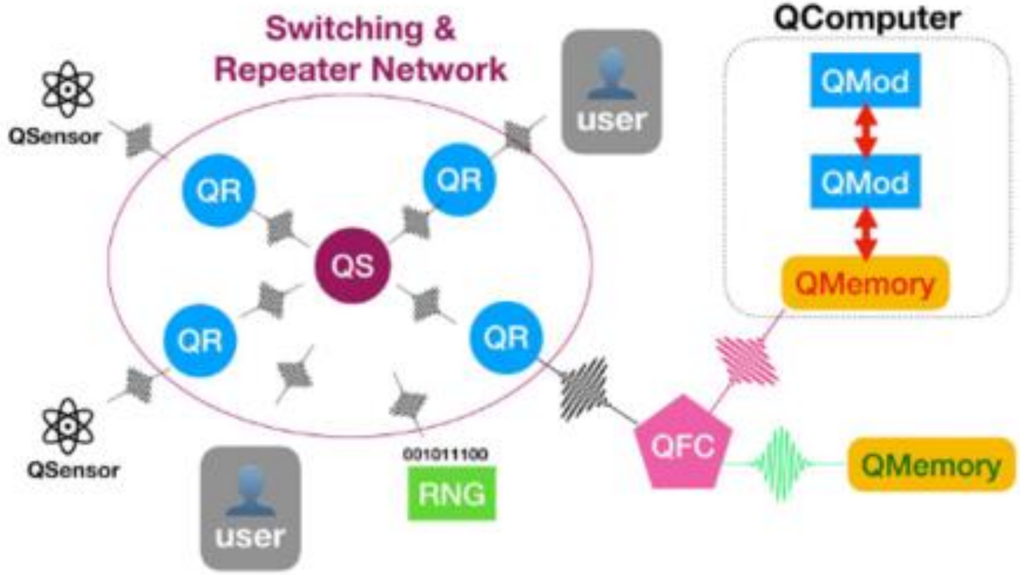
บทที่ 6 AN INTRODUCTION TO QUANTUM NETWORKING

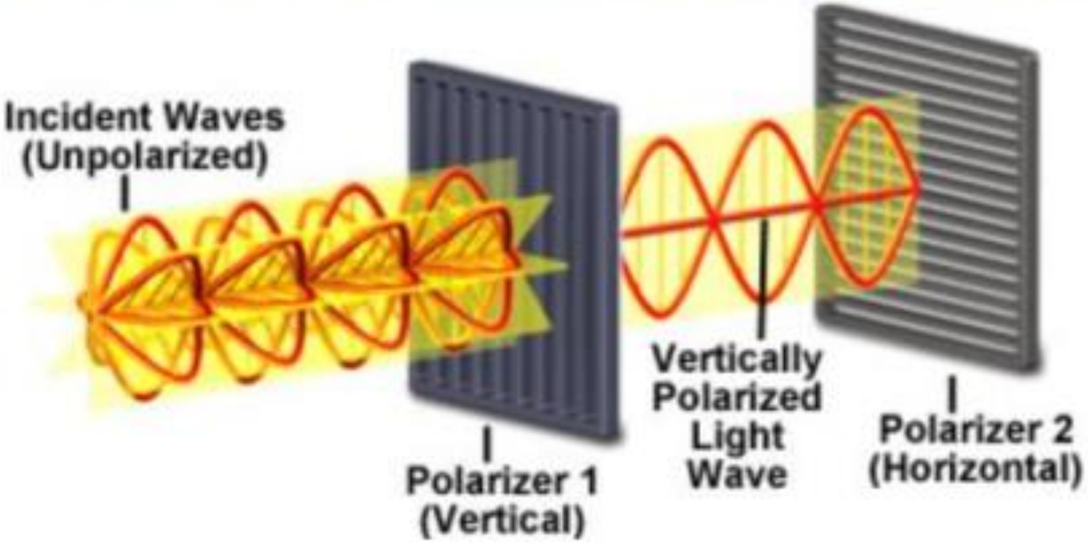


ผู้ช่วยศาสตราจารย์จุฑาวุฒิ จันทรมาลี

หลักสูตรวิทยาศาสตรบัณฑิต สาขาวิชาวิทยาการคอมพิวเตอร์
คณะวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยสวนดุสิต

Photonic Qubits

- Photons can represent Qubits, as well as electrons
- Photons are more conducive to quantum networking than electrons
  - electrons are more conducive to computing
- The logical states of 0 or 1 are not determined by the spin of photons, but rather by their polarization
  - Horizontal Polarization |1⟩
  - Vertical Polarization |0⟩



What Happens When Two Waves Intersect?

- When two waves intersect, the resulting displacement of the medium at any location is the *algebraic sum* of the displacements of the individual waves at that same location
- Therefore, another algebraic operation (specifically, a subtraction) can completely reverse the effects of the intersection

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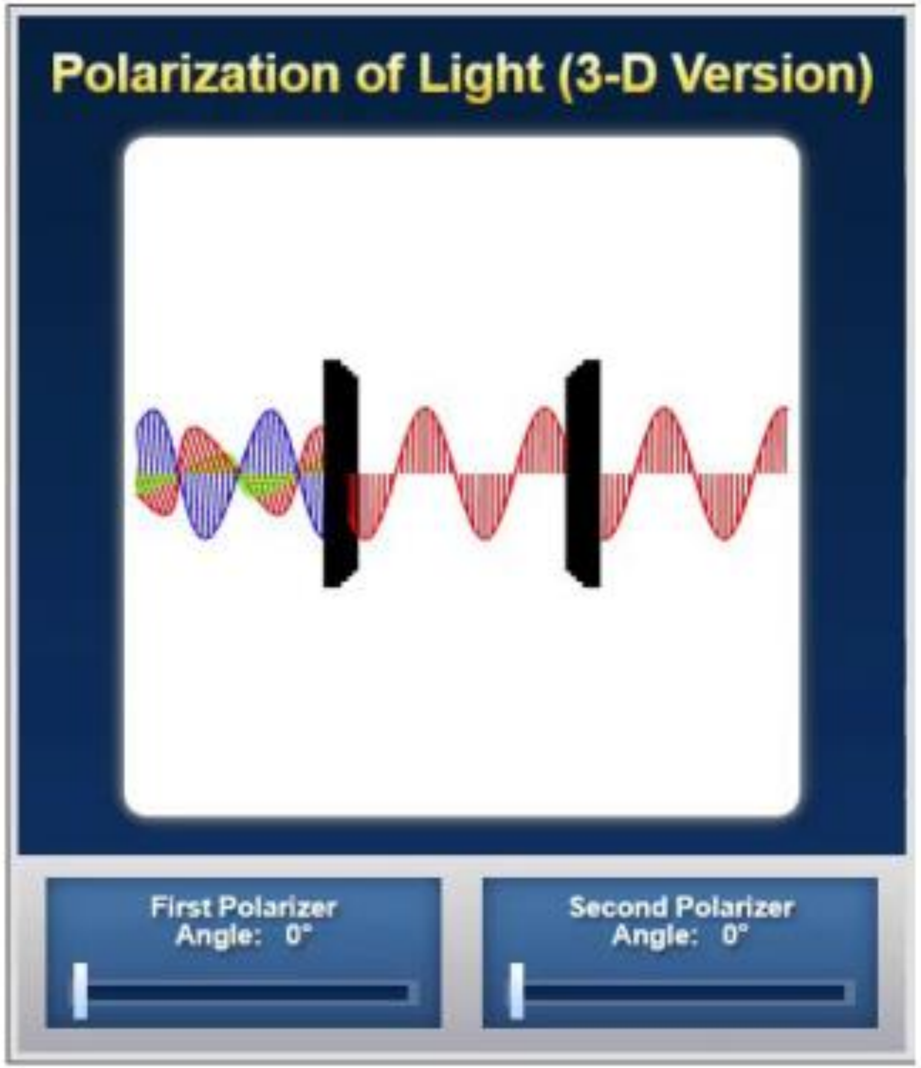
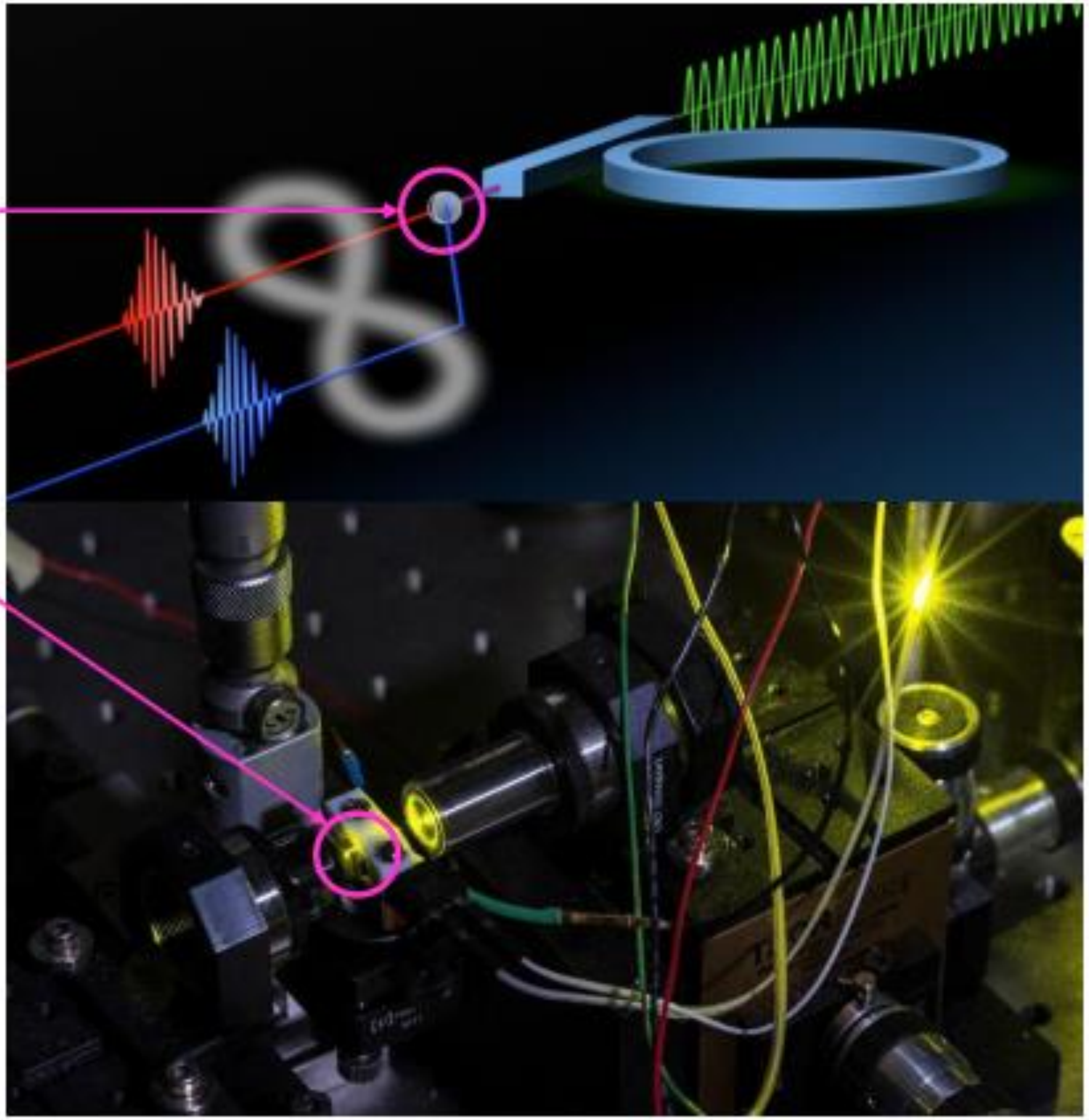


https://www.olympus-lifescience.com/en/microscope-resource/primer/java/polarizedlight/3dpolarized/

How Are Photons Entangled?

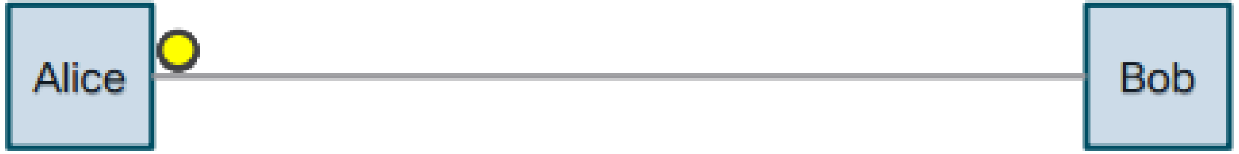
- The most common approach to generate entangled photons is via **Spontaneous Parametric Down-Conversion** (SPDC) in nonlinear crystals
- SPDC is an instant optical process that converts one photon of higher energy into a pair of photons of lower energy



https://www.nature.com/articles/s41377-021-00537-2
https://spectrum.ieee.org/entanglement-on-a-chip
https://www.nist.gov/image/non-linear-crystal

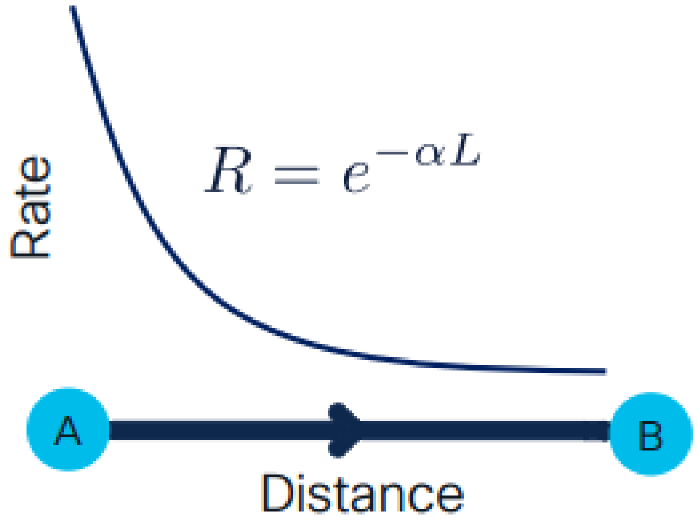
Classical Optical Communication

Quantum Communication via Transporting



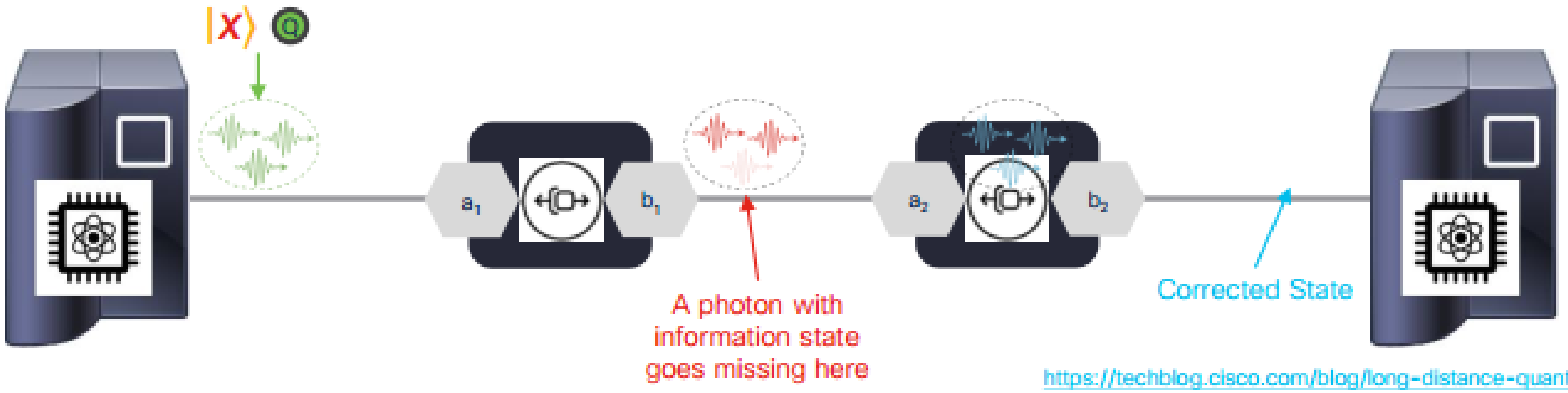
Primary Challenge to Quantum Transport

- Rate decays exponentially with distance
- Can we amplify the signal?
  - No, because of the No Cloning Theorem



(One-Way) Quantum Repeaters

- Quantum Repeaters leverage Quantum Error Correction, where encoded quantum information is transmitted in the form of multi-photon states
  - Parity information is included in the multi-photon state
- Intermediate repeater stations check the incoming state for errors and prepare a fresh encoded qubit as the output to be sent to the next repeater
- This does NOT violate the No Cloning Theorem, as quantum repeaters perform a multi-qubit measurement that does not disturb the quantum information in the encoded state, but rather, retrieves indirect information about a potential error



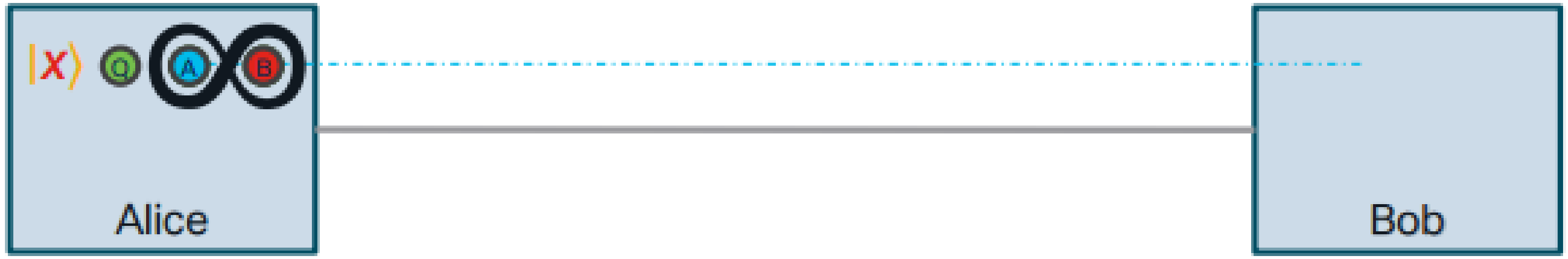
https://techblog.cisco.com/blog/long-distance-quantum-communication

(Two-Way) Quantum Communication via Teleporting

Initial State

Quantum Communication via Teleporting

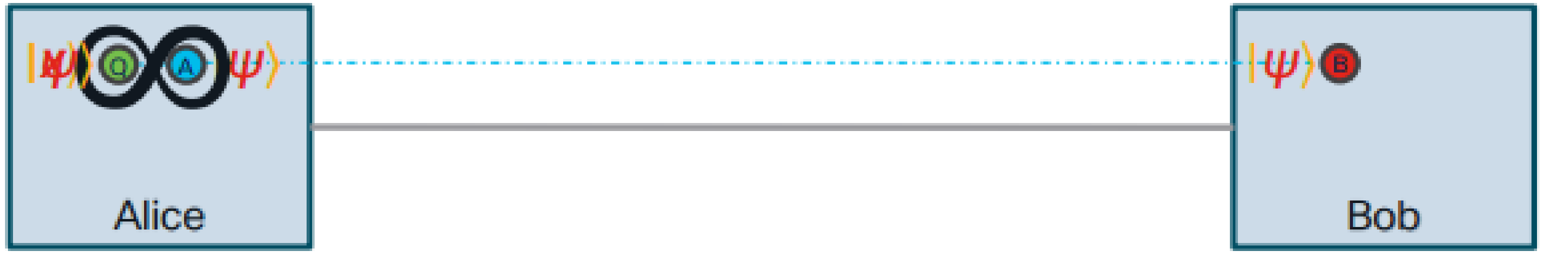
Step 1: Entangle a Pair of Photons and Send One to the Receiver



Quantum Communication via Teleporting

Step 2: Perform Another Entanglement Operation at the Sender

Note: This step results in a teleportation of the ***combination*** of the states of qubits Q and A to qubit B

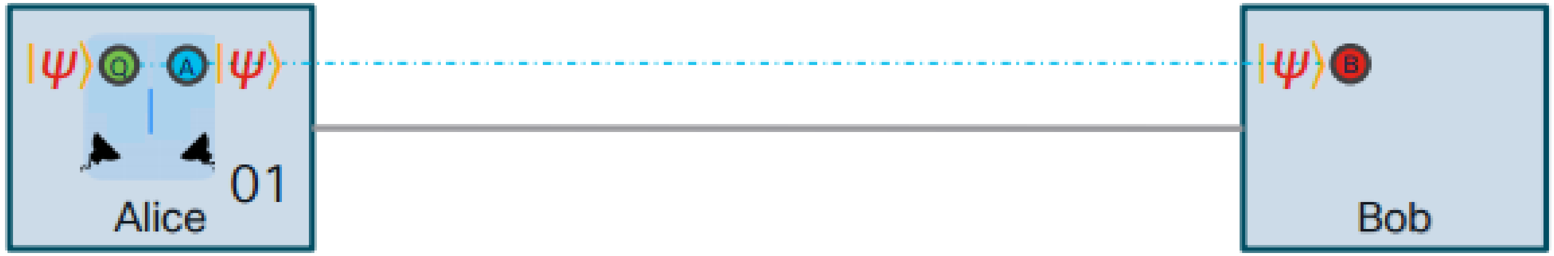


Quantum Communication via Teleporting

Step 3: Perform a Bell State Measurement at the Sender

Note: $\otimes$ is a mathematical notation for a tensor product; that is, a product of two quantum states, $|\psi\rangle$ and $|\Phi\rangle$

Note: The Bell State Measurement simultaneously:
- breaks the three-way entanglement,
- collapses the superpositions of qubits Q and A, and
- produces a result of 1 of 4 Bell States



The Four Bell States:

$|\Phi^+\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|0\rangle + |1\rangle\otimes|1\rangle)$ represented by binary 00

$|\Phi^-\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|0\rangle - |1\rangle\otimes|1\rangle)$ represented by binary 01

$|\psi^+\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|1\rangle + |1\rangle\otimes|0\rangle)$ represented by binary 10

$|\psi^-\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|1\rangle - |1\rangle\otimes|0\rangle)$ represented by binary 11

Quantum Communication via Teleporting

Step 4: Send the Bell State Measurement Result over a Classical Channel

The Four Bell States:

$|\Phi^{+}\rangle = (1/\sqrt{2})\,(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle)$ represented by binary 00

$|\Phi^{-}\rangle = (1/\sqrt{2})\,(|0\rangle \otimes |0\rangle - |1\rangle \otimes |1\rangle)$ represented by binary 01

$|\psi^{+}\rangle = (1/\sqrt{2})\,(|0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle)$ represented by binary 10

$|\psi^{-}\rangle = (1/\sqrt{2})\,(|0\rangle \otimes |1\rangle - |1\rangle \otimes |0\rangle)$ represented by binary 11

Quantum Communication via Teleporting

Step 5: Perform a Correction Operation on the Received Qubit (if necessary)

Note: $|x\rangle$ represents the original state of the qubit, which has now been received in its corrected form

The Four Bell States:

$|\Phi^+\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|0\rangle + |1\rangle\otimes|1\rangle)$ represented by binary 00 → nothing to correct

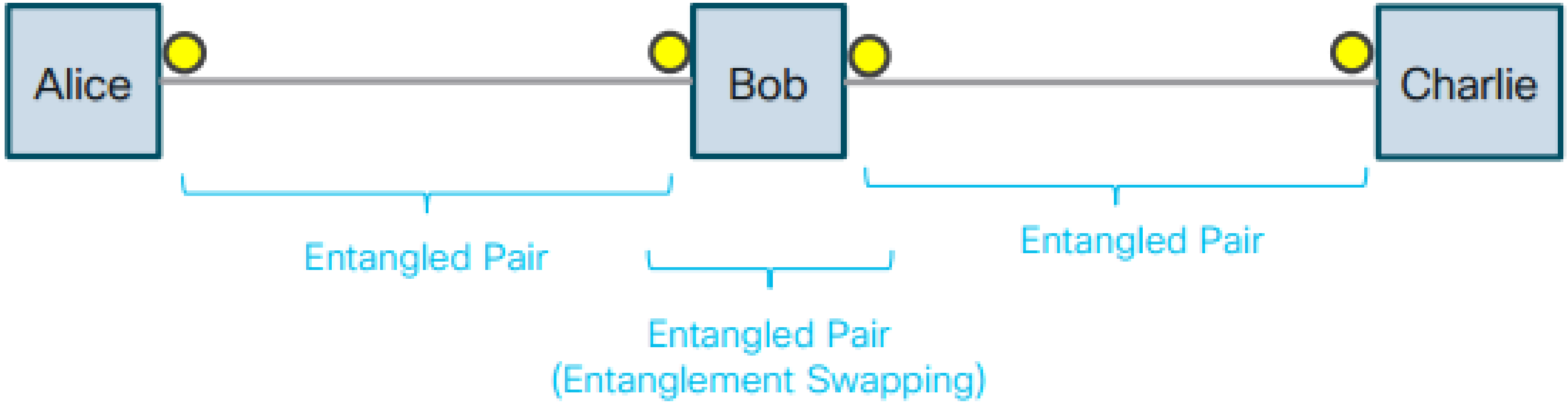
$|\Phi^-\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|0\rangle - |1\rangle\otimes|1\rangle)$ represented by binary 01 → correct x (only)

$|\psi^+\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|1\rangle + |1\rangle\otimes|0\rangle)$ represented by binary 10 → correct z (only)

$|\psi^-\rangle = (1/\sqrt{2})\,(|0\rangle\otimes|1\rangle - |1\rangle\otimes|0\rangle)$ represented by binary 11 → correct (x and z)

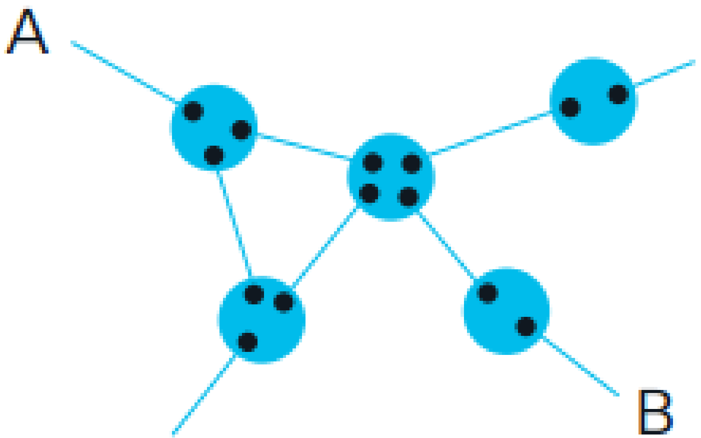
Refer to Bloch Sphere diagram for x,y and z axis

Extending Quantum Teleporting



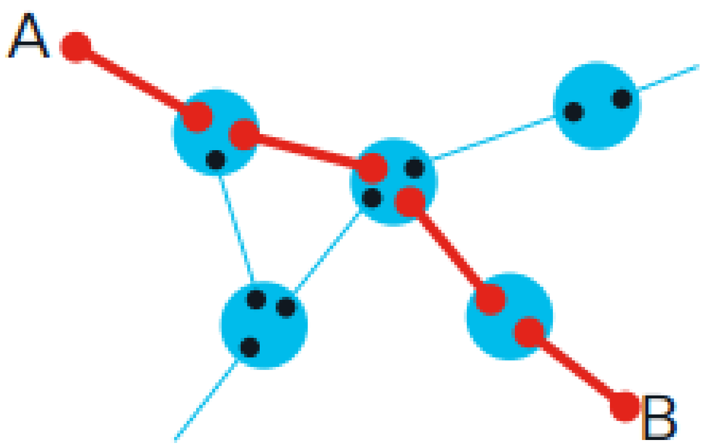
Quantum Routers & Protocols

Two-Way Entanglement Distribution Network Example



Quantum Routers & Protocols

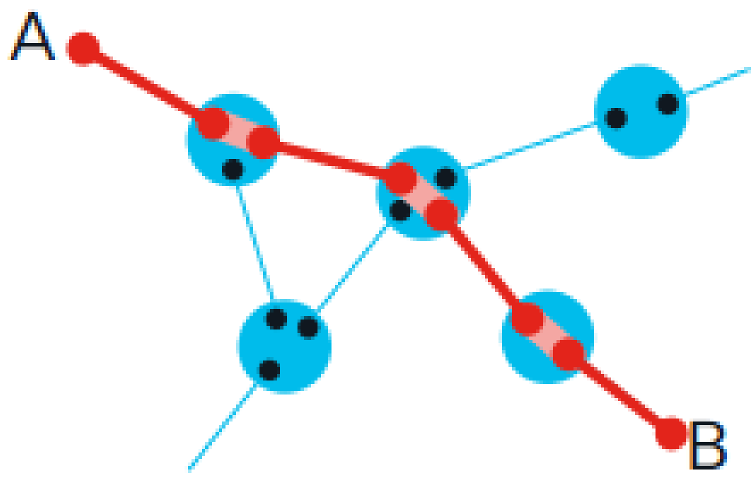
Two-Way Entanglement Distribution Network Example



Elementary link entanglement

Quantum Routers & Protocols

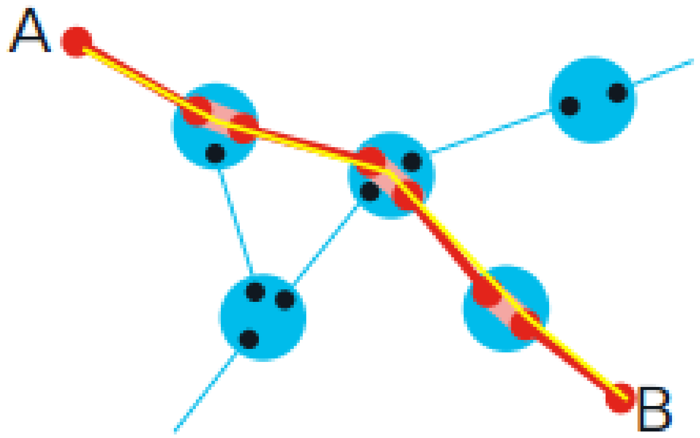
Two-Way Entanglement Distribution Network Example



Elementary swapping

Quantum Routers & Protocols

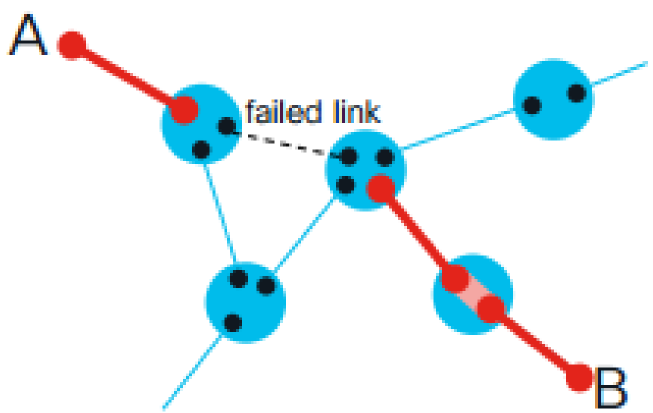
Two-Way Entanglement Distribution Network Example



End-to-end entanglement

Quantum Routers & Protocols

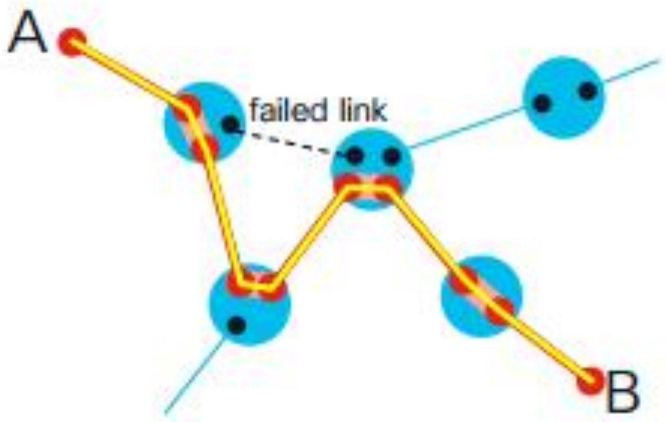
Two-Way Entanglement Distribution Network Example



Network failure event

Quantum Routers & Protocols

Two-Way Entanglement Distribution Network Example

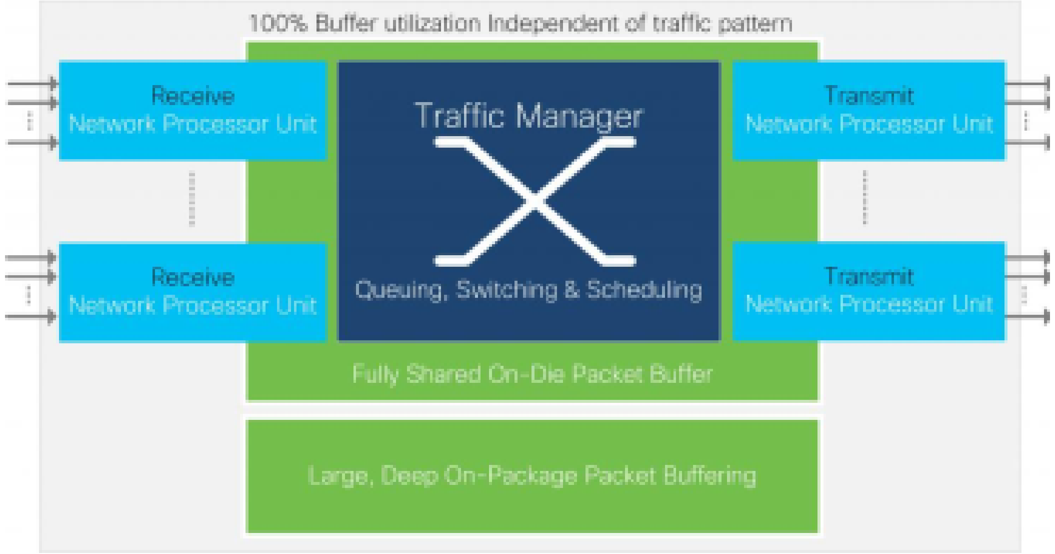


Reestablishing end-to-end entanglement

The Key Role of Memory in a Network Switch

- A major component of any network switch is memory
- Memory enables:
  - Ingress buffering and queuing
  - Switching
  - Egress buffering and queuing

Cisco Silicon One ASIC Architecture

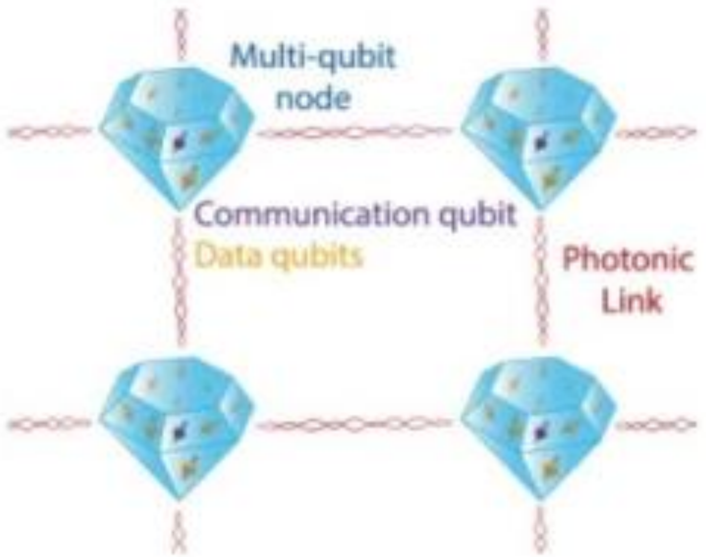


(everything shaded green represents memory)

Note: Cisco Silicon One is **NOT** an ASIC for a quantum switch, but rather is only being used as an example to illustrate how extensive memory is within switching architectures

Quantum Memory Methods and Storage Times

- Optical Quantum Memory
  - milliseconds to seconds.
- Superconducting Qubits
  - microseconds to milliseconds.
- Trapped Ions
  - seconds to minutes
- Note: techniques such as Quantum Error Correction may be employed to extend the effective storage times



An Example of Optical Quantum Memory Using Engineered Diamonds
https://www.nature.com/articles/s41534-022-00637-w

Quantum Networking Challenges by OSI Layer

Application	Cryptography, privacy-preserving computing, enhanced sensing, …
Transport	End-to-end (logical) quantum information transmission
Network Link Physical	Routing, Scheduling Quantum circuit switching Error correction, Purification Transporting/Teleporting qubits Photon loss, channel noise, hardware noise


QUESTIONS
ANSWERS