The Quantum Internet: Prospects, Progress, and Challenges

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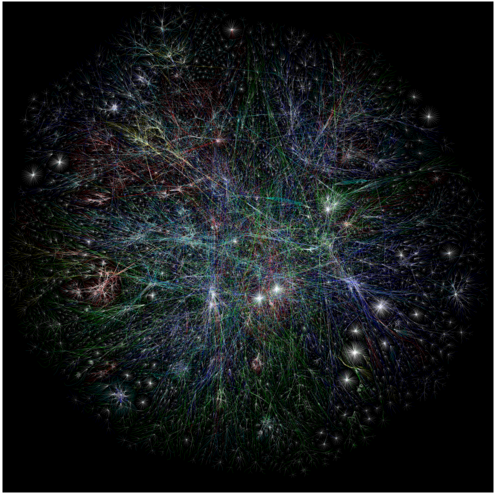
Louisiana State University

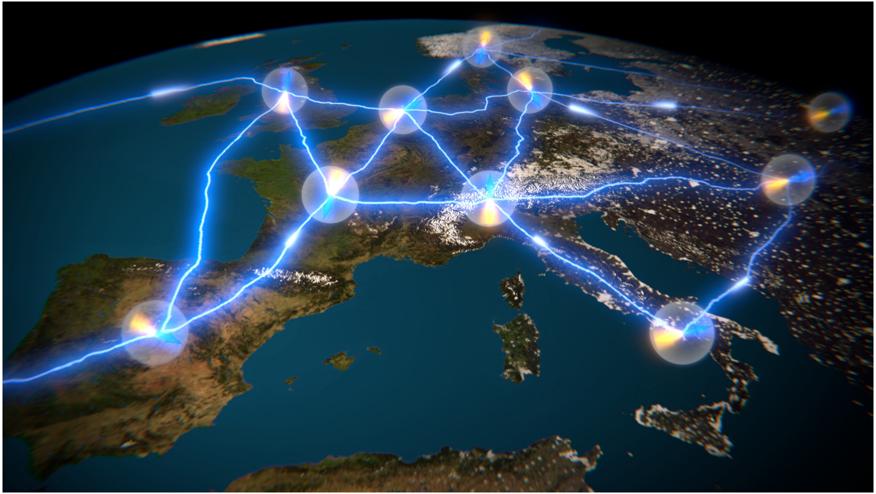
March 17, 2021

Internet = interconnected network of networks



The internet in 2003 – **www.opte.org**

Quantum Networking = Quantum Communication & Computing + (Classical) Networking



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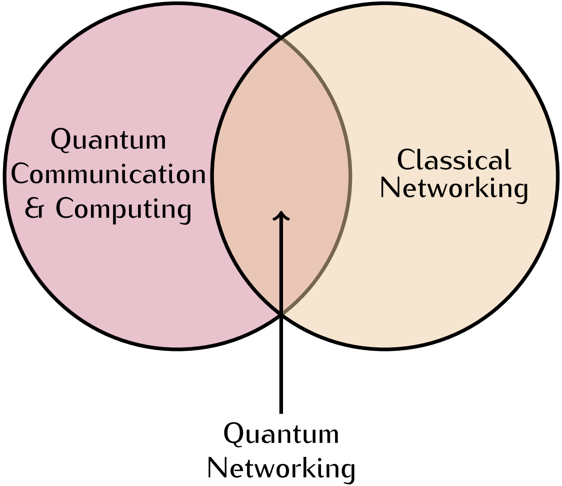
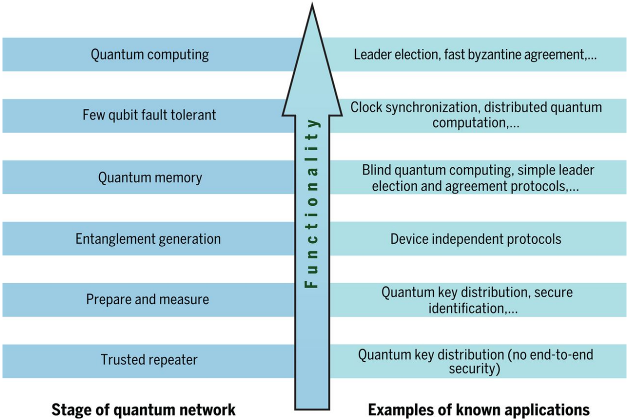


What can we do with quantum networks?

- ✓ "Point-to-point" communication tasks (e.g., teleportation, quantum key distribution).
- ✓ Distributed quantum computation.

Many others, with lots of room to explore!



[Science **362**, 2018]

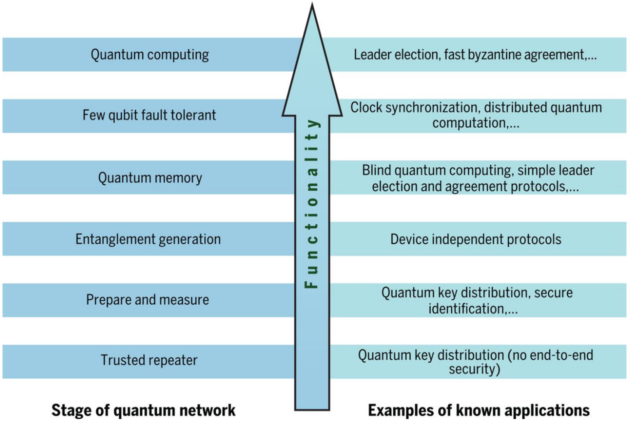
What can we do with quantum networks?

- ✓ "Point-to-point" communication tasks (e.g., teleportation, quantum key distribution).
- ✓ Distributed quantum computation.

Many others, with lots of room to explore!

What *can't* we do with quantum networks?

- ✗ Faster-than-light communication.
- ✗ Replace current internet.



[Science **362**, 2018]

Outline

1. Background
2. The promise of the quantum internet (prospects)
3. What has been done so far (progress)
4. How to fulfill the promise (challenges)
5. Outlook

Outline

1 Background

2 The promise of the quantum internet (prospects)

3 What has been done so far (progress)

4 How to fulfill the promise (challenges)

5 Outlook

Quantum mechanics

- In short, the study of matter on small scales.

Quantum mechanics

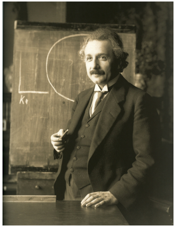
- In short, the study of matter on small scales.

Foundational discoveries

Planck
Blackbody radiation
$E = h\nu$
(Discrete energies)

Heisenberg
$\Delta X \Delta P \geq \frac{\hbar}{2}$
(Uncertainty relation)

Schrödinger
$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle = H|\psi(t)\rangle$
(Dynamics)



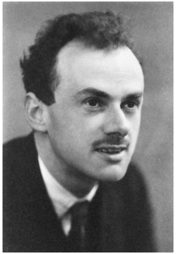
Einstein
Photoelectric effect
EPR paradox
(Entanglement)

Born
Born rule
(Measurements)

Quantum mechanics

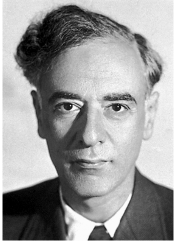
- In short, the study of matter on small scales.

Axiomatic mathematical formulation



Dirac

von Neumann



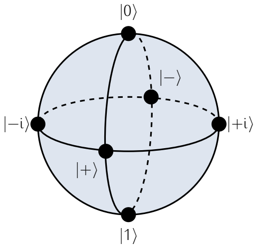
Landau

Quantum mechanics → quantum information

- View physical, quantum-mechanical systems as *carriers of information*.

Bit

0 or 1;
or probabilistic mixture



Qubit

$|0\rangle$ or $|1\rangle$;
or *superposition*

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle,$$
$$\alpha, \beta \in \mathbb{C},$$
$$|\alpha|^2 + |\beta|^2 = 1$$

$$|\pm\rangle = \tfrac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$
$$|\pm i\rangle = \tfrac{1}{\sqrt{2}}(|0\rangle \pm i|1\rangle)$$

Abstract picture:

- Quantum system (atoms, photons, etc.) ≡ Hilbert space.
- Physical evolution ≡ quantum channel.

No-cloning theorem

Foundations of Physics, Vol. 1, No. 1, 1970

The Concept of Transition in Quantum Mechanics

James L. Park

Department of Physics, Washington State University, Pullman, Washington

Nature Vol. 299 28 October 1982

A single quantum cannot be cloned

W. K. Wootters*

Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712, USA

W. H. Zurek

Theoretical Astrophysics 130–33, California Institute of Technology, Pasadena, California 91125, USA

Volume 92A, number 6 PHYSICS LETTERS 22 November 1982

COMMUNICATION BY EPR DEVICES

D. DIEKS

Fysisch Laboratorium, Rijksuniversiteit Utrecht, Utrecht, The Netherlands

Received 17 August 1982
Revised manuscript received 21 September 1982

A recent proposal to achieve faster-than-light communication by means of an EPR-type experimental set-up is examined. We demonstrate that such superluminal communication is not possible. The crucial role of the linearity of the quantum mechanical evolution laws in preventing causal anomalies is stressed.

There does not exist a unitary (linear) operation that can copy an arbitrary quantum state.

Bell's theorem

Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

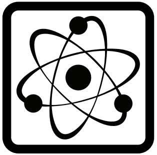
J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

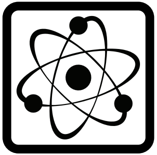
(*Received 4 November* 1964)

Correlations in quantum mechanics do not generally correspond to a local-hidden-variable model.

Entanglement

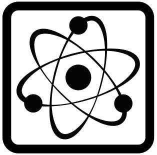
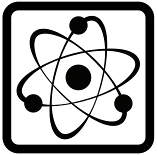
Alice





Bob

Alice and Bob images from https://levelup.gitconnected.com/quantum-key-distribution-for-everyone-f08dd5646f33


Alice



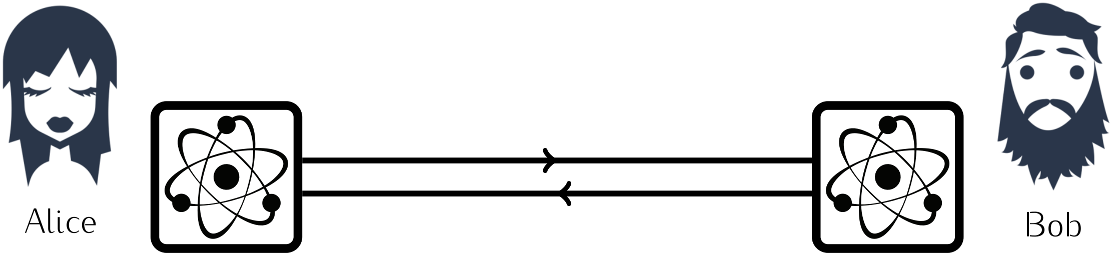
Bob

$$\rho_{AB} = \sigma_A \otimes \tau_B$$

Product state

Alice and Bob individually prepare their systems.

Entanglement

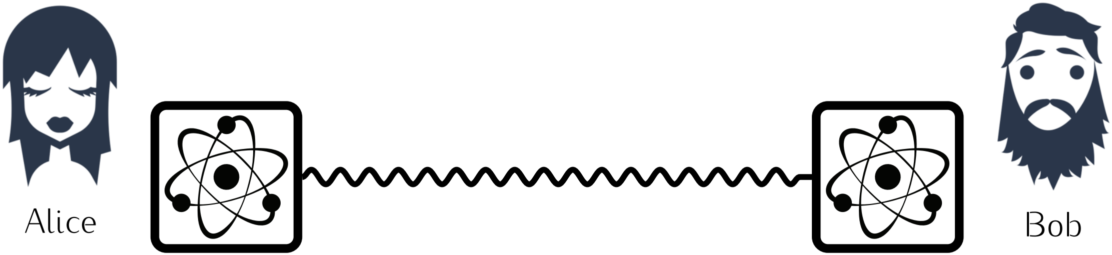


$$\rho_{AB} = \sum_{x \in \mathcal{X}} p(x) \sigma_A^x \otimes \tau_B^x$$

Separable state

Alice and Bob individually prepare their systems via local operations and classical communication.

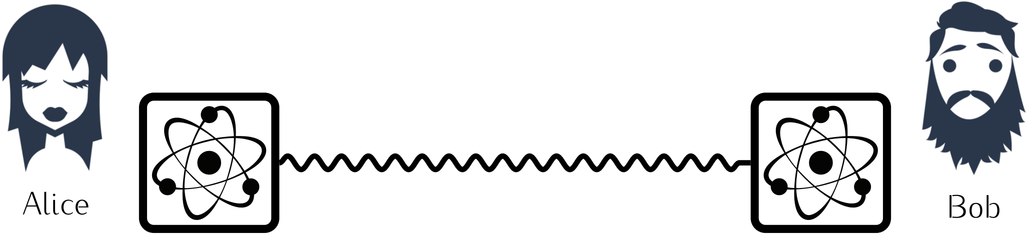
Entanglement



$$\rho_{AB} \neq \sum_{x \in \mathcal{X}} p(x) \sigma_A^x \otimes \tau_B^x$$

Entangled state

Correlations between Alice and Bob are non-local.
State of the individual systems not sufficient to describe the pair.



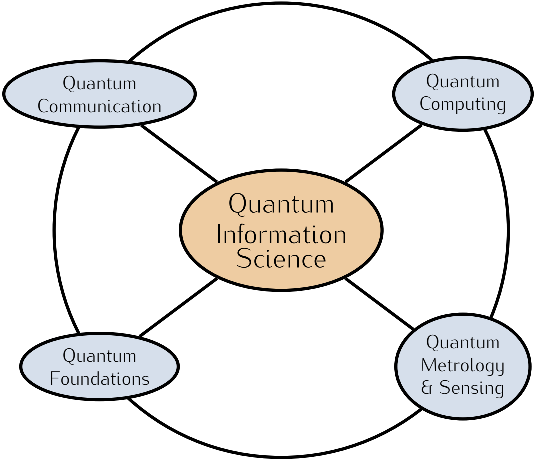
$$|\Phi^{\pm}\rangle_{AB} = \frac{1}{\sqrt{2}}(|0,0\rangle_{AB} \pm |1,1\rangle_{AB}), \quad |\Psi^{\pm}\rangle_{AB} = \frac{1}{\sqrt{2}}(|0,1\rangle_{AB} \pm |1,0\rangle_{AB})$$

Bell states

State is locally random,
but joint measurement results are correlated.

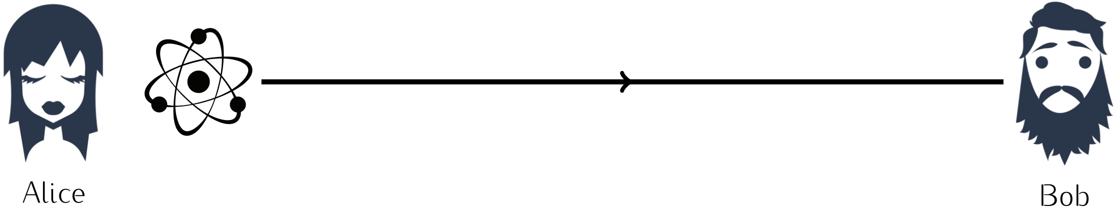
Quantum information science

- Harness superposition and entanglement to do certain tasks better/faster. (e.g., factoring, simulation)
- Also discover *new* things. (e.g., teleportation, QKD)



Quantum communication

⋆ Using quantum systems and quantum strategies to send bits and qubits.



Ideal quantum channel from Alice to Bob.

Quantum communication

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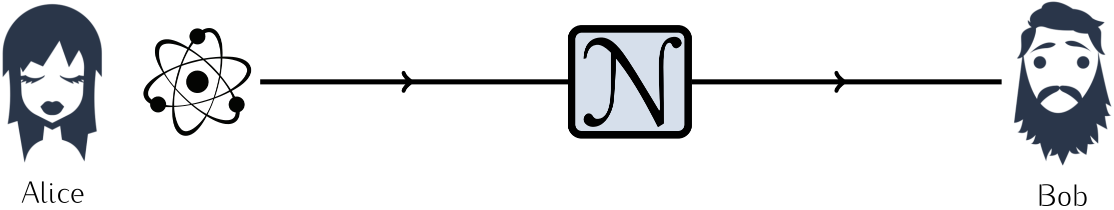
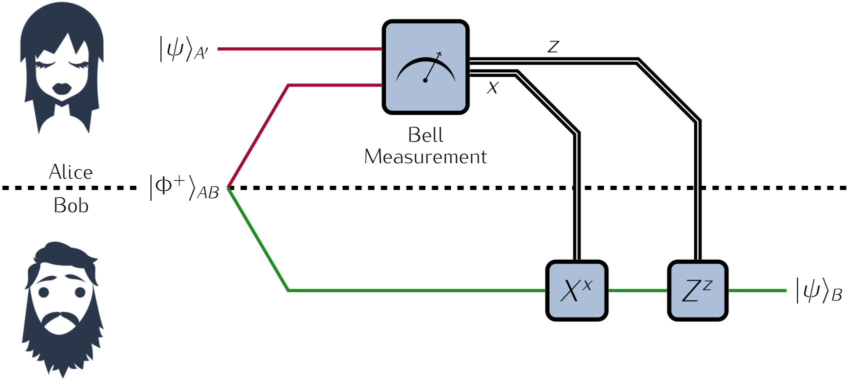


Noisy quantum channel from Alice to Bob, models imperfections in the transmission medium.

Quantum communication

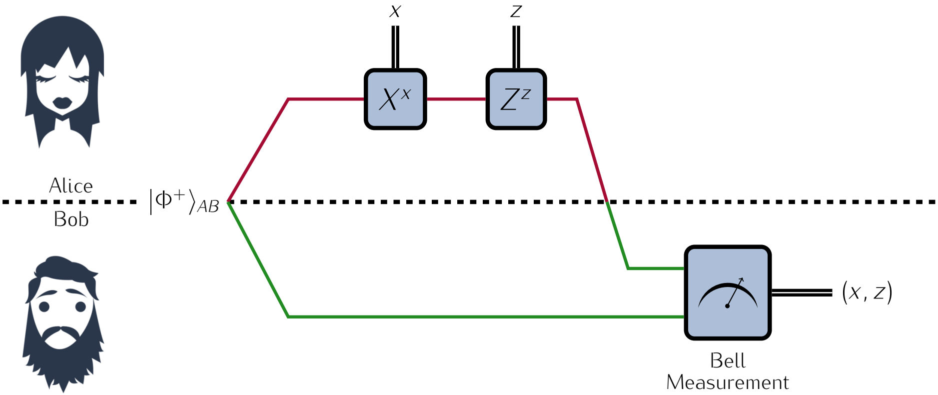
Teleportation: shared entanglement + classical communication = transmission of an arbitrary quantum state



No physical transmission of quantum systems! Only classical communication!

Quantum communication

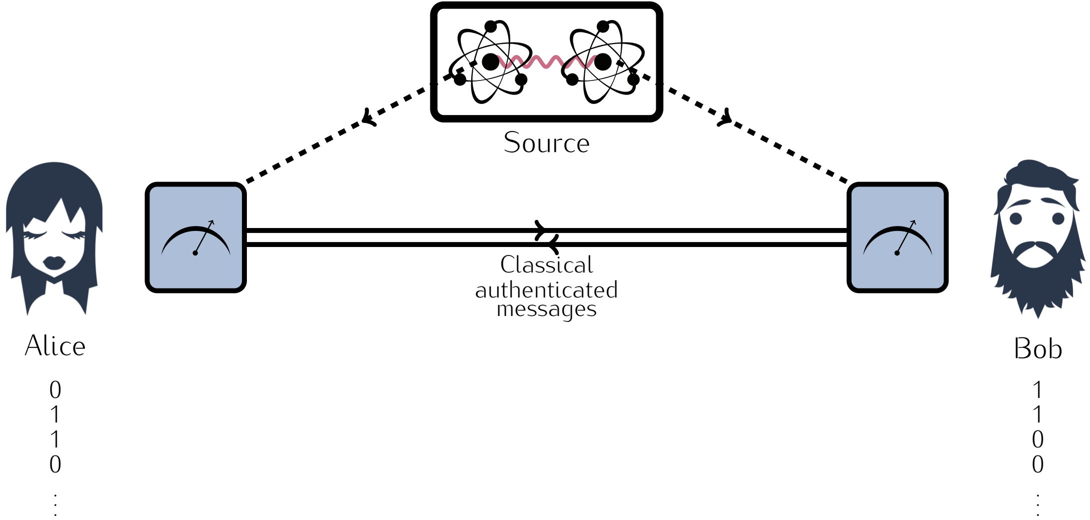
Superdense coding: entanglement-assisted classical communication



Two classical bits with one use of an ideal quantum channel and a shared entangled state!

Quantum communication

Quantum key distribution: private classical communication with quantum strategies/resources



Quantum communication

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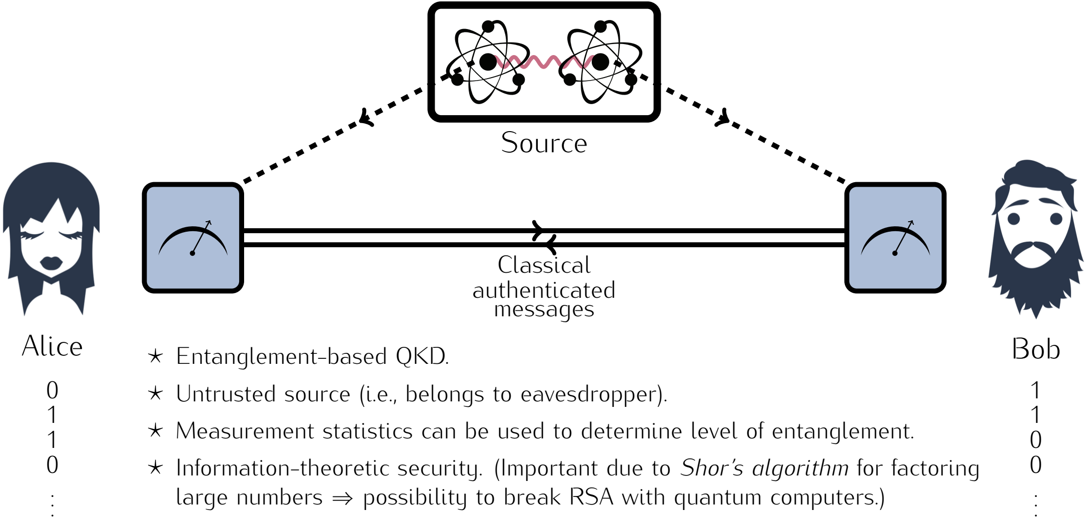

- ⋆ Entanglement-based QKD.
- ⋆ Untrusted source (i.e., belongs to eavesdropper).
- ⋆ Measurement statistics can be used to determine level of entanglement.
- ⋆ Information-theoretic security. (Important due to *Shor's algorithm* for factoring large numbers ⇒ possibility to break RSA with quantum computers.)

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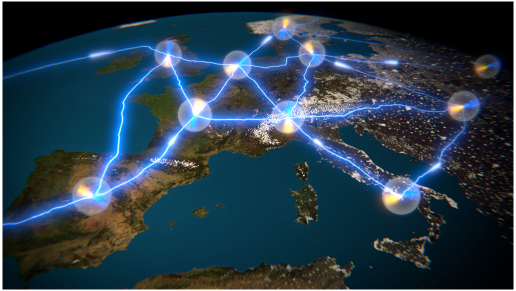
Quantum communication → quantum networks

⋆ From two nodes (Alice and Bob) to multiple!

- Communication (teleportation, superdense coding, QKD) between arbitrary sets of nodes.
- Multiparty protocols (e.g., conference key agreement, secret sharing)
- Routing (finding paths).
- Resource allocation.



Edges indicate physical links (quantum channels), e.g., fiber-optic links.

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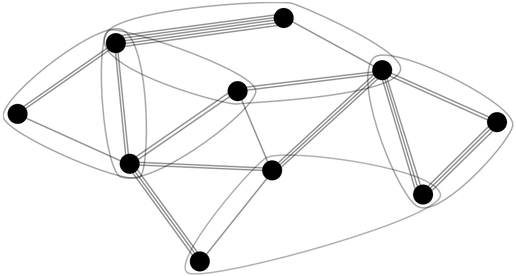

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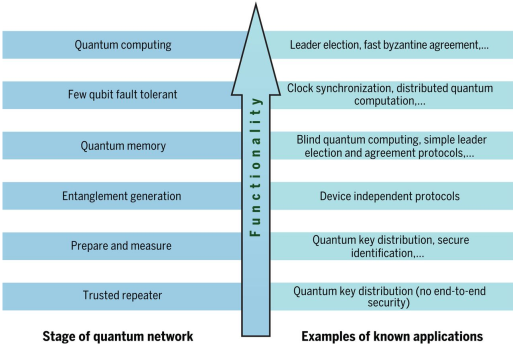
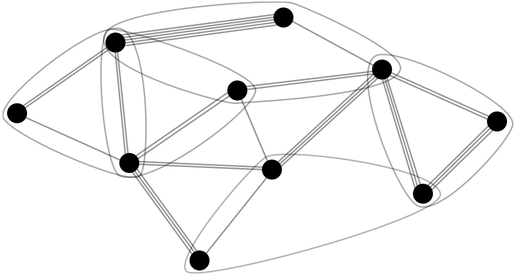
Applications of quantum networks



[Science **362**, 2018]



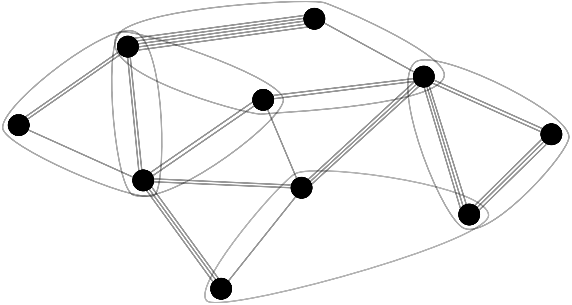
Edges indicate physical links (quantum channels), e.g., fiber-optic links.

⋆ Most of these tasks are based on entanglement ⇒ need to distribute entanglement in the network!

Entanglement distribution

Start with the physical graph.

Physical graph



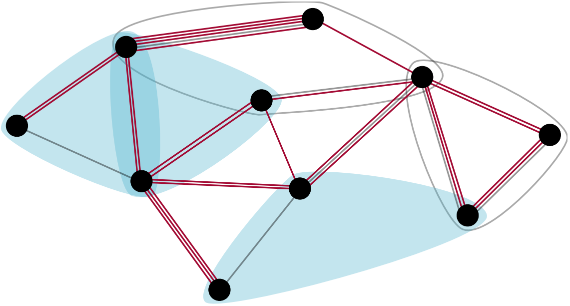
Edges indicate physical links (quantum channels), e.g., fiber-optic links.

Entanglement distribution

Start with the physical graph.

1. **Generate *elementary links*:** entangled states shared by adjacent nodes.

Subgraph of active elementary links



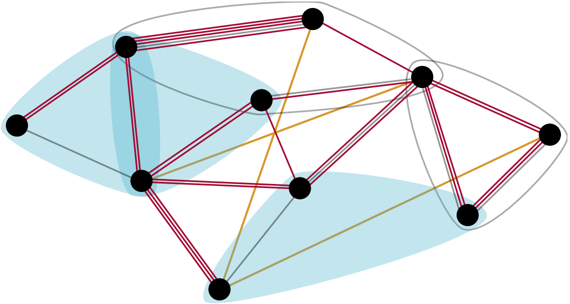
Colored edges indicate entangled states (*elementary links*) distributed using the quantum channels.

Entanglement distribution

Start with the physical graph.

1. **Generate *elementary links*:** entangled states shared by adjacent nodes.
2. **Generate *virtual links*:** entangled states shared by non-adjacent nodes.
   - Joining measurements (e.g., entanglement swapping).
   - Routing.

Graph of elementary and virtual links



Red and blue edges indicate elementary links; orange edges indicate virtual links.

Start with the physical graph.

1. **Generate *elementary links***: entangled states shared by adjacent nodes.

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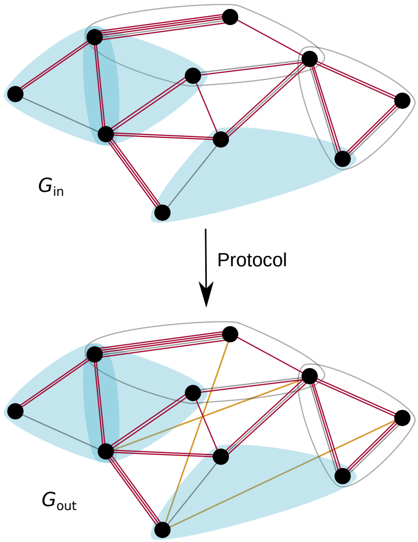
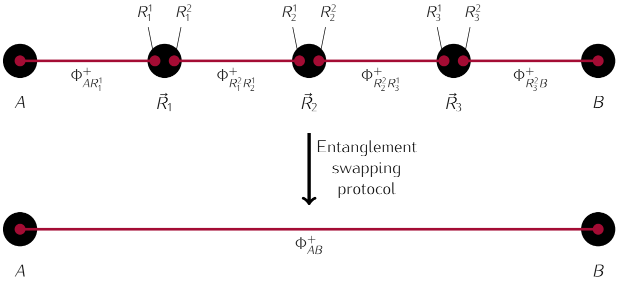


Joining protocol: entanglement swapping

⋆ Generalization of quantum teleportation.

1. Every intermediate node $\vec{R}_j$ performs a Bell-basis measurement; outcomes are communicated to B.

2. B applies correction operation based on outcomes.



⋆ Intermediate nodes are called "repeaters"; similar in spirit to classical amplifiers, which has no direct quantum analogue due to no-cloning!

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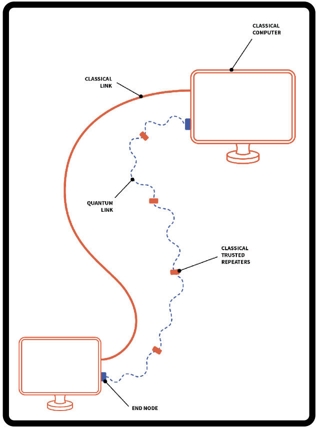
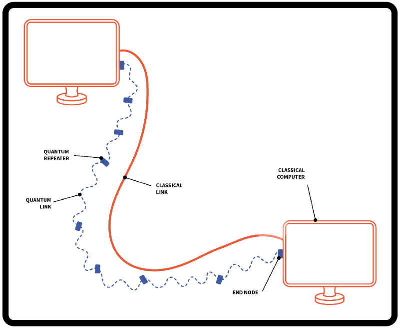
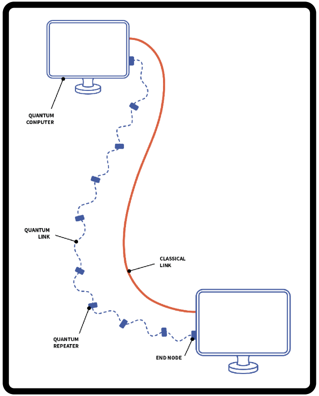
Stages of development



Pre-quantum network



Proto-quantum network



Advanced quantum network

https://tu-delft.foleon.com/tu-delft/quantum-internet/the-six-stages-of-quantum-networks/

Pre-quantum networks

Trusted QKD network in Vienna, Austria

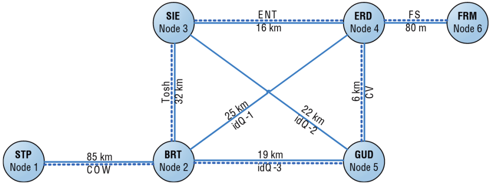


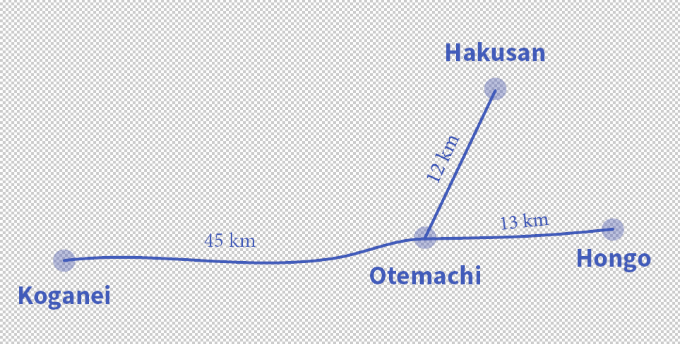
Figure 2. Network topology of the SECOQC QKD network prototype. Solid lines represent quantum communication channels, dotted lines denote classical communication channels.

Figure 3. Satellite map with the locations of the nodes of the prototype.

[NJP **11**, 075001 (2009)]

Pre-quantum networks

Trusted QKD network in Japan

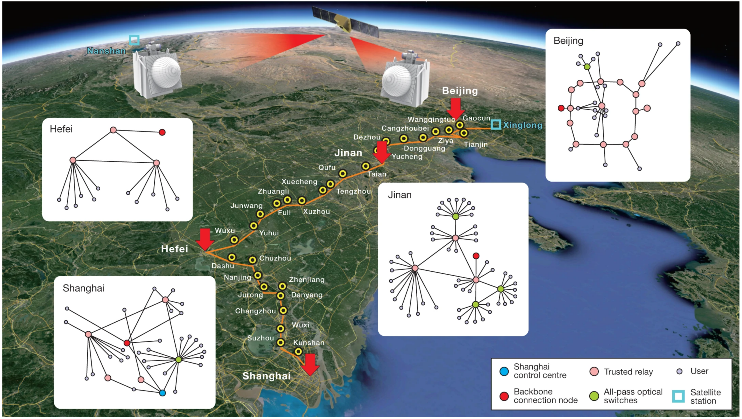


[Opt. Exp. **19**(11), 10387 (2011)]

Image from https://tu-delft.foleon.com/tu-delft/quantum-internet/the-six-stages-of-quantum-networks/

Pre-quantum networks

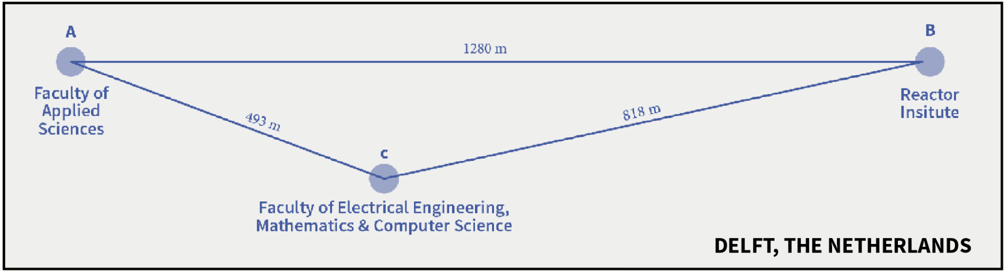
2000km Beijing-to-Shanghai trusted QKD network



[Nature **589**, 214 (2021)]

Proto-quantum networks

Entanglement distribution in Delft, Netherlands



[Nature **526**, 682 (2015)] (see also [Nature **558**, 268 (2018)])

Image from `https://tu-delft.foleon.com/tu-delft/quantum-internet/the-six-stages-of-quantum-networks/`

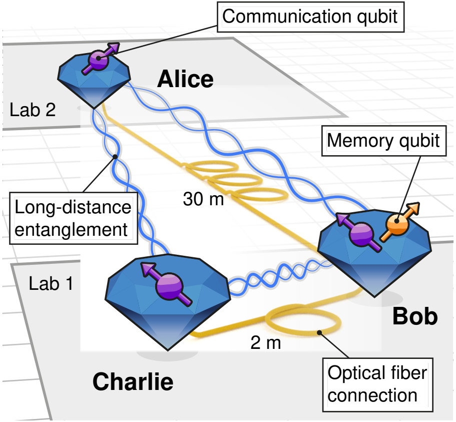
Towards advanced quantum networks

Planned Network in the Netherlands

https://tu-delft.foleon.com/tu-delft/quantum-internet/the-six-stages-of-quantum-networks/

Towards advanced quantum networks

Small-scale three-node network in Delft, Netherlands



[arXiv:2102.04471]

- Distribution of multipartite entanglement.
- Entanglement swapping at B.

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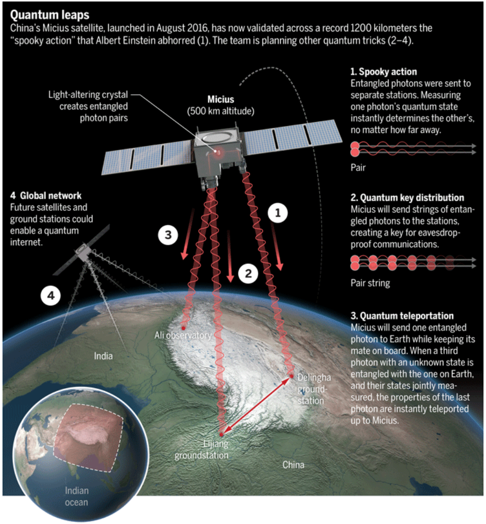
Satellites

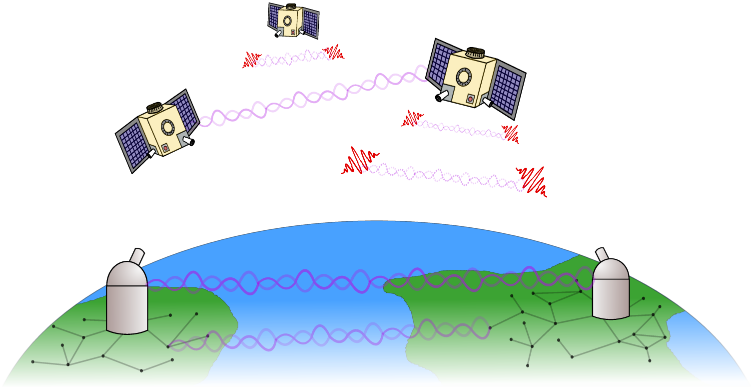


[Science **356**(6343), 1140 (2017)]

https://www.sciencemag.org/news/2017/06/china-s-quantum-satellite-achieves-spooky-action-record-distance

- Longer elementary links.
- Lower overall loss (due to free space).

Proposal for global satellite-based quantum internet [npjQI 7(1), 1-15 (2021)]



Satellites

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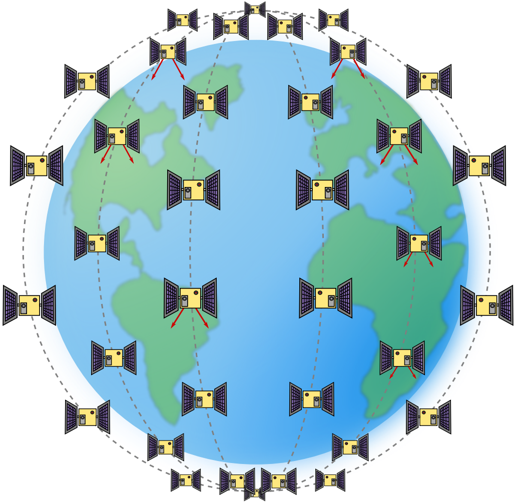

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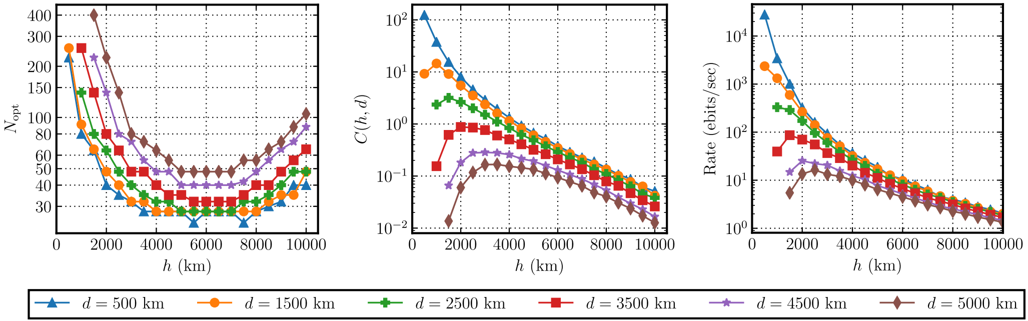

Left: number of satellites; Center: cost function; Right: ebit rate

Satellites

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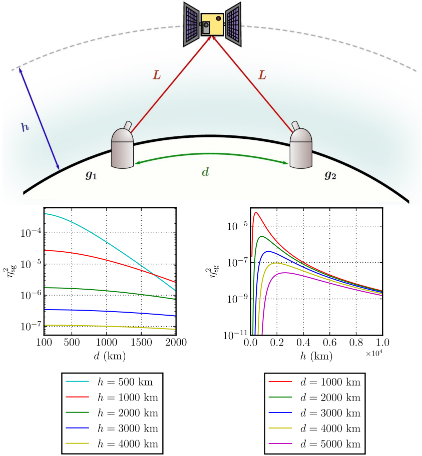

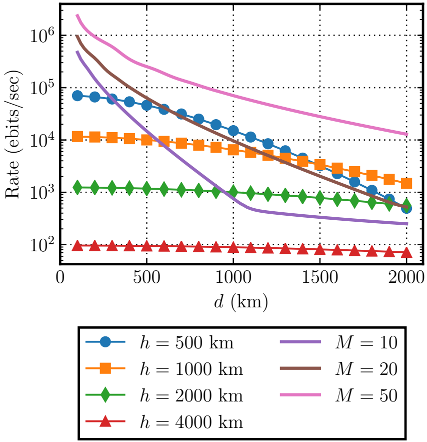

M: number of ground-based repeaters

Fighting errors

- ⋆ Quantum systems undergo decoherence ⇒ imperfect quantum memories.
- ⋆ Imperfect entanglement sources ⇒ noisy entangled states.

Fighting errors

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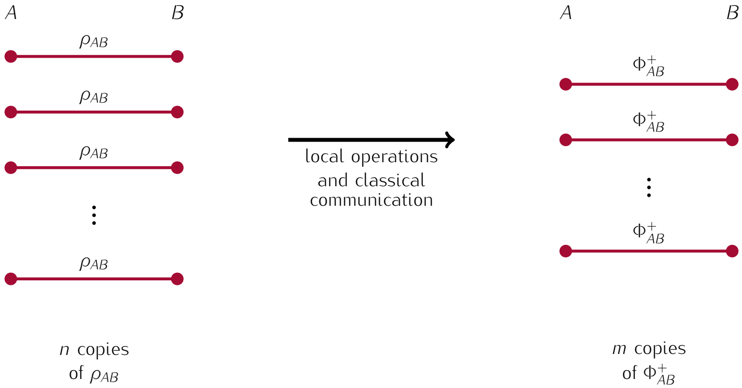
- ⋆ Imperfect entanglement sources ⇒ noisy entangled states.

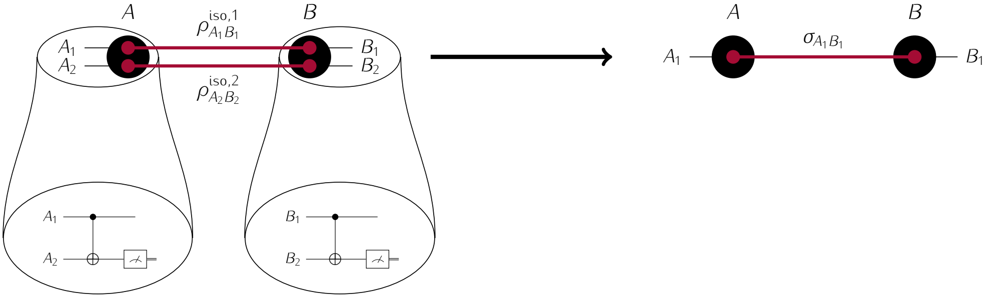
Entanglement distillation



Fighting errors

- ⋆ Quantum systems undergo decoherence ⇒ imperfect quantum memories.
- ⋆ Imperfect entanglement sources ⇒ noisy entangled states.

Entanglement distillation



[PRL **76**, 722 (1996)]

Towards fault-tolerance

⋆ More generally **error correction**: encoding data in a redundant fashion, such that errors can be corrected, original quantum state can be recovered.

Fault-tolerant quantum repeater schemes

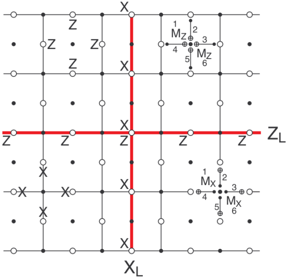


FIG. 1 (color online). A surface code logical qubit. Stabilizers *ZZZZ* (*XXXX*) are associated with the data qubits (open circles) around each face (vertex). Syndrome qubits (dots) measure stabilizers using the indicated sequences of gates. Logical operators Z_L, X_L connect opposing boundaries.

[PRL **104**, 180503 (2010)]

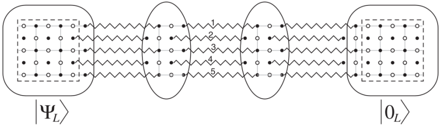


FIG. 3. Repeater-based surface code quantum communication. The qubit pattern in each quantum repeater (ovals) is for $d = 3$. The pattern width is independent of d.

Towards fault-tolerance

⋆ More generally **error correction**: encoding data in a redundant fashion, such that errors can be corrected, original quantum state can be recovered.

Fault-tolerant quantum repeater schemes

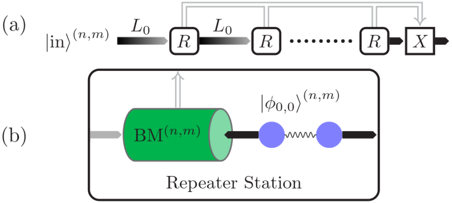


FIG. 1. One-way communication scheme. (a) To send a quantum state $|\text{in}\rangle^{(n,m)}$ over a long distance, repeater stations (R) at shorter distances L_0 are used to recover the qubit from accumulated losses (fading arrows). A classical signal (double line) defines a single Pauli correction X at the receiver. (b) Each repeater station consists of an encoded Bell state and a highly efficient, loss-resistant, logical Bell measurement [$\text{BM}^{(n,m)}$] acting on the incoming signal and one half of the Bell state. The other half of the Bell state is sent to the next station along with the result of the BM (classical signal).

$$|\text{in}\rangle^{(n,m)} := \alpha|0\rangle^{(n,m)} + \beta|1\rangle^{(n,m)},$$

$$|0\rangle^{(n,m)} := \frac{1}{\sqrt{2}}\left(|+\rangle^{(n,m)} + |-\rangle^{(n,m)}\right),$$

$$|1\rangle^{(n,m)} := \frac{1}{\sqrt{2}}\left(|+\rangle^{(n,m)} - |-\rangle^{(n,m)}\right),$$

$$|\pm\rangle^{(n,m)} := \frac{1}{\sqrt{2^n}}\left(|0\rangle^{\otimes m} \pm |1\rangle^{\otimes m}\right)^{\otimes n},$$

[PRL **117**, 210501 (2016) & PRA **95**, 012327 (2017)]

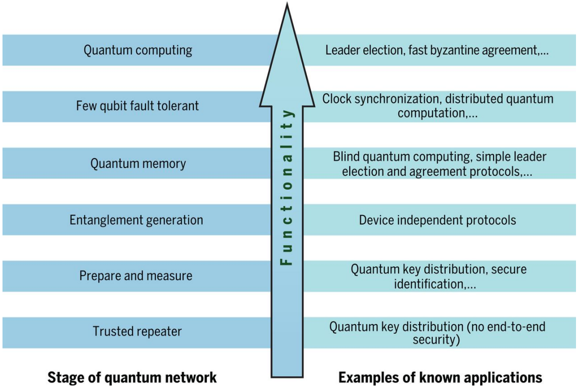
Towards fault-tolerance

- ⋆ More generally **error correction**: encoding data in a redundant fashion, such that errors can be corrected, original quantum state can be recovered.

Fault-tolerant quantum repeater schemes

These schemes require:

- ⋆ Physical qubits with low error rate;
- ⋆ Gate operations with low error rate;



Outline

1. Background
2. The promise of the quantum internet (prospects)
3. What has been done so far (progress)
4. How to fulfill the promise (challenges)
5. Outlook

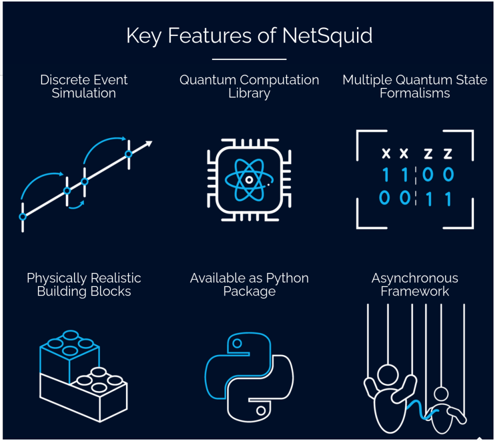
Research directions

Investigate *near-term quantum networks*

- Optimal protocols, making best use of non-ideal current and near-term resources.
- Develop simulation tools.

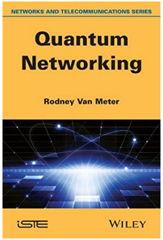
NetSquid
The Network Simulator for Quantum Information using Discrete events

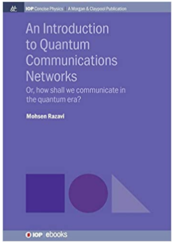
https://netsquid.org/



Resources

- Quantum internet alliance: `https://quantum-internet.team/`
- Quantum internet research group: `https://datatracker.ietf.org/group/qirg/about/`
- QuTech Academy: `https://qutechacademy.nl/academy-2/online-learning/`
- Quantum networking books





Thank you!