Quantum Teleportation &Its Application:

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CCL

Contents

Teleportation

- Teleportation = Telecommunication + Transportation
- Teleportation is the hypothetical transfer of *matter* or *energy* from one point to another without traversing the physical space between them
- Teleportation is commonly portrayed in science fiction

Dr. Strange

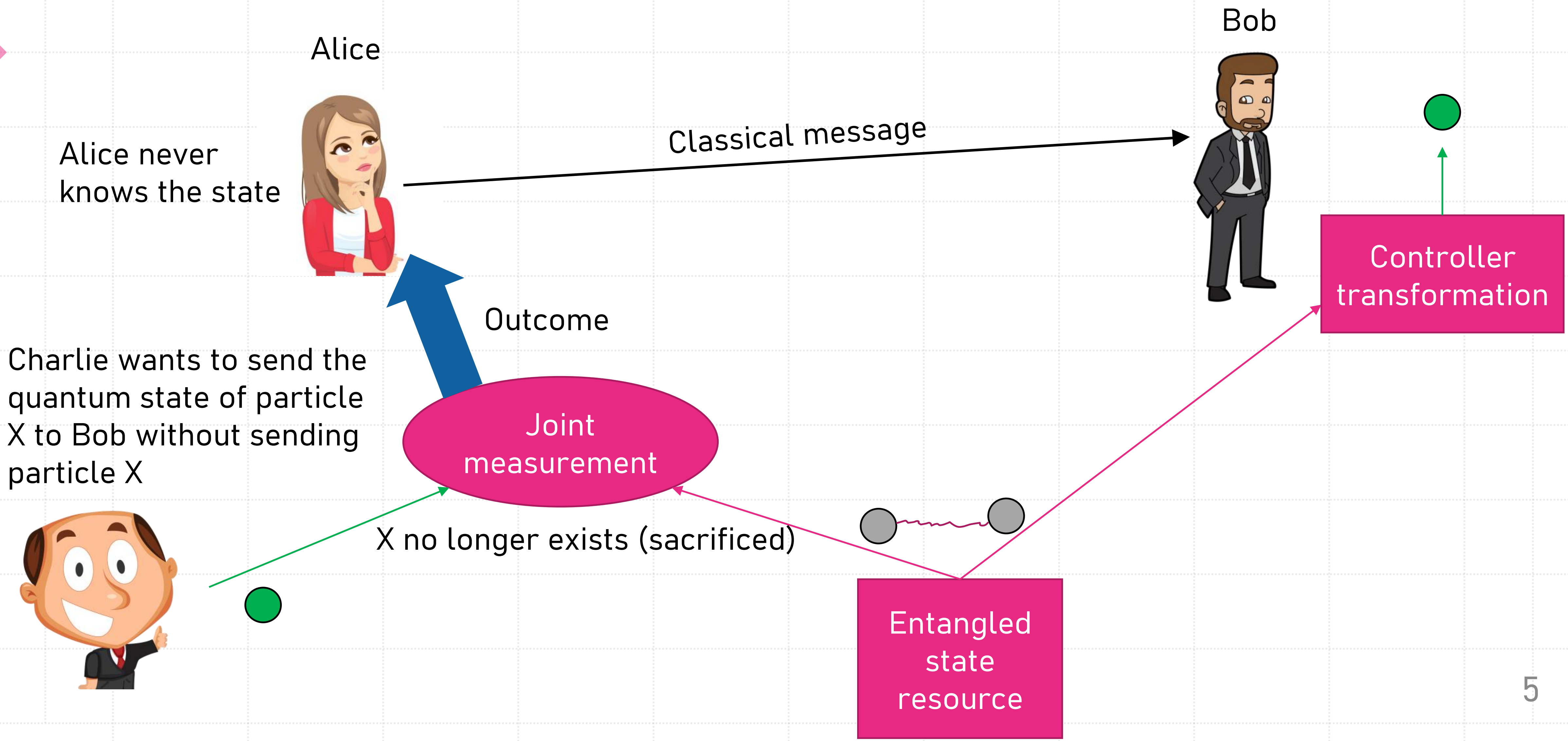
Star Trek

Doraemon- Anywhere Door

Concept of Quantum Teleportation

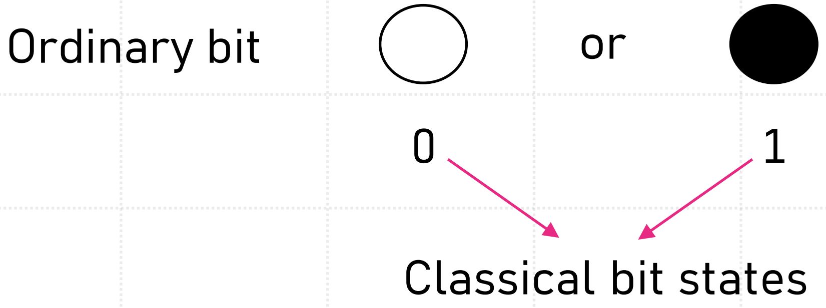
- Quantum information: information is encoded in quantum states of physical objects
- Quantum teleportation is a technique for transferring *quantum information* from a sender at one location to a receiver some distance away
  - Based on the quantum entanglement phenomenon
- The sender does not have to know the particular quantum state being transferred
- The location of the recipient can be unknown
- However, to complete the quantum teleportation, classical information needs to be sent from sender to receiver
- Quantum teleportation is used for passing *quantum information* between quantum computers

How Is Quantum Teleportation Work? (1)

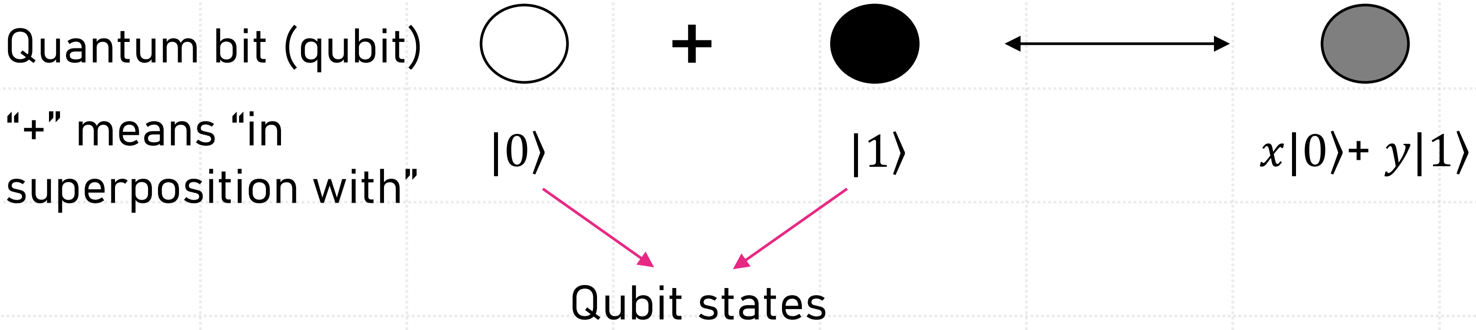


How Is Quantum Teleportation Work? (2)

- Concept of Quantum Bit (Qubit)
  - A memory element in a conventional computer: “Either-or”



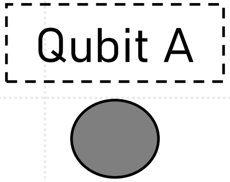
  - A memory element in a quantum computer: “Quantum Superposition”



Measuring the qubit gives either 1 (Probability x^2) or 0 (Probability y^2)

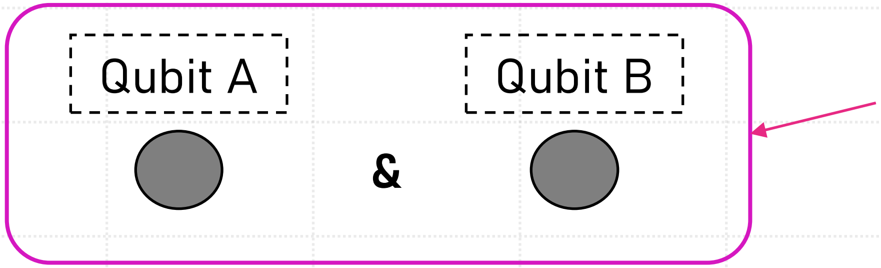
How Is Quantum Teleportation Work? (3)

- State of a qubit



- Combined state of two qubits

& means "and"

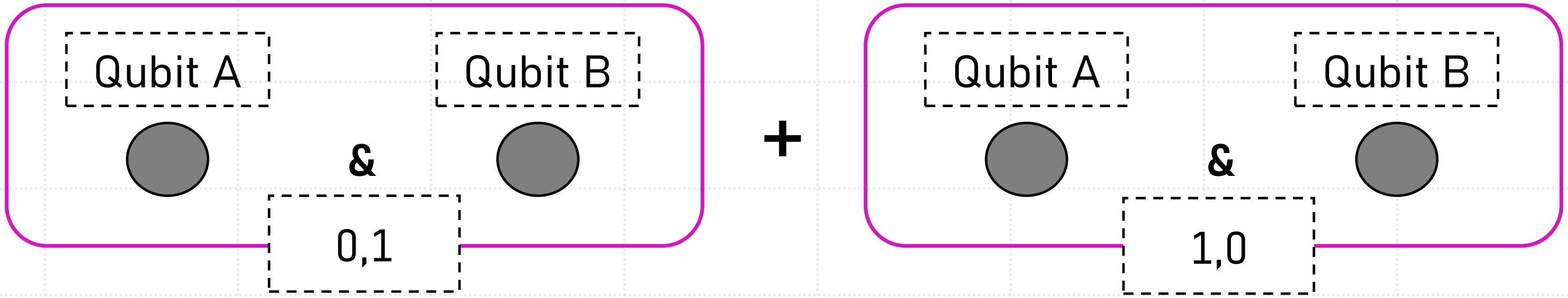


Purple Box= Two qubits in a combined quantum state

  - State = $x\,(0_A \,\&\, 0_B) + y(0_A \,\&\, 1_B) + z(1_A \,\&\, 0_B) + w(1_A \,\&\, 1_B)$
  - The probability to observe $(0_A \,\&\, 0_B)$ equals x^2
  - The probability to observe $(0_A \,\&\, 1_B)$ equals y^2
  - The probability to observe $(1_A \,\&\, 0_B)$ equals z^2
  - The probability to observe $(1_A \,\&\, 1_B)$ equals w^2

How Is Quantum Teleportation Work? (4)

- Example: Entangled state of two qubits



State = $\frac{1}{\sqrt{2}}(0_A \; \& \; 1_B) + \frac{1}{\sqrt{2}}(1_A \; \& \; 0_B)$

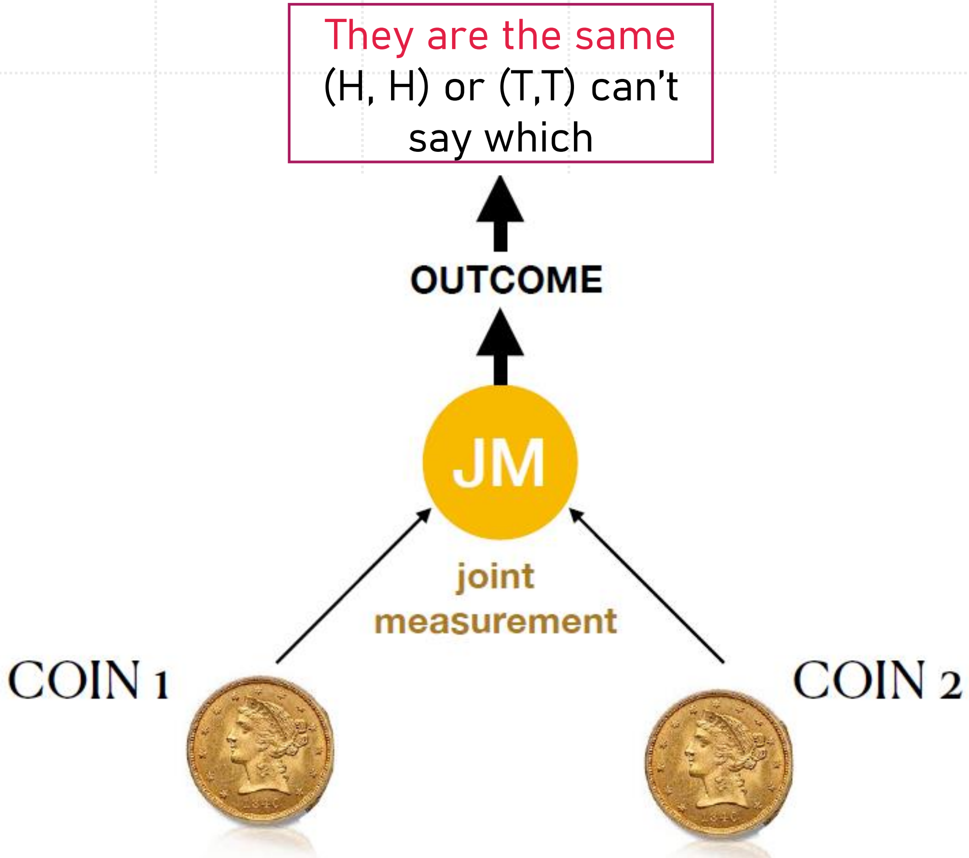
Say you measure the qubit A and obtain 0 (1)

Then you know that if qubit B is measured, it must yield 1 (0)

→The observed outcome of A allows you to infer that B is in the 1 (0) state

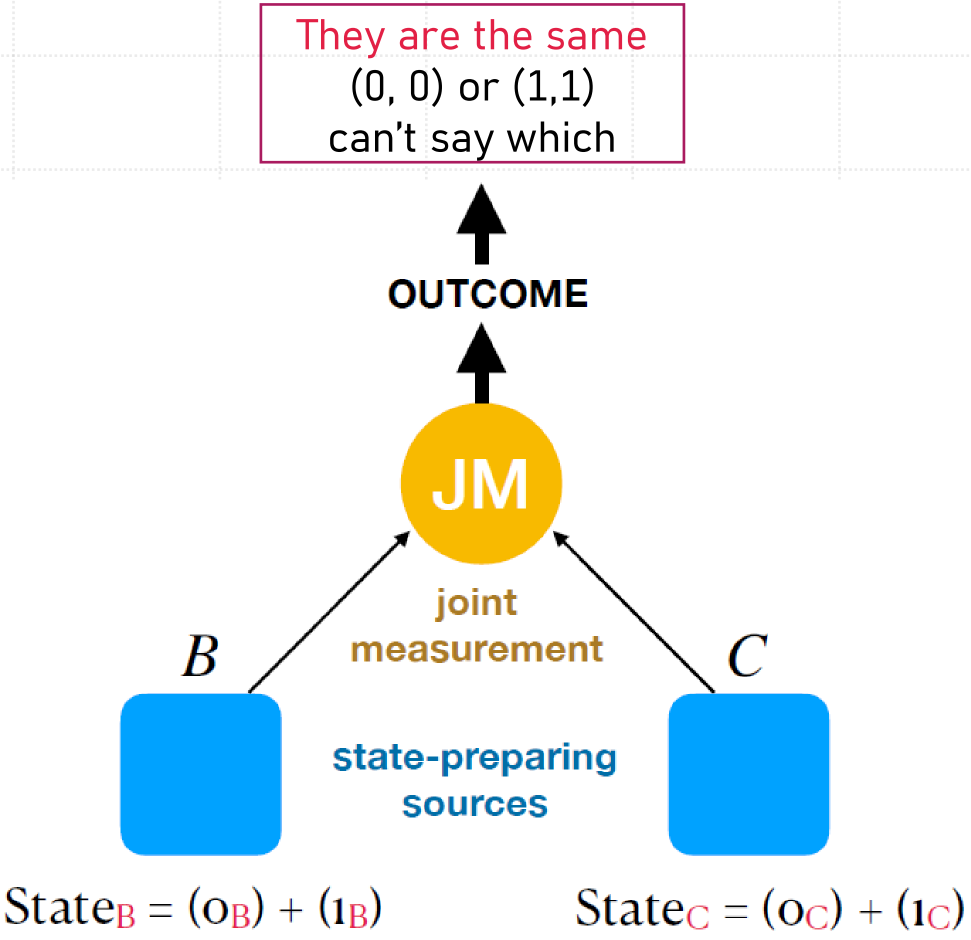
How Is Quantum Teleportation Work? (5)

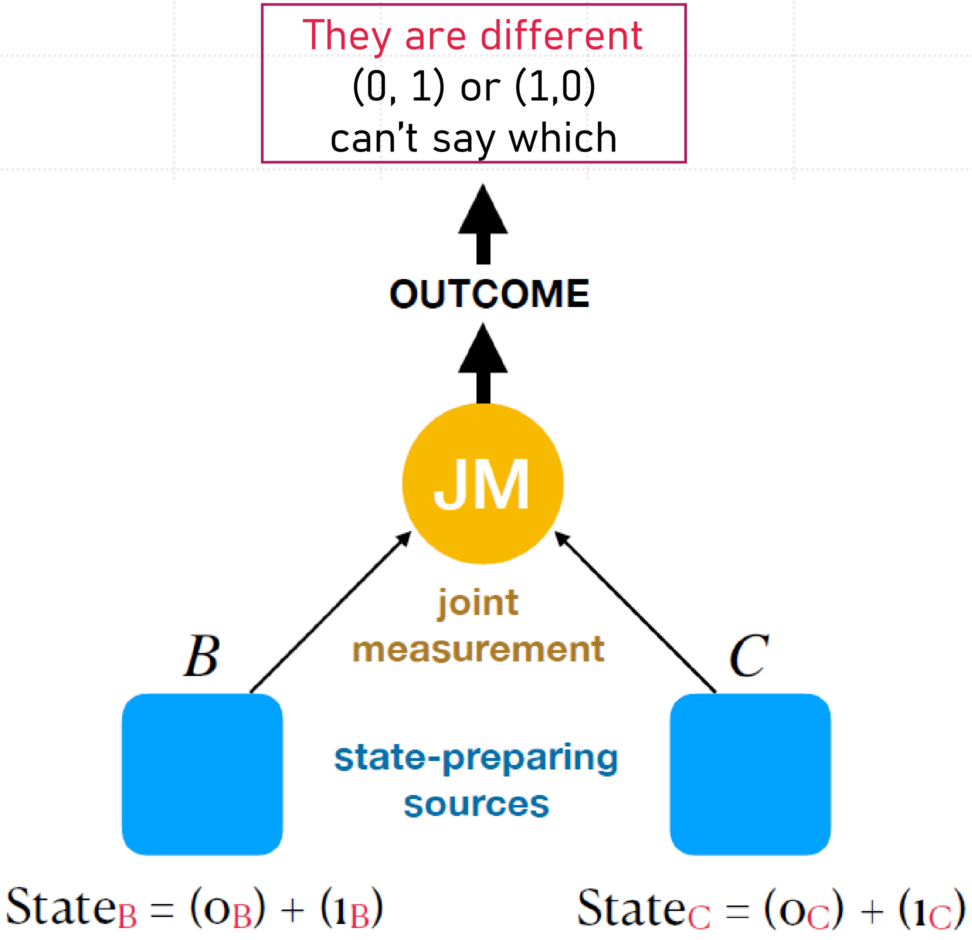
- Joint Measurement:
  - Joint measurement gives information about the pair but not full information about each member



How Is Quantum Teleportation Work? (6)

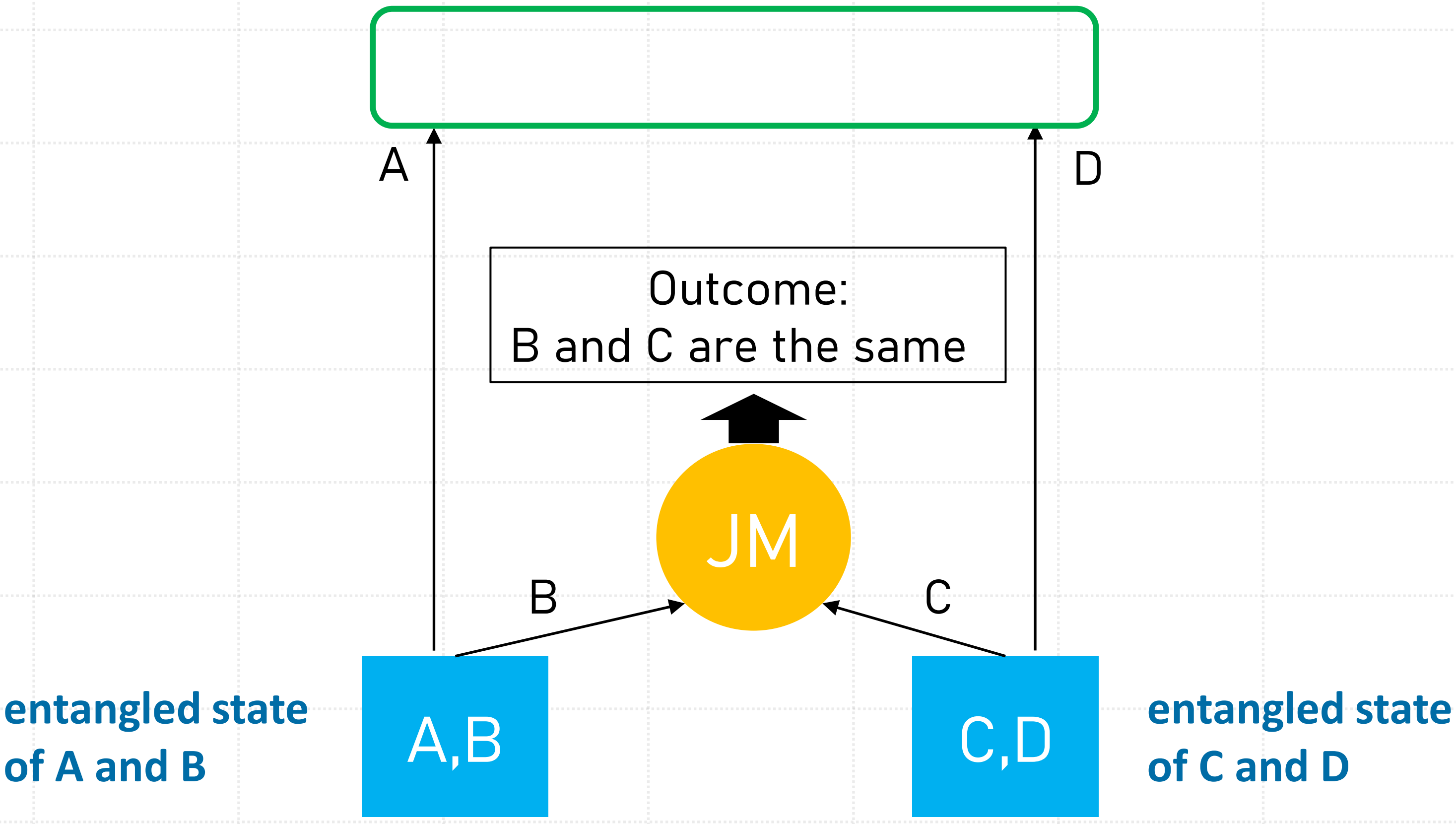
- Joint Measurement:





How Is Quantum Teleportation Work? (8)

- An simple example of quantum teleportation: Entanglement swapping



$(0_A \ \& \ 1_B) + (1_A \ \& \ 0_B)$ $(0_C \ \& \ 1_D) + (1_C \ \& \ 0_D)$

Two possible cases:

B = C = 1
Then

$(0_A \ \& \ 1_B) +$ ~~$(1_A \ \& \ 0_B)$~~

&

~~$(0_C \ \& \ 1_D)$~~ $+ (1_C \ \& \ 0_D)$

in superposition with
B = C = 0

~~$(0_A \ \& \ 1_B)$~~ $+ (1_A \ \& \ 0_B)$

&

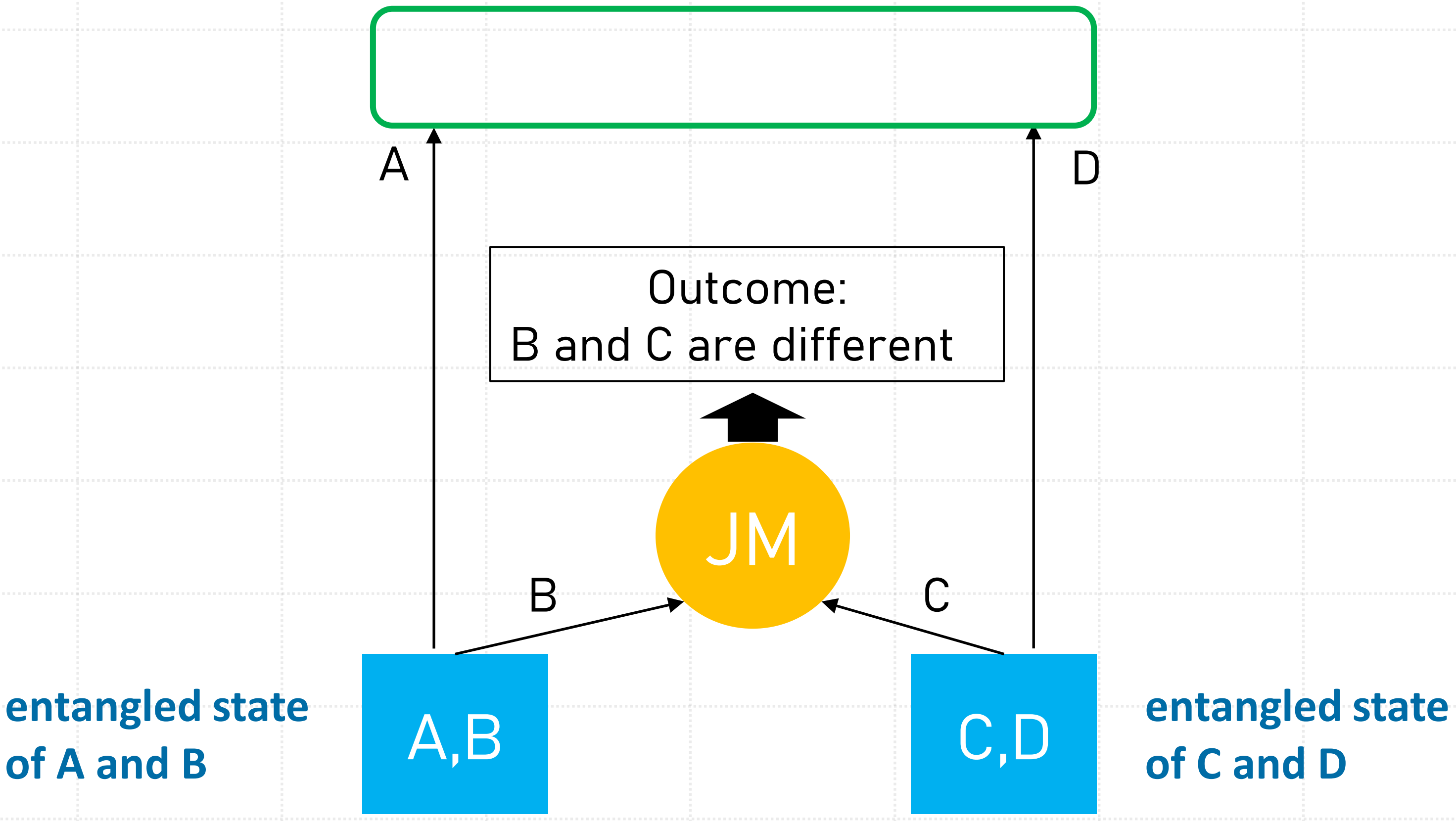
$(0_C \ \& \ 1_D) +$ ~~$(1_C \ \& \ 0_D)$~~

Final State:

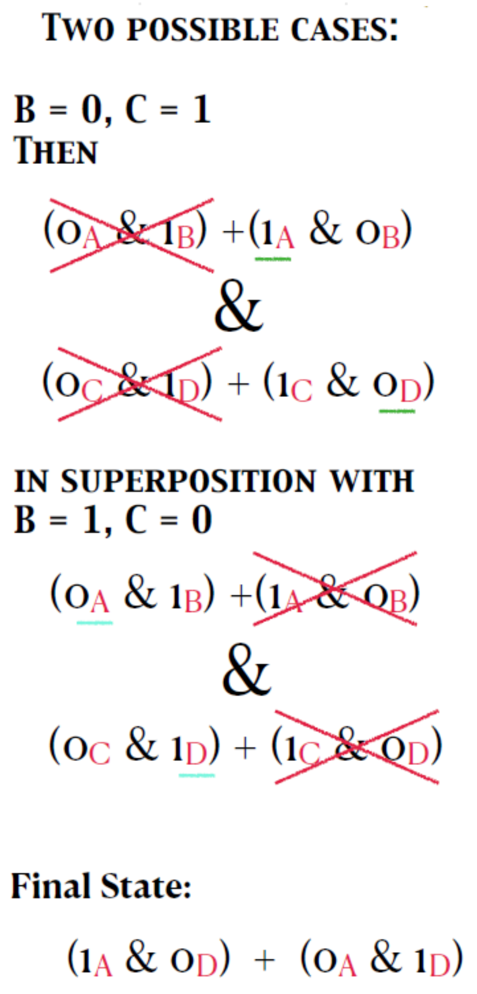
$(0_A \ \& \ 0_D) + (1_A \ \& \ 1_D)$

How Is Quantum Teleportation Work? (9)

- An simple example of quantum teleportation: Entanglement swapping



$(0_A \ \& \ 1_B) + (1_A \ \& \ 0_B)$ $(0_C \ \& \ 1_D) + (1_C \ \& \ 0_D)$



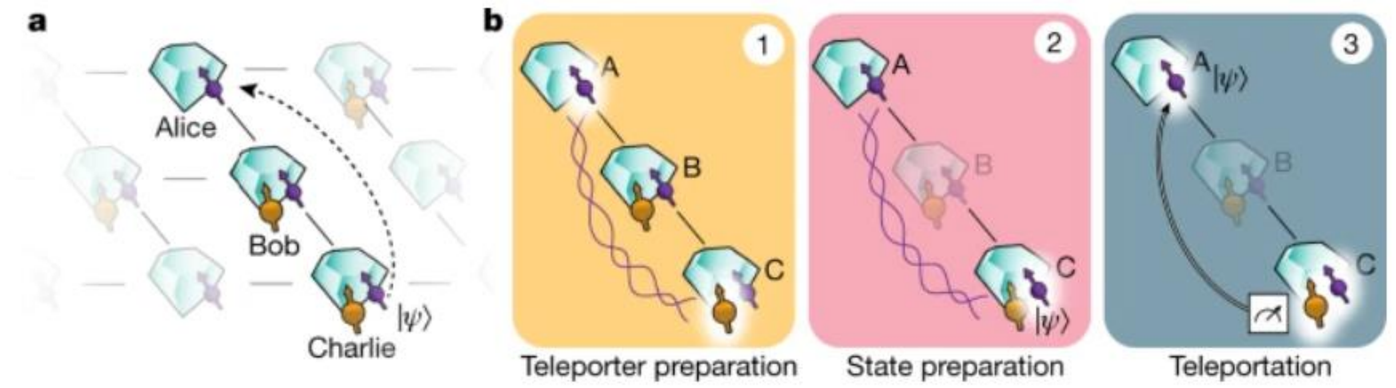
Experimental Results

- 1997: First realization by demonstrating quantum teleportation using photons (Anton Zeilinger's group) [1]
- 2004: The distance of quantum teleportation was increased to 600 meters using optical fiber [2]
- 2010: The distance for quantum teleportation increased to 16 kilometres through free space [3]
- 2012: The distance for quantum teleportation increased to 97 kilometres through free space[4]

  Zeilinger's group successfully demonstrated quantum teleportation over a distance of 143 km through free space [4]
- 2017: The current record is the teleportation of photons 1,400 kilometres from Earth to the Micius satellite in Earth orbit [5]

Quantum Teleportation: paving the way for Quantum Internet

- Future quantum internet applications will derive their power from the ability to share quantum information across the network
- Quantum teleportation allows for the reliable transfer of quantum information between distant nodes, even in the presence of highly lossy network connections

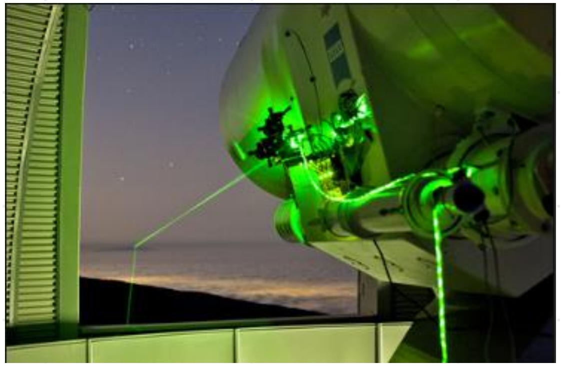


Teleporting a qubit between non-neighbouring nodes of a quantum network

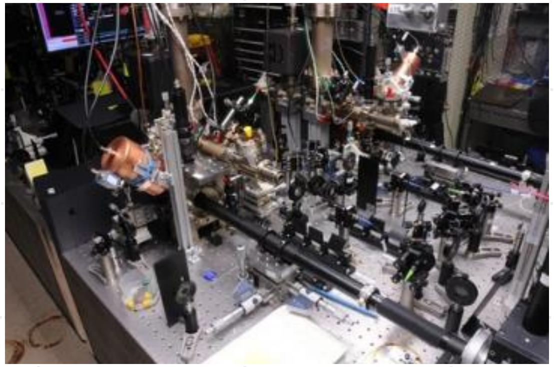
Future of Quantum Teleportation

- **Present Technology**

1. The photon teleporter, off the coast of Africa, at the Canary Islands, in the telescope observatory



2. The atomic information teleporter in Maryland



- **Future Technology**

1. Two pods of entangled molecules and a copying/ destroying pod in quantum teleportation

2. People and large objects may be teleported in the far future

Thank you!

References

[1] Bouwmeester, D., Pan, JW., Mattle, K. *et al.* Experimental quantum teleportation. *Nature* **390**, 575–579 (1997). https://doi.org/10.1038/37539

[2] Rupert Ursin (August 2004). "Quantum teleportation across the Danube". Nature. 430 (7002): 849.

[3] Jin, Xian-Min; Ren, Ji-Gang; Yang, Bin; Yi, Zhen-Huan; Zhou, Fei; Xu, Xiao-Fan; Wang, Shao-Kai; Yang, Dong; Hu, Yuan-Feng; Jiang, Shuo; Yang, Tao; Yin, Hao; Chen, Kai; Peng, Cheng-Zhi; Pan, Jian-Wei (16 May 2010). "Experimental free-space quantum teleportation". Nature Photonics. 4 (6): 376.

[4] Ma, X. S.; Herbst, T.; Scheidl, T.; Wang, D.; Kropatschek, S.; Naylor, W.; Wittmann, B.; Mech, A.; et al. (2012). "Quantum teleportation over 143 kilometres using active feed-forward". Nature. 489 (7415): 269–273.

[5] Ren, JG., Xu, P., Yong, HL. et al. Ground-to-satellite quantum teleportation. Nature 549, 70–73 (2017). https://doi.org/10.1038/nature23675

The Copenhagen Interpretation (cont.)

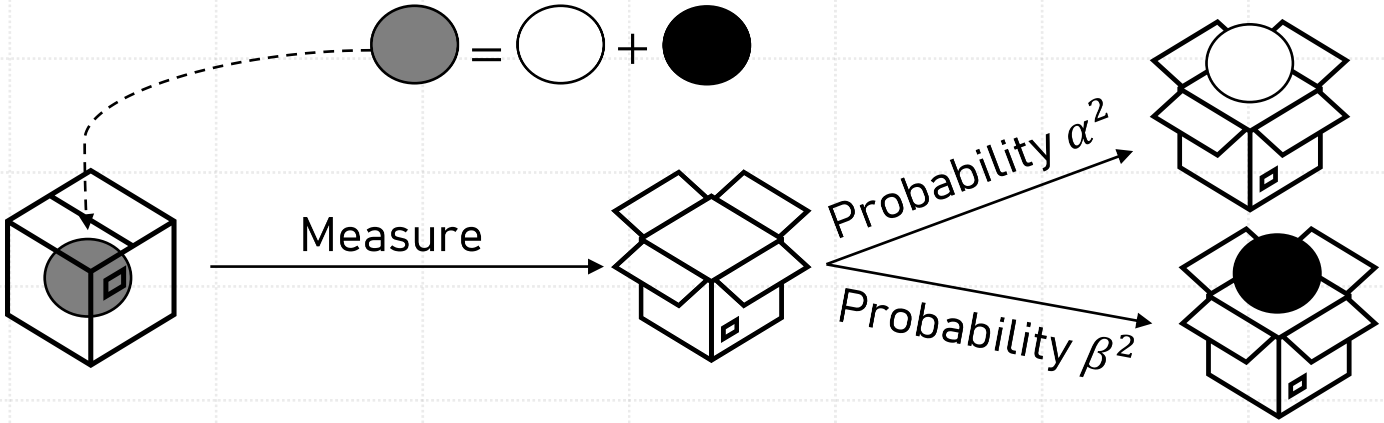
- We consider the simplest quantum mechanical system– the **quantum bit (qubit)**
  - A qubit has a 2-dimensional state space
  - The two states of the qubit: $|0\rangle$ and $|1\rangle$
  - $|0\rangle$ and $|1\rangle$ form an orthonormal basis for the state space
  - The system can be in an arbitrary **superposition** of the two states:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where α, β are complex numbers, $|\psi\rangle$ is the wave function

  - Analogy :

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



What is Quantum Entanglement?

- When two particles (e.g., a pair of photons or electrons) become entangled, they remain connected even when separated by vast distance

$$|\psi\rangle = \frac{1}{\sqrt{2}}|01\rangle + \frac{1}{\sqrt{2}}|10\rangle$$