communicate. Hence, Fidelity cannot be used.

The CSHS Inequality

Instead we can use the CSHS Inequality to check the quality of entanglement.
Consider,

$$
\begin{aligned}
A_1 &= Z \\
A_2 &= X \\
B_1 &= \frac{Z - X}{\sqrt{2}} \\
B_2 &= \frac{Z + X}{\sqrt{2}}
\end{aligned}
$$

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$$A_1 = Z$$
$$A_2 = X$$
$$B_1 = \frac{Z - X}{\sqrt{2}}$$
$$B_2 = \frac{Z + X}{\sqrt{2}}$$

Then the CSHS Inequality is

$$S = |\langle A_1 B_1 \rangle + \langle A_1 B_2 \rangle + \langle A_2 B_1 \rangle - \langle A_2 B_2 \rangle|$$

The CSHS Inequality

For Entanglement Quality

If $S > 2$, the state is entangled.
If $S = 2\sqrt{2}$, the state is maximally entangled.
If $S \leq 2$, the test was inconclusive.

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Multipartite Entanglement

We seen bipartite entanglement.

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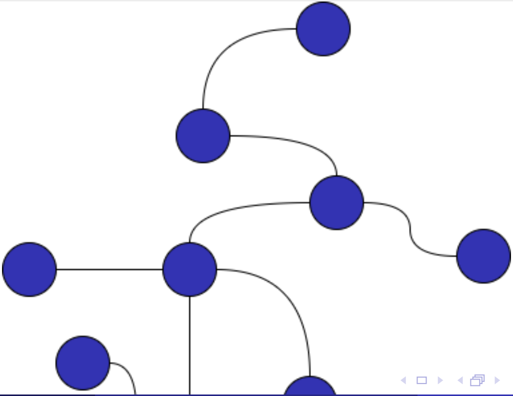
We seen bipartite entanglement. where we have one quantum network of n qubits and we are focusing entanglement between 2 qubits.

Multipartite entanglement

same as discovering entanglement between n qubits called n-partite entanglement so multipartite entanglement is between more than 2 qubits.



Multipartite Entanglement

Let suppose first we see tripartite entanglement which means we are dealing with 3 qubits.

Example

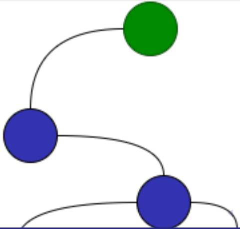
so all possible states are: 000 , 001 , 010 , 011 , 100 , 101 , 110 , 111

Example

for n there are

$$2^n$$

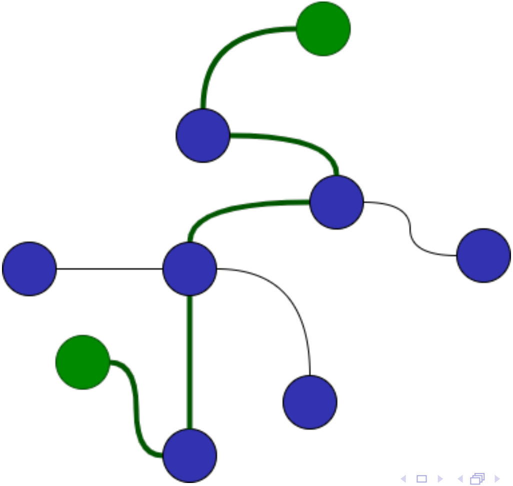
possible states.



Multipartite Entanglement

Let we discuss 2 states with 3 qubits.

- GHZ state.



Multipartite Entanglement

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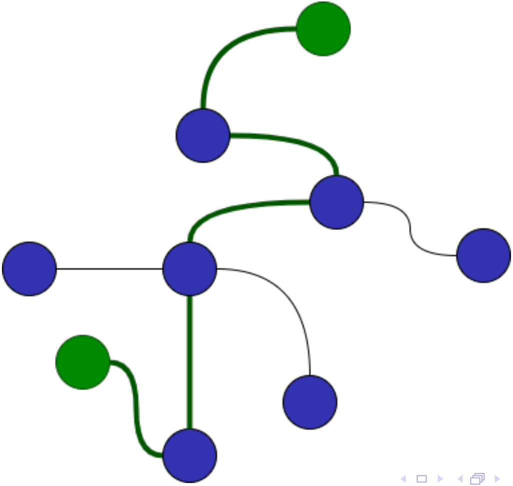
- GHZ state.
- W state.

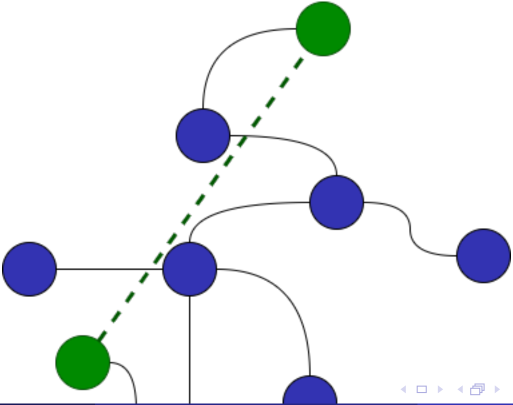


here in 3 qubits we have 8 choices but the basis in GHZ is 000 , 111. so

$$|GHZ >= 2^{-1/2}(|000 > +|111 >)$$

here consider for 1 qubit in Z basis

- prob+1 $= 1/2$ for state 000 .



Multipartite Entanglement , GHZ state

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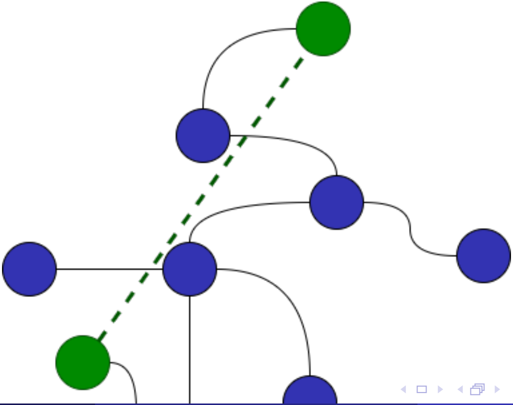

Multipartite Entanglement , GHZ state

so the thing is here if we consider only one qubit than entire entanglement are destroyed because it is depend on all three qubit there for GHZ states are important. eg. we can make security system

Multipartite Entanglement , W state

here in 3 we have 8 choices but the basis in W is 001 , 010 , 100. so

$$|W >= 3^{-1/2}(|001 > +|010 > +|100 >)$$

here consider for 1 qubit in Z basis

- prob$+1 = 2/3$ for state 001 , 011 . so pair is 0 psi$+$

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- prob+1 = 2/3 for state 001 , 011 . so pair is 0 psi+
- prob-1 = 1/3 for state 100 .

Multipartite Entanglement , W state

so the thing is here if we consider only one qubit than entire entanglement are not destroyed because it is depend entanglement on only two qubits. so if 2 qubits are in entangled state than 3rd qubit are weak entangled with other two.

- qubit 1 and 2 are entangled than state is phi+ 12 psi3

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- qubit 1 and 2 are entangled than state is phi+ 12 psi3
- qubit 3 and 2 are entangled than state is phi+ 32 psi1
- qubit 1 and 3 are entangled than state is phi+ 13 psi2

Multipartite Entanglement

now let see both state for n-partite entanglement. here we have

$$2^n$$

possible states.

Multipartite Entanglement , GHZ state

here in n qubits we have

$$2^n$$

choices but the basis in GHZ is 000...0 , 111...1 . so

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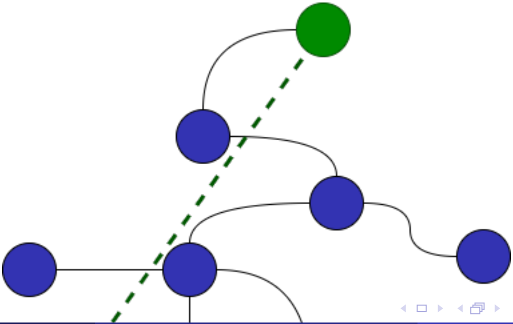
- prob+1 = 1/2 for state 000...0 .



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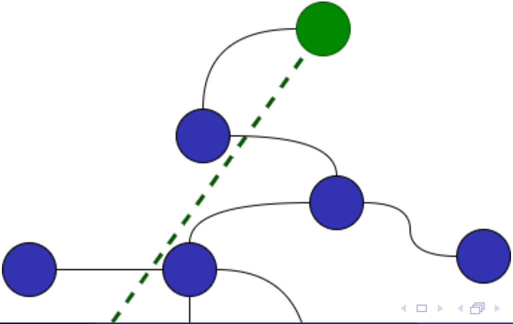

Multipartite Entanglement , W state

here in 3 we have 8 choices but the basis in W is 0..001 , 0..010 , 0..100 , ... , 1..000 . so

$$|W >= n^{-1/2}(|0..001 > +|0..010 > +|0..100 > +... + |1..000 >)$$

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Establishing Entanglement

It is crucial for the physical realization of quantum information networks to first establish entanglement among multiple space-separated quantum memories and then, at a user-controlled moment, to transfer the stored entanglement to quantum channels for distribution and conveyance of information.
Flying photons or bright optical beams are the best natural quantum channels, while usually matter systems are employed for memories at quantum nodes.
At first, a tripartite optical entangled state is off-line prepared, and then the entanglement is transferred into three atomic ensembles located at some distance from each other via electromagnetically induced transparency interaction.

Establishing Entanglement

After a given storage time, the preserved atomic entanglement is controllably released into three separated quantum channels consisting of three entangled optical submodes.
The dependence of entanglement among three released optical submodes on systematic parameters is theoretically deduced and multipartite entanglement transfer as well as storage are experimentally proved.
Since the tripartite optical entangled state is generated by linearly optical transformation of three squeezed states of light, its three submodes are naturally space separated.
The presented scheme can be directly extended to generate optical entangled states with more submodes if more squeezed states of light are available.
In this way, entanglement of more atomic ensembles can be established.

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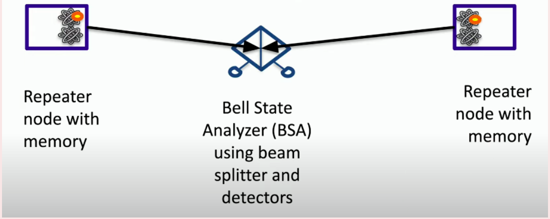
Distance Swapping

For long-distance communication, the only viable communication approach is teleportation of quantum states, which requires a prior distribution of entangled pairs (EPs) of qubits. Establishment of EPs across remote nodes can incur significant latency due to the low probability of success of the underlying physical processes. Usually some photons are lost during travel through optical fibres or other devices. This is the reason why probability of success in distance swapping is low.

Distance Swapping

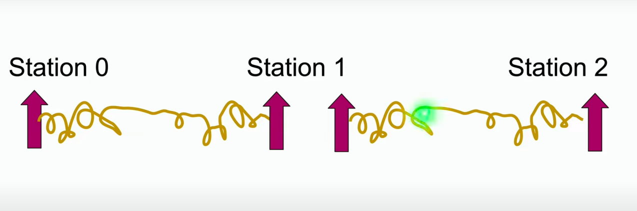
Midpoint interference



Condiser two nodes with quantum memory . we wish to transfer information from one node to another. In the center we have a bell state analyzer.Now in the next step these atoms are made to generate a photon.These photons are collected into the fibre that lead to the repeater(bell state analyzer). when the left and the right photon arrives at the center bell state measurement takes place. this ends up photons in one of the bell state. in this way we established entanglement between both the nodes.

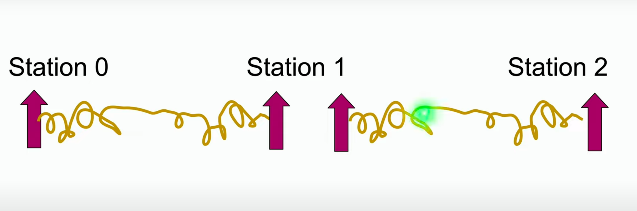
Distance Swapping

let us consider an example:-



Station 0 has a qubit entangled with a qubit of station 1 and station 1 has a different qubit entangled with a qubit of station 2.

Distance Swapping

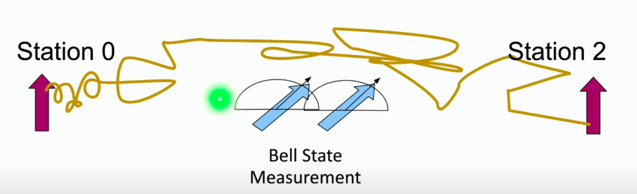


Now , we wish to establish entanglement between station 0 and station 2.

Bell State

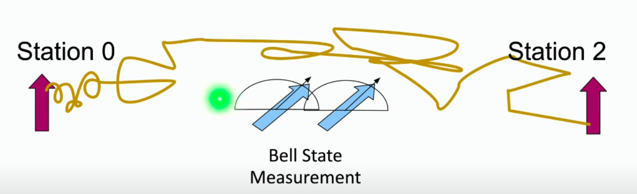
Bell state measurement is the crucial step in quantum teleportation. The result of a Bell state measurement is used by one's co-conspirator to reconstruct the original state of a teleported particle from half of an entangled pair (the "quantum channel") that was previously shared between the two ends.

Distance Swapping



What we can do is,we can perform a bell state measurement at station 1 and depending upon the outcome we establish end to end long distance entanglement between station 0 and station 1.

Distance Swapping



What we can do is,we can perform a bell state measurement at station 1 and depending upon the outcome we establish end to end long distance entanglement between station 0 and station 1.

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Quantum Network

In a very simple picture a Quantum Network is essentially a set of small quantum computers connected by quantum channels so they can exchange qubits and they can generate entanglement between each other.
The fundamental operation in quantum networks is to generate quantum entanglements , which you can use to send qubits via quantum teleportation between physically separated quantum processors.

Quantum Network

Quantum networks work in a similar way to classical networks. The main difference is that quantum networking, like quantum computing, is better at solving certain problems, such as modeling quantum systems.

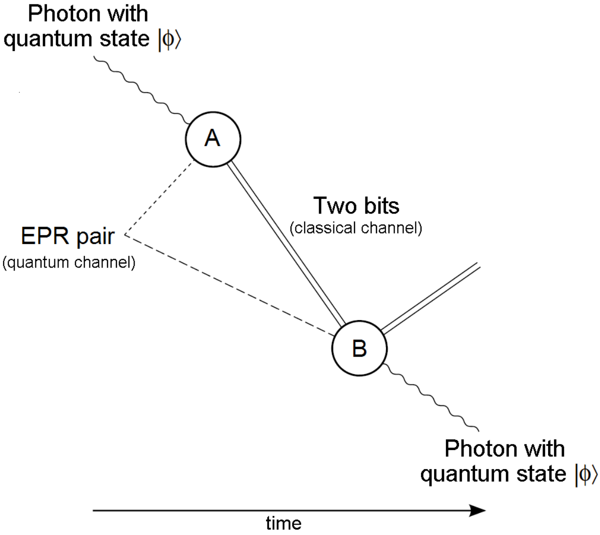

Figure: An image of a Quantum teleportation over a Quantum Network

Elements of Quantum Network

End Nodes: Quantum Processors

- End nodes can both receive and emit information

Elements of Quantum Network

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- Their chief advantage is that they can store and re-transmit quantum information without disrupting the underlying quantum state. The quantum state being stored can either be the relative spin of an electron in a magnetic field or the energy state of an electron.

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End Nodes: Quantum Processors

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- Their chief advantage is that they can store and re-transmit quantum information without disrupting the underlying quantum state. The quantum state being stored can either be the relative spin of an electron in a magnetic field or the energy state of an electron.
- One way of realizing such end nodes is by using color centers in diamond, such as the nitrogen-vacancy center.NV centres is one of the numerous point defects in Diamond.An individual NV center can be used as a qubit. They esentially have an electron which you can entangle with other electron in another NV center and around the NV center there are carbon spins which you can use to store the qubits and further they have a very long coherence time. This system forms a small quantum processor featuring several qubits. NV centers can be utilized at room temperatures.Another example are Ion Traps.

Elements of Quantum Network

Communication lines: physical layer

- Over long distances, the primary method of operating quantum networks is to use optical networks and photon-based qubits. This is due to optical networks having a reduced chance of decoherence. Optical networks have the advantage of being able to re-use existing optical fiber

Elements of Quantum Network

Communication lines: physical layer

- Over long distances, the primary method of operating quantum networks is to use optical networks and photon-based qubits. This is due to optical networks having a reduced chance of decoherence. Optical networks have the advantage of being able to re-use existing optical fiber
- Alternately, free space networks can be implemented that transmit quantum information through the atmosphere or through a vacuum.

Elements of Quantum Network

Repeaters

- Long-distance communication is hindered by the effects of signal loss and decoherence inherent to most transport mediums such as optical fiber. In classical communication, amplifiers can be used to boost the signal during transmission, but in a quantum network amplifiers cannot be used since qubits cannot be copied – known as the no-cloning theorem.

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- A true quantum repeater allows the end to end generation of quantum entanglement, and thus - by using quantum teleportation - the end to end transmission of qubits.
- Quantum repeaters allow entanglement and can be established at distant nodes without physically sending an entangled qubit the entire distance.

Noise in Quantum Network

- Noise can be considered the natural enemy of quantum information. Until now, it has always stood in the way of quantum communication outside of research laboratories. This is because one of the most important quantum phenomena, entanglement, which is characterized by strong correlations between particles over arbitrary distances and forms the basis for the advantages of quantum communication over conventional methods, is considered to be particularly susceptible to any disturbances from the environment. Even a minor interaction with the environment can lead to the destruction of entanglement.

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- High-dimensional entanglement reduces noise

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SimulaQron

A simulator for developing quantum internet software

- While many simulators exist for local quantum processors, there is presently no simulator for a quantum internet tailored towards software development. Quantum internet protocols require both classical as well as quantum information to be exchanged between the network nodes, next to the execution of gates and measurements on a local quantum processor. This requires quantum internet software to integrate classical communication programming practises with novel quantum ones

SimulaQron

A simulator for developing quantum internet software

- While many simulators exist for local quantum processors, there is presently no simulator for a quantum internet tailored towards software development. Quantum internet protocols require both classical as well as quantum information to be exchanged between the network nodes, next to the execution of gates and measurements on a local quantum processor. This requires quantum internet software to integrate classical communication programming practises with novel quantum ones
- SimulaQron is built to enable application development and explore software engineering practises for a quantum internet.

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- Each simulated processor may thereby run on a different classical computer, and supports the execution of local quantum gates and measurements, as well as commands for sending qubits to remote nodes.

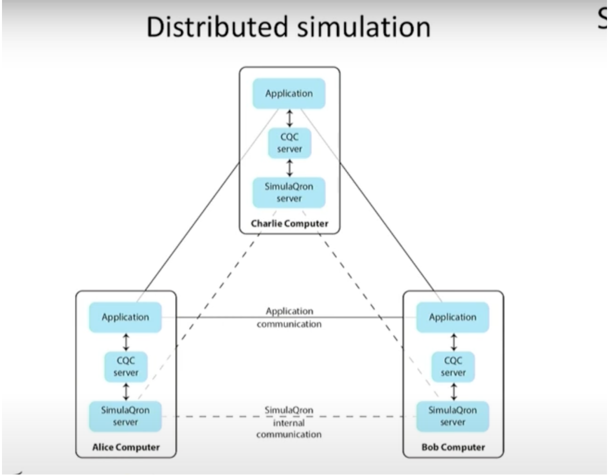

Figure: An image of a SimulaQron Distributed Simulation

SimulaQron

SimulaQron features a modular design that performs a distributed simulation based on any existing simulation of a quantum computer capable of integrating with Python. Programming libraries for Python and C are provided to facilitate application development.

Internal Working of SimulaQron

Let us here briefly sketch how the SimulaQron backend works internally. But Before that we need to know what's a Virtual Quantum Node.

- A virtual quantum node is a server program running on a particular computer that pretends to be quantum hardware, simulating qubits and quantum communication. That is, you may think of these nodes as fake hardware programmable directly via SimulaQron's native interface. Each node presents a number of virtual qubits for you to use. These virtual qubits would correspond to the physical qubits available at this node in a real physical implementation of the quantum network node. By connecting to the virtual quantum node server, a client program that depends on using quantum hardware, may manipulate these qubits as if they were local physical qubit and also instruct to send them to remote nodes. The virtual quantum node servers are identified by their common names (eg Alice, Bob, Charlie), and amongst themselves connect classically to form a virtual simulation network as a backend.

Internal Working of SimulaQron

- An important internal element in SimulaQron is the distinction between virtual qubits and simulated qubits. Virtual qubits are the qubits as they would be present in real quantum hardware. A virtual qubit is local to each virtual quantum node server and may be manipulated there. Each virtual qubit is simulated somewhere, by a simulated qubit. Importantly, this simulated qubit may be located at a different simulating node than the node holding the corresponding virtual qubit. To see why this is necessary, note that entangled qubits cannot be locally represented by any form of classical information (hence the quantum advantage of entanglement in the first place!). As such, if two (or more) virtual nodes share qubits which are somehow entangled with each other, then these qubits will actually need to be simulated at just one of these nodes. That is, they appear to be virtually local (as if they were real physical qubits), yet they are actually simulated at just one of the network nodes.

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- virtualQubit - this is the object representing a virtually local qubit. This carries information about the remote simulating qubit. These virtualQubit objects can in turn be accessed by the clients who can access these virtual qubits as if they were real local physical qubits without having to know where they are actually simulated.

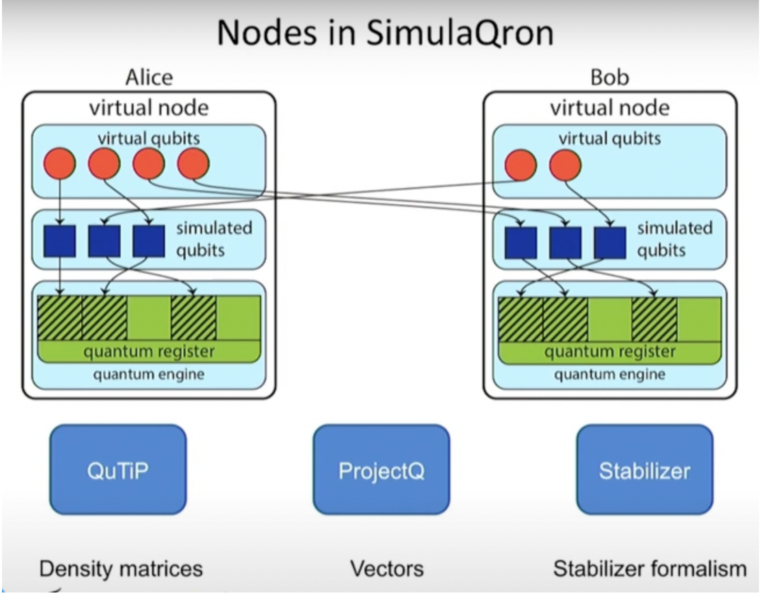

Figure: An image of SimulaQron