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The bridge to possible

An Overview of Quantum Network Technologies

Hassan Shapourian, Senior Research Scientist
@Hasan_Shap
BRKNWT-1301

/Cisco/ET&I/Research

- Hassan Shapourian
- Ph.D. in Quantum Physics
- Technical Lead at Cisco Quantum Lab
  - Analyze, design, and simulate
    - Quantum hardware
    - Architectures for quantum networks
    - Quantum network applications

Email: hshapour@cisco.com
twitter: @Hasan_Shap

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with the speaker after the session

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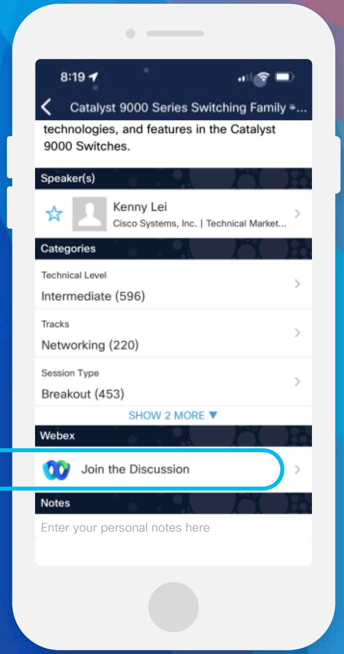
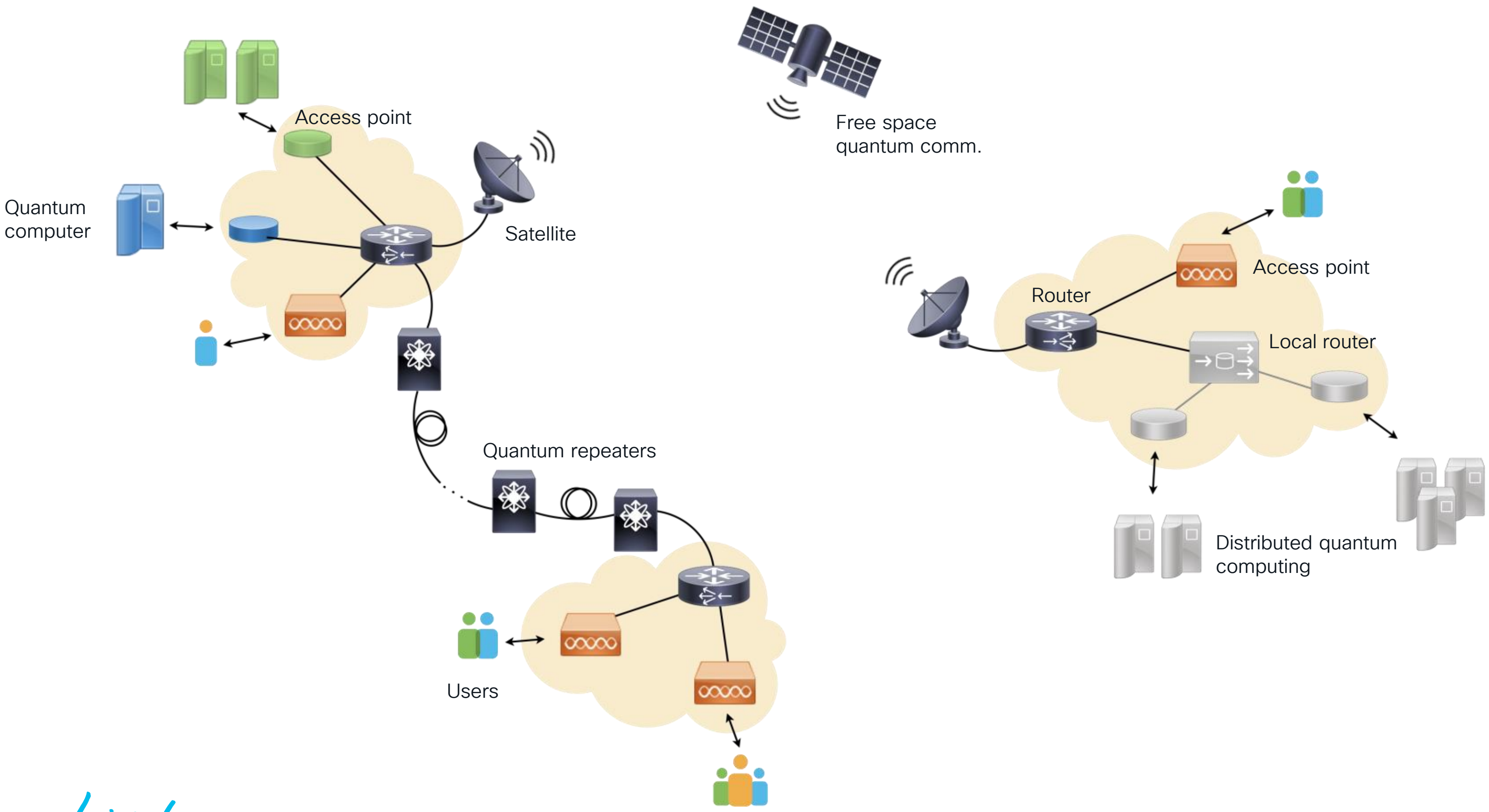


Webex spaces will be moderated by the speaker until June 9, 2023.

https://ciscolive.ciscoevents.com/ciscolivebot/#BRKNWT-1301

Quantum networks



Agenda

- Crash course on quantum physics
- Intro to quantum networks
- Challenges and opportunities
- Conclusion

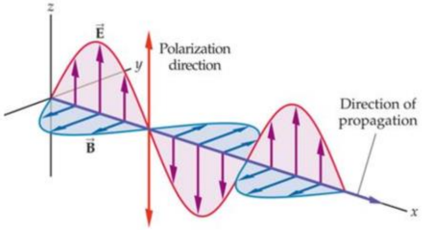
Part I
Quantum physics

Quantum Physics

1. Qubits in the lab
2. Qubits (probability, superposition)
3. Multi-qubit states (entanglement)
4. Quantum information processing
5. Quantum speedup

Qubits in the lab

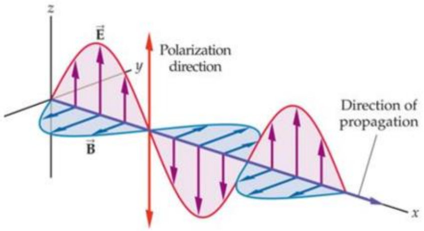
- Photons
  - Small packets of electromagnetic wave (e.g., light)



Polarization encoding
0: horizontal
1: vertical
Wikipedia

Qubits in the lab

- Photons
  - Small packets of electromagnetic wave (e.g., light)
- Electron spin
  - Elementary charged particles



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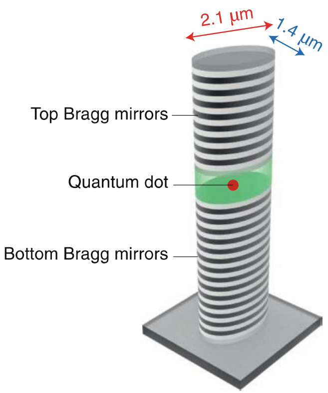
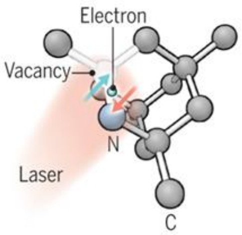
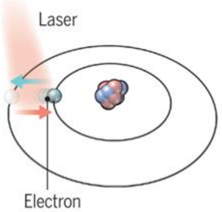


Quantum dots
M. Reimer, Nat. Photonics (2019)



Diamond vacancies



Atoms/ions

C. Bickel, Science (2016)

Qubits and superposition principle

- Two possible states: $|0\rangle$ or $|1\rangle$
- Superposition: Linear combination of states

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

- 50-50 chance of being in 0 or 1.

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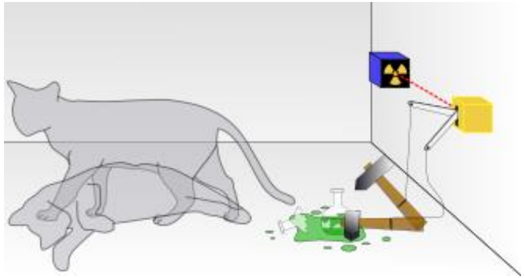
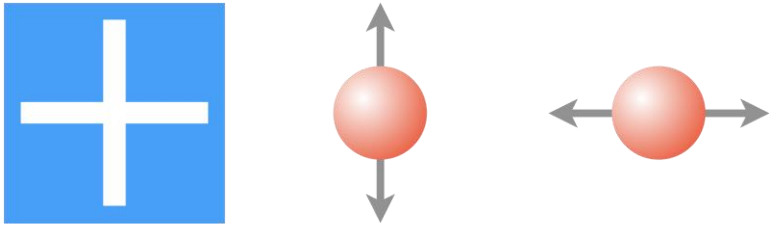
Cat state!



Wikipedia

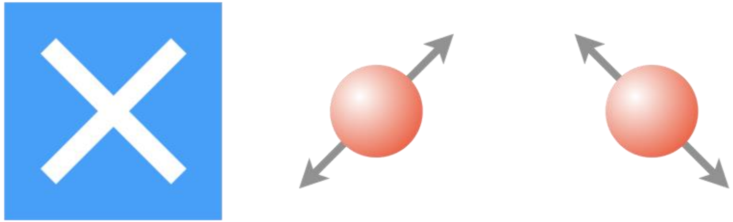
Measurement bases

- Z-measurement basis: $|0\rangle \,, |1\rangle$



- X-measurement basis: $|+\rangle \,, |-\rangle$

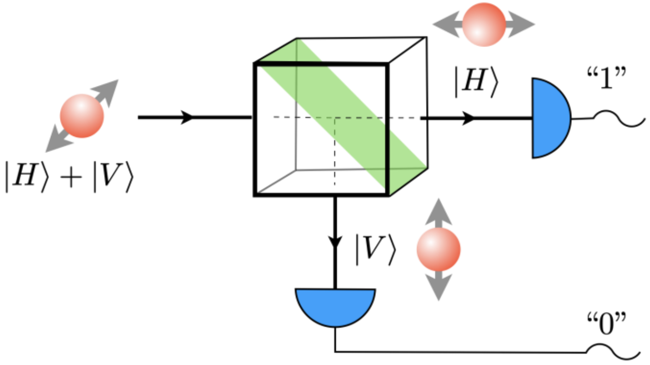
$$|\pm\rangle = \frac{1}{\sqrt{2}}|0\rangle \pm \frac{1}{\sqrt{2}}|1\rangle$$



Quantum random number generator (QRNG)

Random bit string 0011101010111001011 0...

- Completely unpredictable



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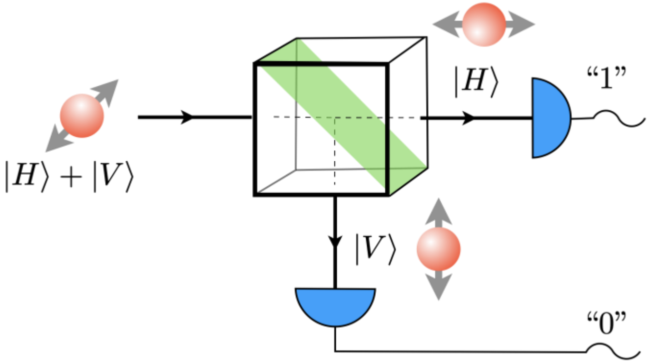
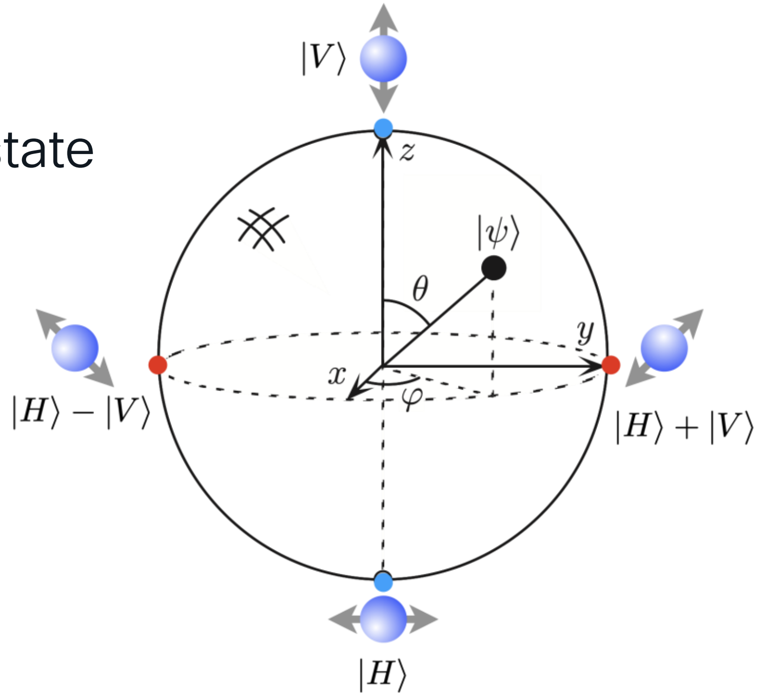


Cryptography
Sampling

Abstract representation

- Computational basis: $|0\rangle, |1\rangle$
- Two angles to represent an arbitrary state

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$



Bloch vector

Multiple qubits

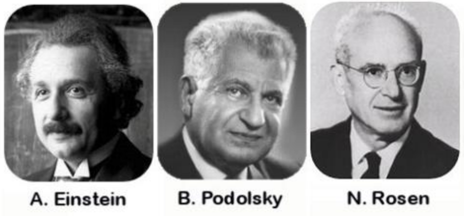
- Two-qubit state

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

- For n qubits, we need 2^n coefficients with the basis $|x_1 x_2 \cdots x_n\rangle$.

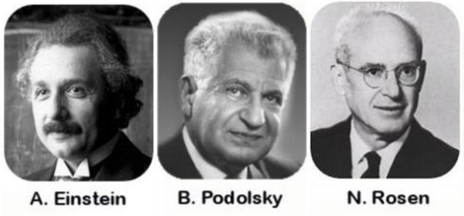
- Bell state (EPR pair)

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



Wikipedia

Quantum entanglement



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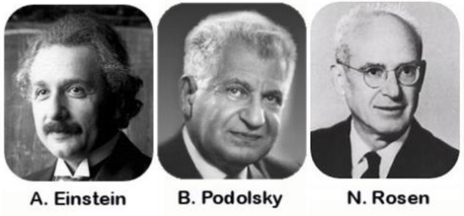

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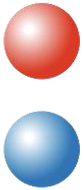
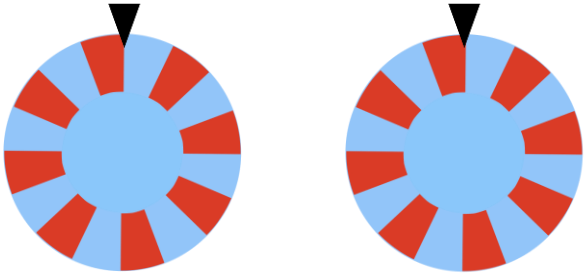
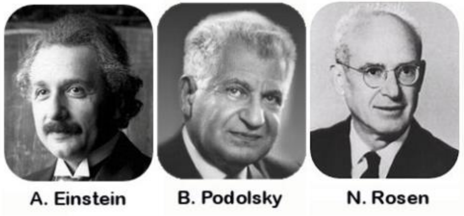


Marble in box



Spinning wheels

Quantum entanglement



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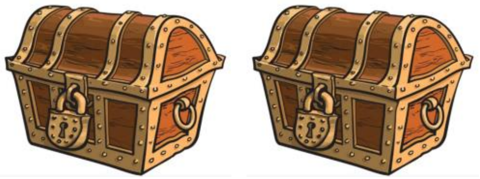

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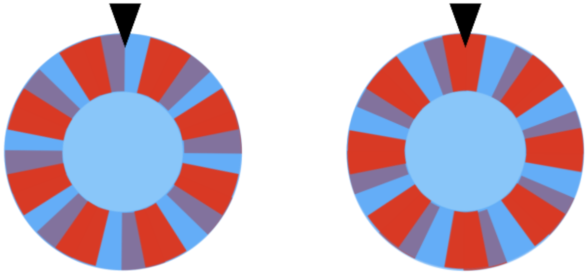
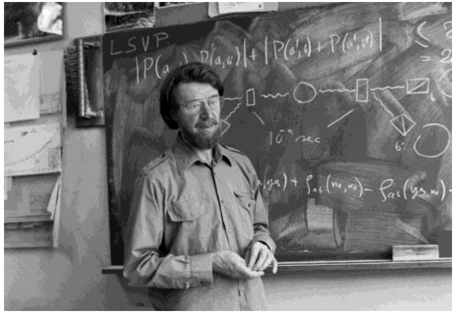


Spinning wheels

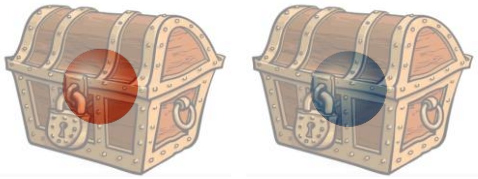
Bell inequality

- Bell state (EPR pair)

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



John Bell (1982)
Wikipedia



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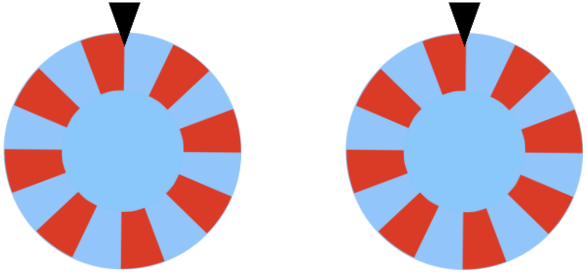
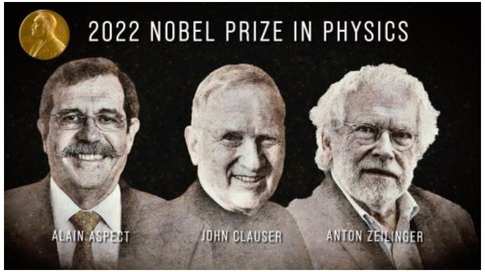


Spinning wheels

Experimental verification of Bell inequality

- Bell state (EPR pair)

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



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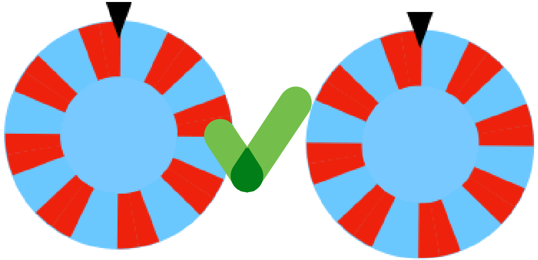


Spinning wheels

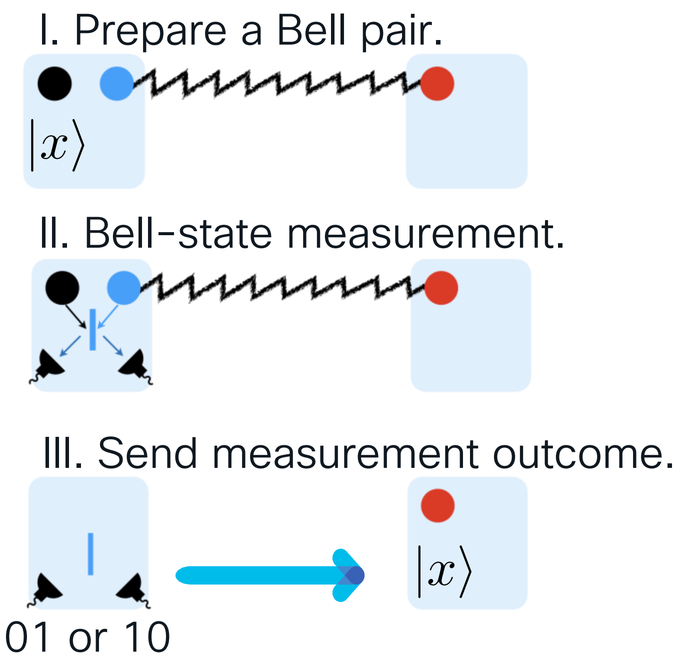
Teleportation

- Transfer a state by making local measurement on a Bell-pair.

I. Prepare a Bell pair.

Teleportation

- Transfer a state by making local measurement on a Bell-pair.



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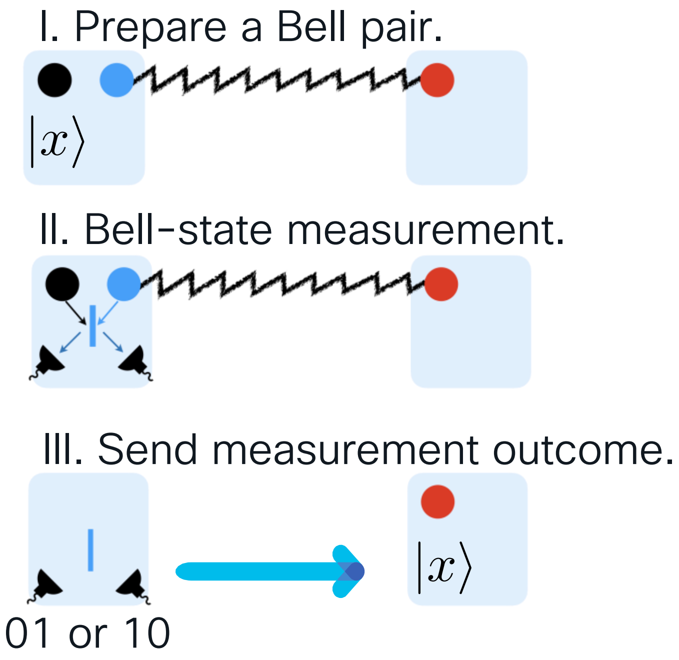
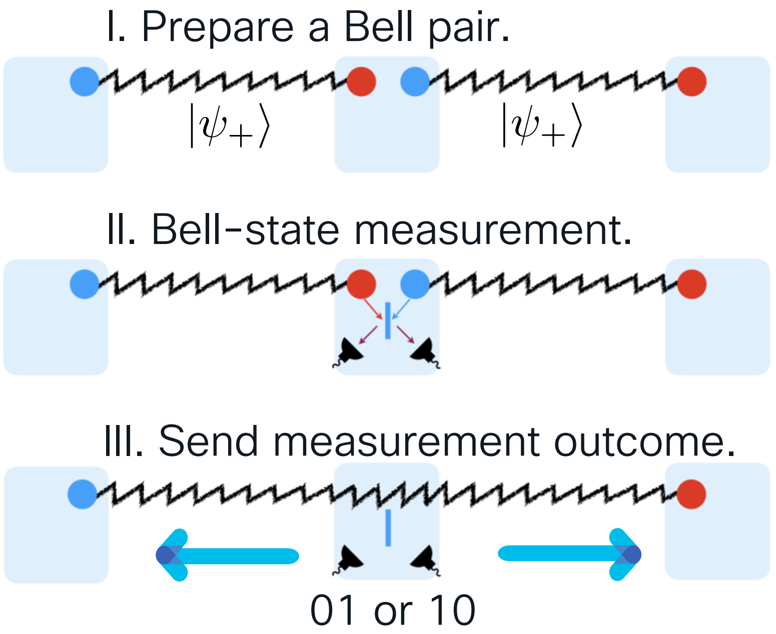


Device-independent secure communication

Entanglement swapping

- Sewing short-range Bell pairs to make long-range Bell pairs!



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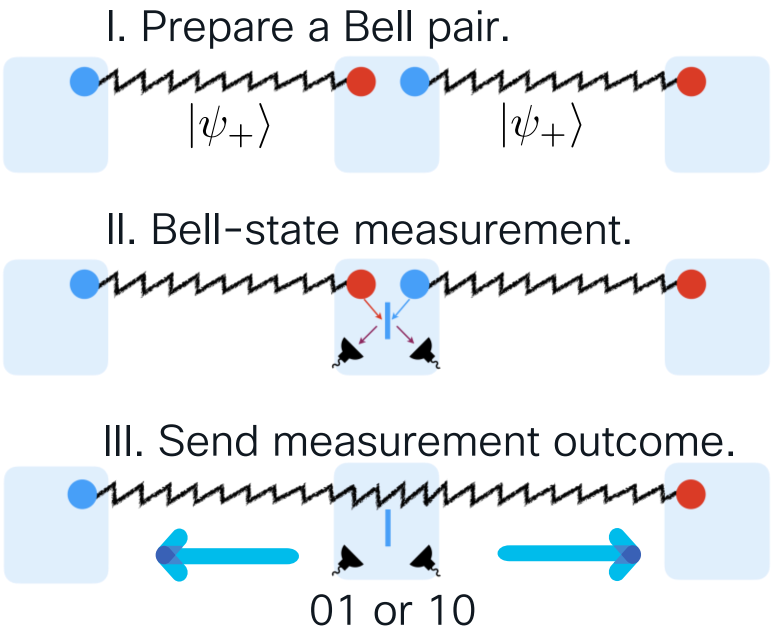


Long-distance communication

No-cloning theorem

- Unknown quantum states cannot be perfectly cloned.

$$|s\rangle \otimes |\psi\rangle \rightarrow |\psi\rangle \otimes |\psi\rangle$$

No-cloning theorem

- Unknown quantum states cannot be perfectly cloned.

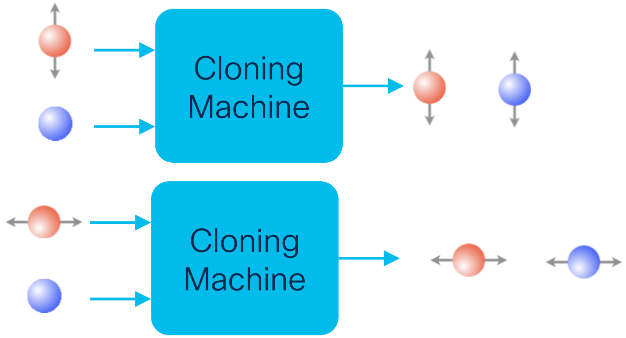
$$|s\rangle \otimes |\psi\rangle \not\rightarrow |\psi\rangle \otimes |\psi\rangle$$

Security
Privacy

No-cloning theorem

- Unknown quantum states cannot be perfectly cloned.
- Proof:

  By contradiction



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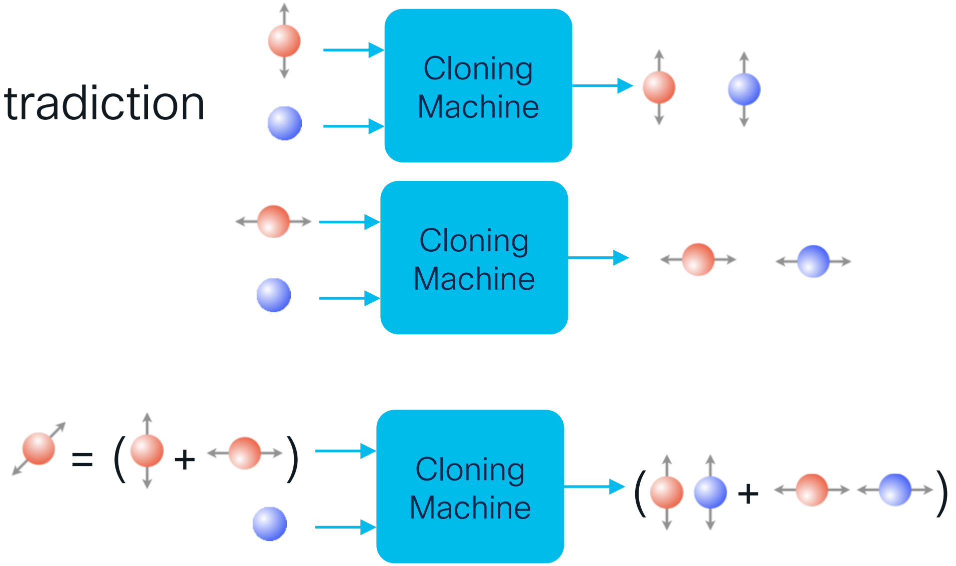

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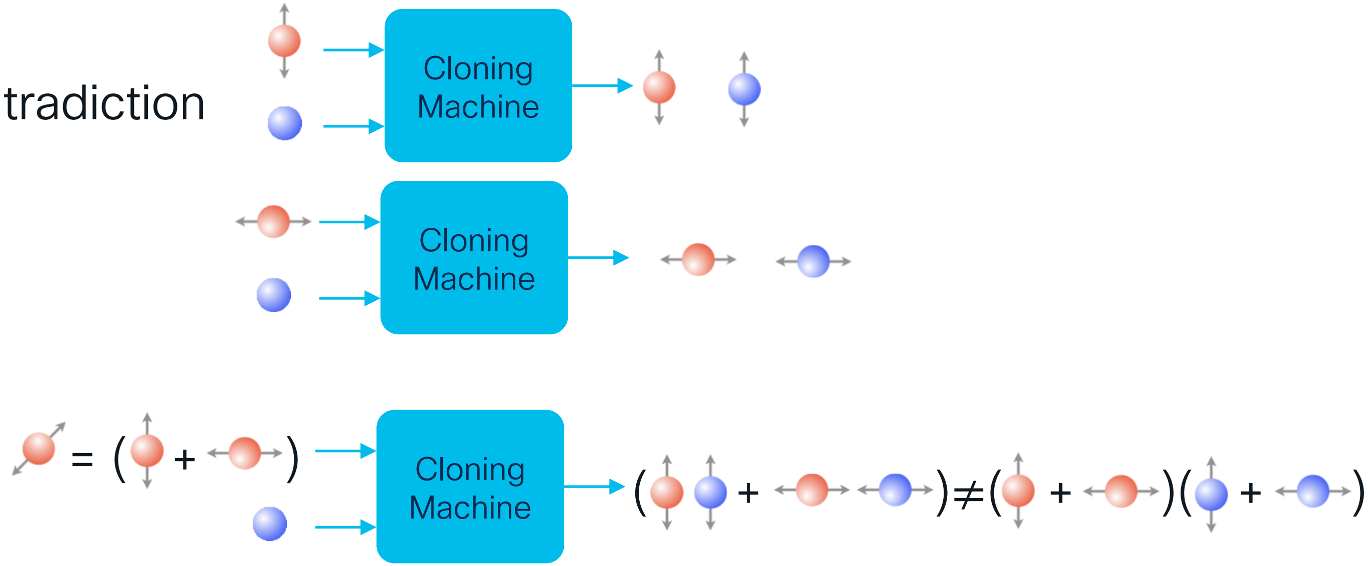
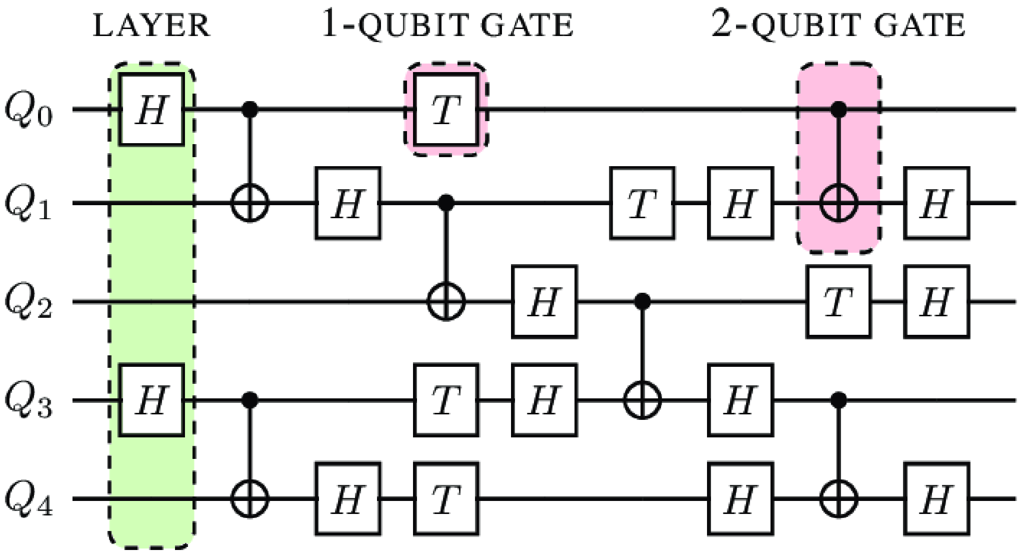


Quantum information processing

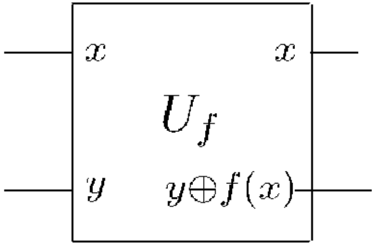
Quantum circuits



D. Ferrari, IEEE Trans. on Quantum (2021)

Quantum speedup

- Rough idea: Quantum parallelism
- Deutsch's algorithm:
  - Find the function $f(x) : \{0,1\} \rightarrow \{0,1\}$ with least querries.
  - Quantum system can evaluate the function in **one shot**!
  - We implement a quantum circuit which does $|x, y\rangle \rightarrow |x, y \oplus f(x)\rangle$



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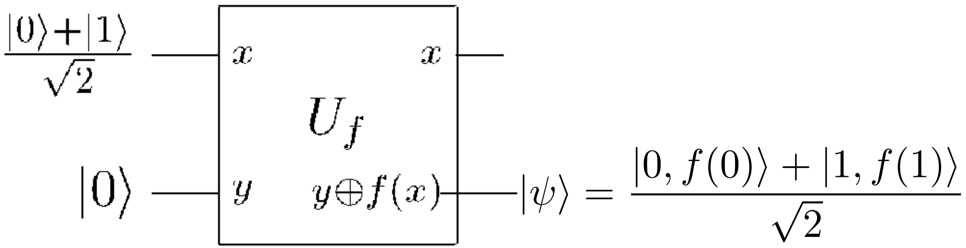

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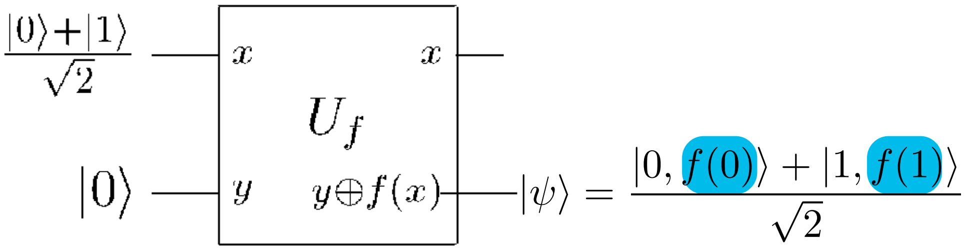
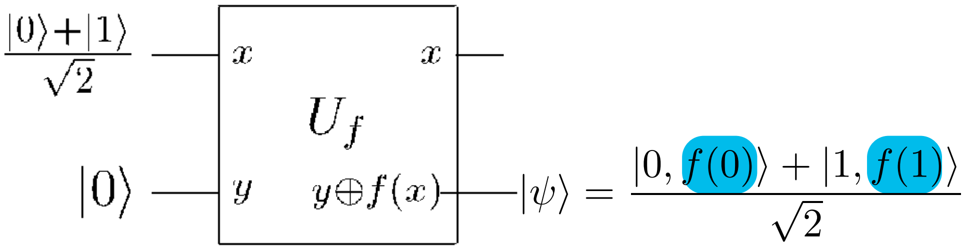


Access to both outputs!

Quantum speedup

Exponentially-fast compute

- Rough idea: Quantum parallelism
- Deutsch's algorithm:
  - Find the function $f(x) : \{0,1\} \rightarrow \{0,1\}$ with least querries.
  - Quantum system can evaluate the function in **one shot**!
  - We implement a quantum circuit which does $|x, y\rangle \rightarrow |x, y \oplus f(x)\rangle$



Access to both outputs!

Part I: Summary

Quantum

Superposition	No-cloning	Entanglement
• Intrinsic randomness • Speedup	• Security • Privacy	• Security • Sensing • Communication

Part II
Quantum networks

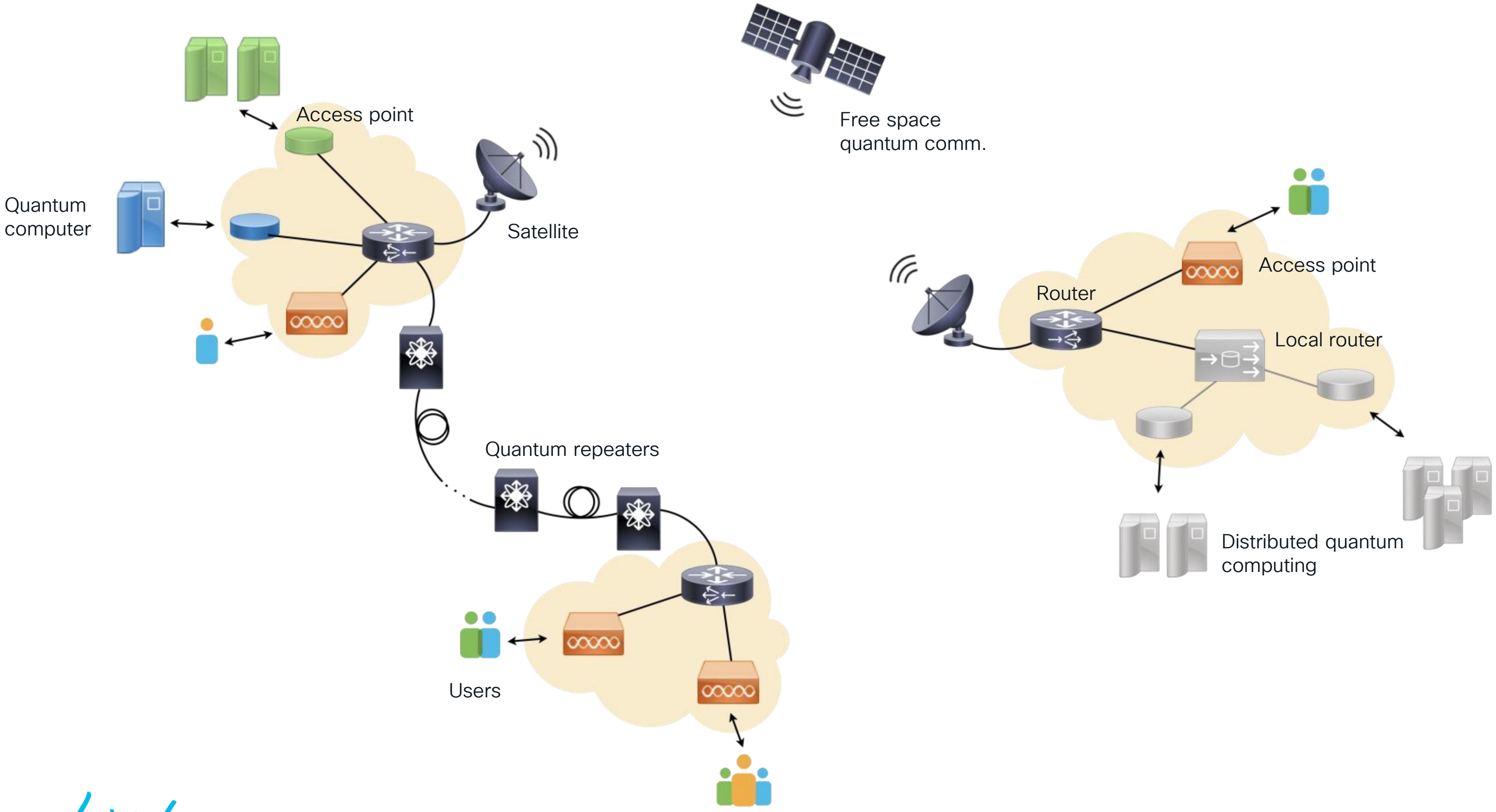
50%

cisco Live!

Quantum networks

1. What is a quantum network?
2. Applications of quantum networks
3. How to realize a quantum network?
4. Quantum networks building blocks

Quantum networks



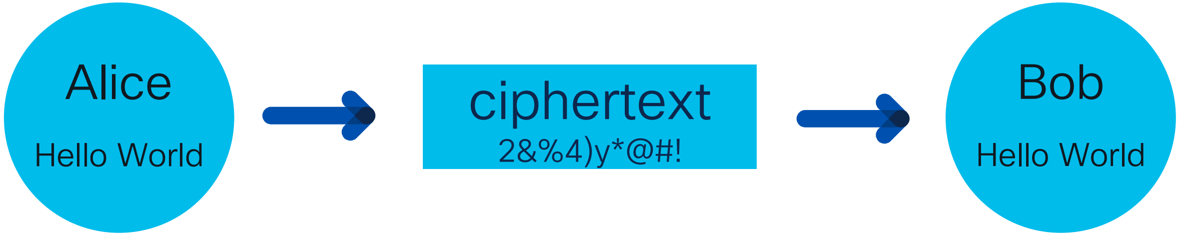
Applications of quantum networks

- Cryptography
- Distributed sensing
- Clock synchronization
- Distributed quantum computing
- Privacy-preserving computing

Applications of quantum networks

Cryptography

Quantum Key Distribution (QKD)

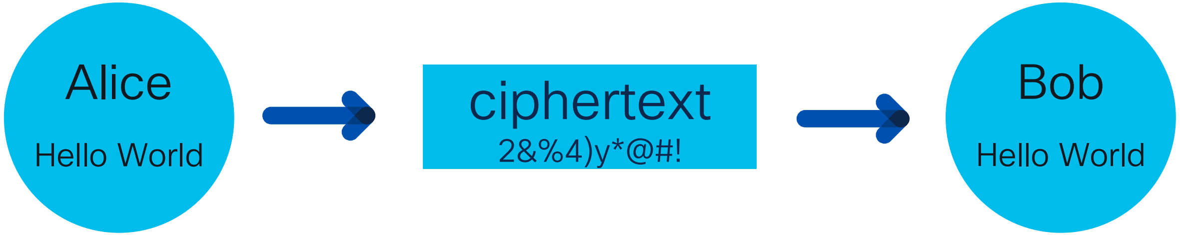


Alice and Bob need a shared key

Applications of quantum networks

Cryptography

Quantum Key Distribution (QKD)



Alice and Bob need a shared key

Related sessions: BRKETI-1302 (on-demand) by Stephen DiAdamo
BRKSEC-3129 (Wed 3pm) by Frederic Detienne

Applications of quantum networks

Distributed sensing

Wikipedia

ATCA telescope (Australia)

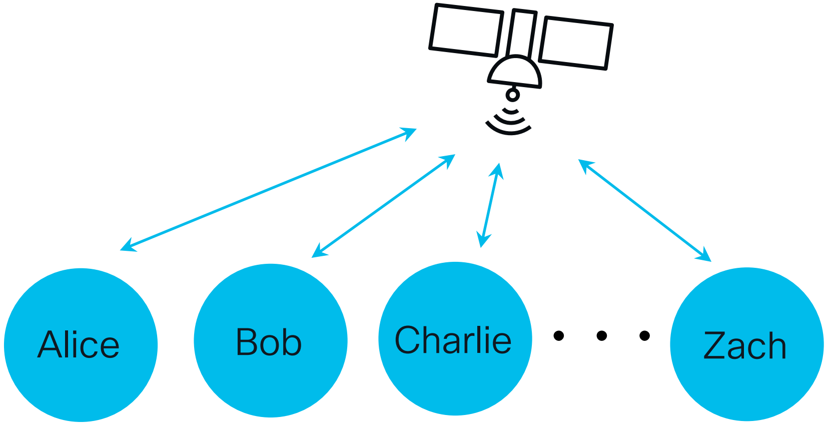
Telescope arrays need to share the same phase.

Classical precision~ $1/\sqrt{N}$

Quantum precision~ $1/N$

Applications of quantum networks

Coordination, clock synchronization



Dynamic coordination of senders/receivers

Applications of quantum networks

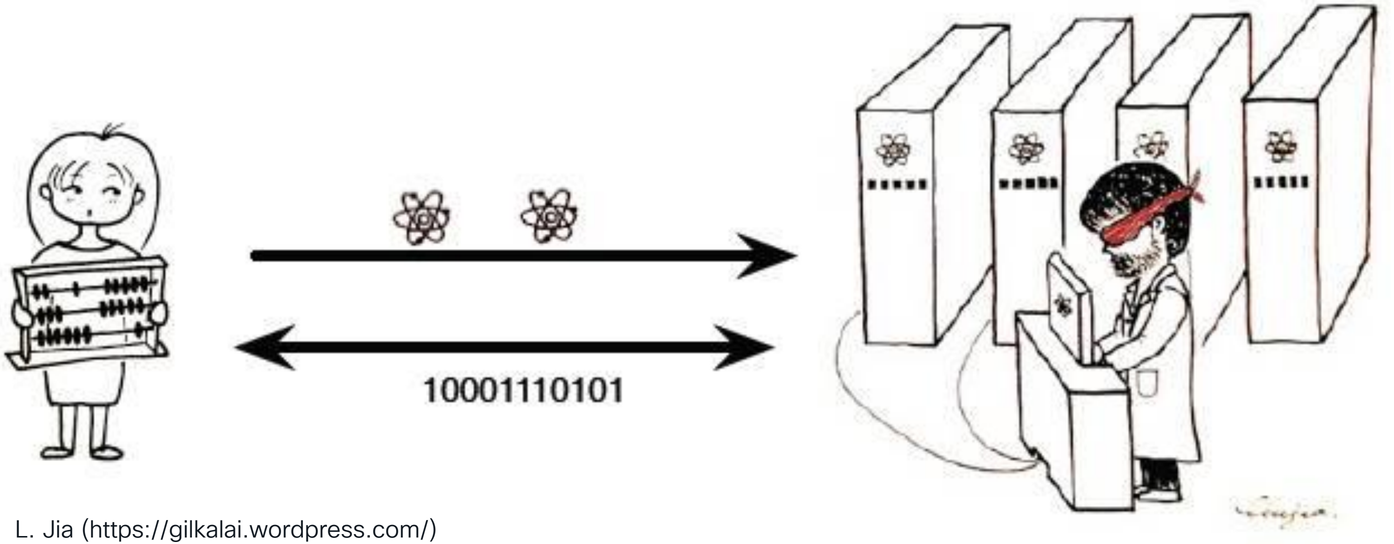
Distributed quantum computing

Superconducting quantum computer
F. Lecocq/NIST

Sandia National Lab

Applications of quantum networks

Privacy-preserving computing



L. Jia (https://gilkalai.wordpress.com/)

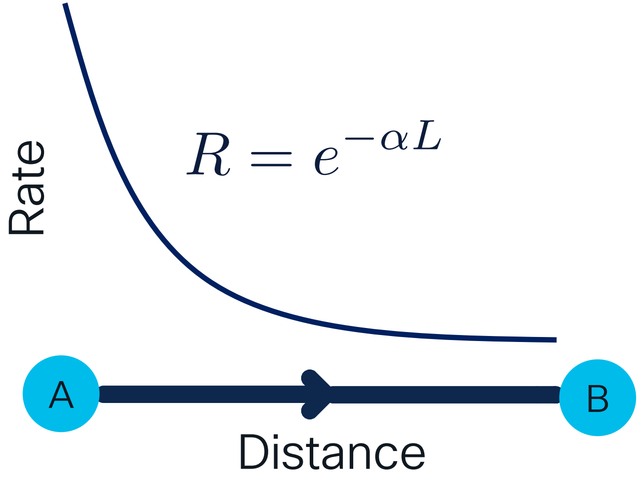
Performance of quantum networks

- **Service to provide**: end-to-end delivery of qubits
- How to measure the performance of quantum networks?

Classical networks	Quantum networks
Rate, latency, jitter, BER	Rate, fidelity

Rate-distance tradeoff

- Why is quantum communication so hard?

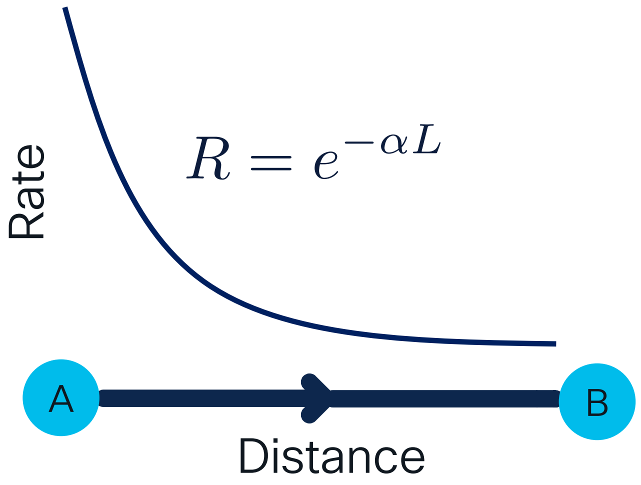


Rate decays exponentially with distance

Can we amplify signal?

Rate-distance tradeoff

- Why is quantum communication so hard?



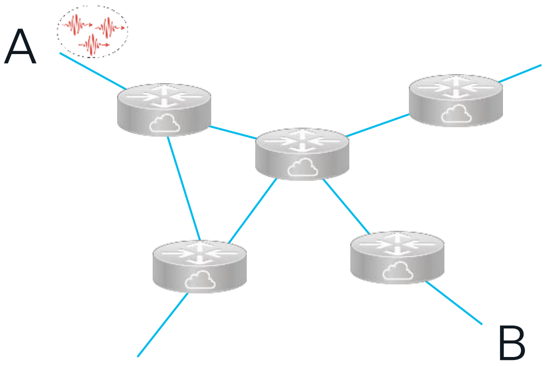
Rate decays exponentially with distance

Can we amplify signal?

No, because of the no-cloning theorem: **Quantum signals cannot be copied!**

Quantum information transfer

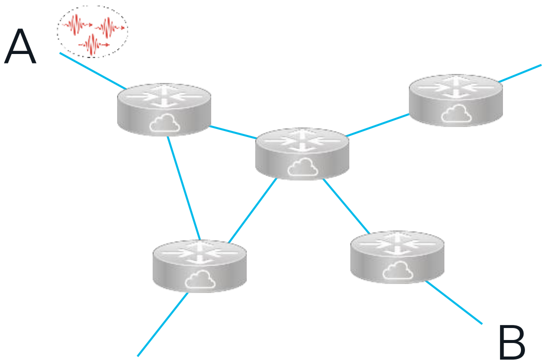
One-way



Quantum error correction is performed at each repeater:

Quantum information transfer

One-way



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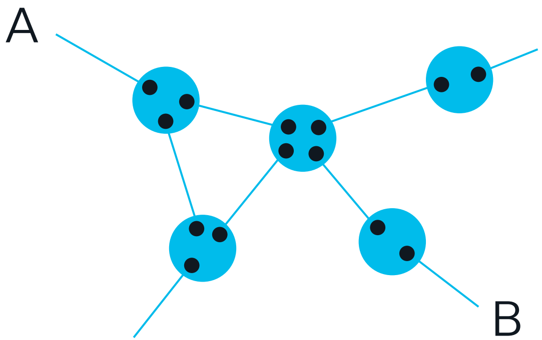
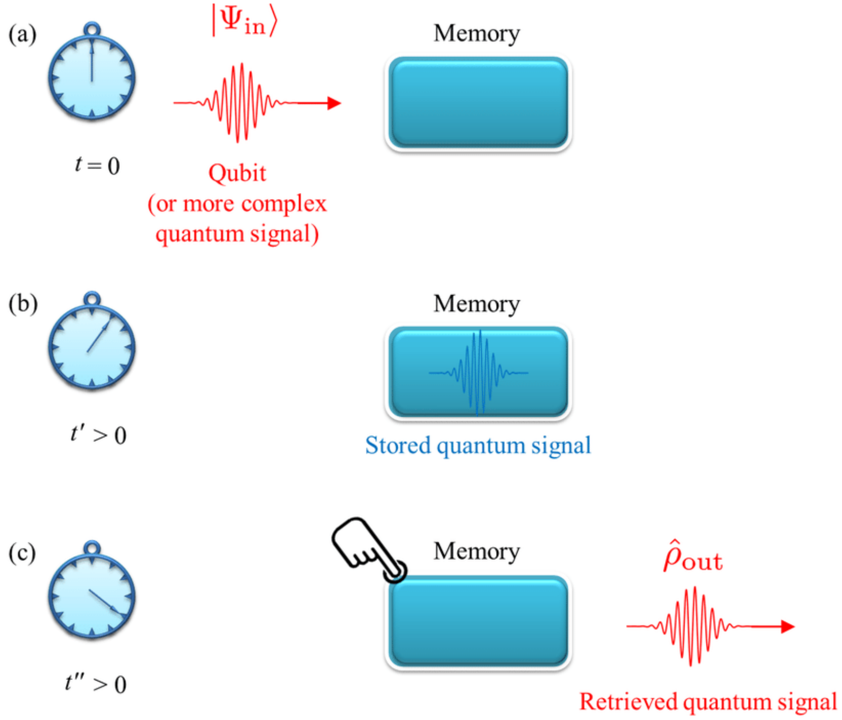


Quantum network components

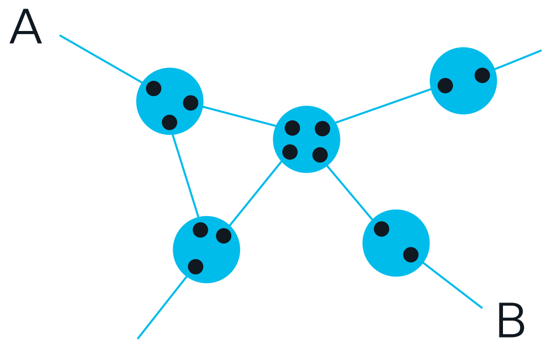
Quantum memory



Adrien Nicolas, PhD thesis (2014)

Quantum information transfer

Two-way = Entanglement distribution network



Quantum information transfer

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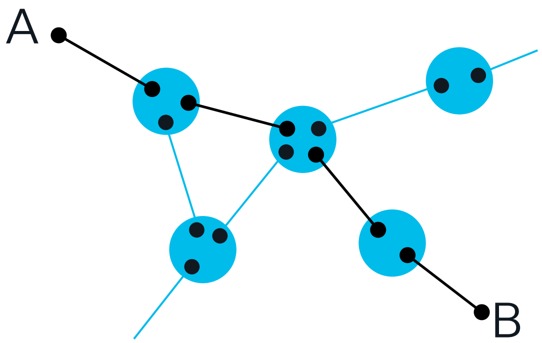
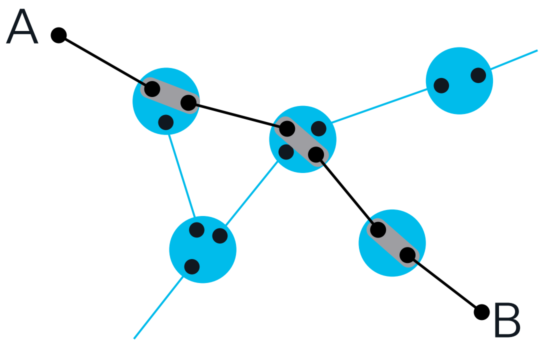


Elementary link entanglement

Quantum information transfer

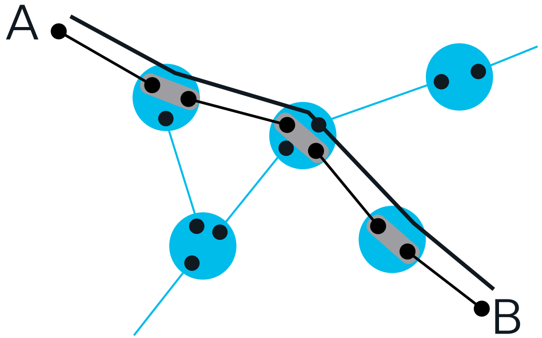
Two-way



Entanglement swapping

Quantum information transfer

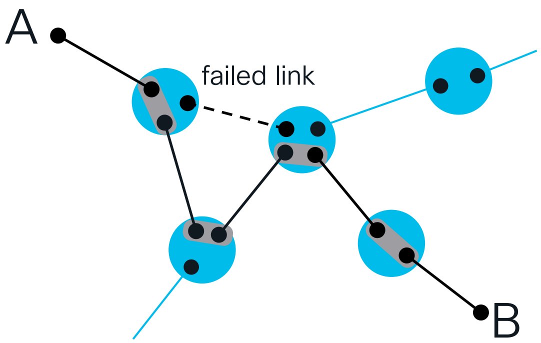
Two-way



End-to-end entanglement

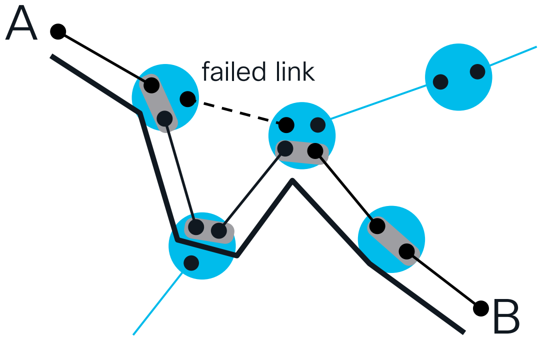
Quantum information transfer

Two-way



Quantum information transfer

Two-way

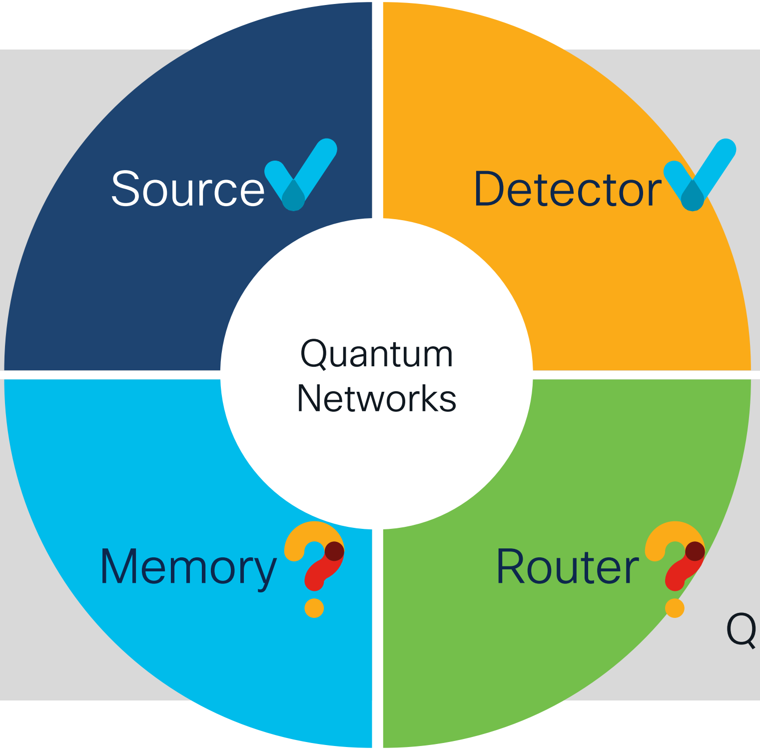


Need for new routing protocols!

Quantum network components

Generate qubits

Measure qubits



Store qubits
Synchronization

Signal routing
Quantum error correction

Part II: Quantum networks

Application	Cryptography, privacy-preserving computing, enhanced sensing,...
Transport	End-to-end (logical) quantum information transmission
Network	Switching, routing, scheduling
Link	Transporting physical qubits, error correction, purification
Physical	**Requirements:** quantum memory, detector, source

Challenges: photon loss/channel noise/noisy quantum hardware

Challenges/ opportunities

Quantum technology road map

Proof-of-principle

10–100 qubit.
Noisy intermediate scale quantum (NISQ)

Quantum error correction (prototype)

10^2–10^3 qubits.
One logical qubit.

Small error-corrected chip

10^3–10^4 qubits.
Perform logical gate.

Academic quantum advantage/ Hybrid ML

10^4–10^6 qubits.
Many logical qubits.

Fault-tolerant quantum computer

10^6+ qubits.
Materials science simulation, Shor's algorithm, etc.

Quantum technology road map

We are here!

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Cisco Quantum Lab opens soon!

Announcing the Opening of the Cisco Quantum Lab

Cisco Quantum Lab

Tuesday, March 14th, 2023

1 min read

Conclusions

- Quantum networks coexist with classical networks and offer new applications.
- Quantum information is fragile (noisy hardware, photon loss).
- Need to design efficient and scalable quantum routers.
- A challenging piece is quantum memory.
- Need for optimal resource allocation and routing protocols.

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The bridge to possible

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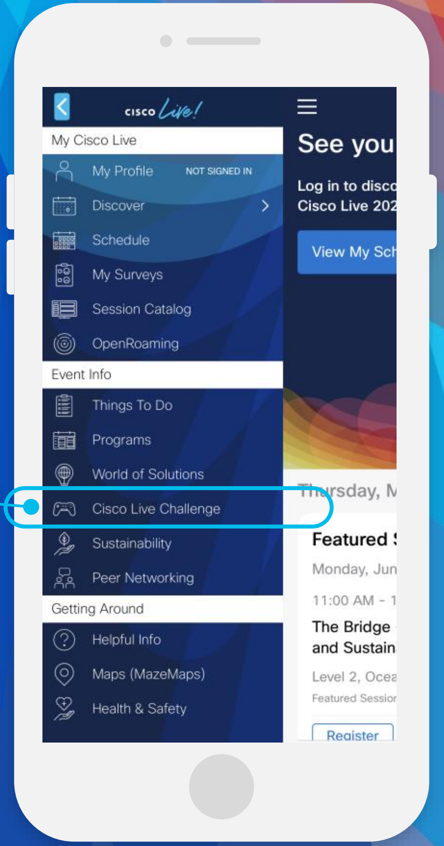

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Let's go