COLLEGE OF ENGINEERING
Electrical & Computer Engineering

Quantum Error Correction for Quantum Computing and Networking

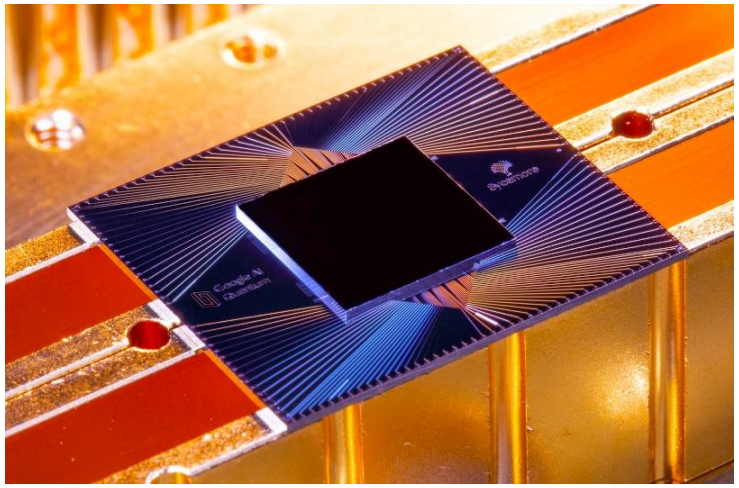
ARIZONA PHOTONICS DAYS
Jan. 25-27, 2023
Tucson, Arizona

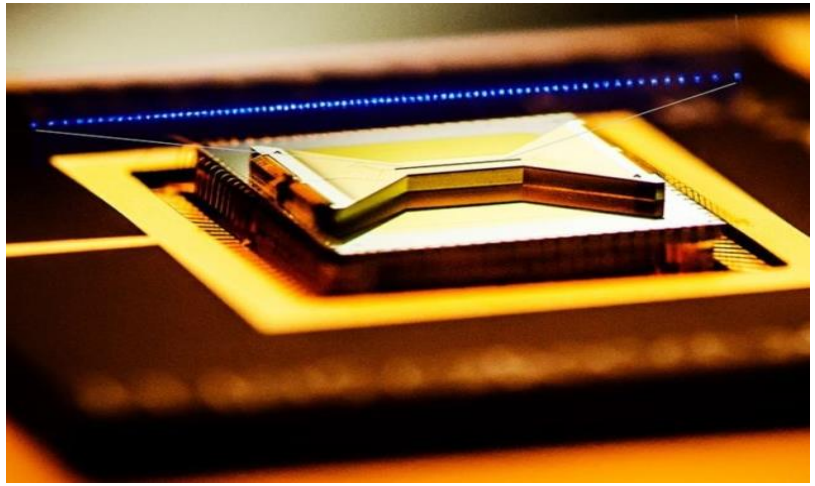
NARAYANAN RENGASWAMY

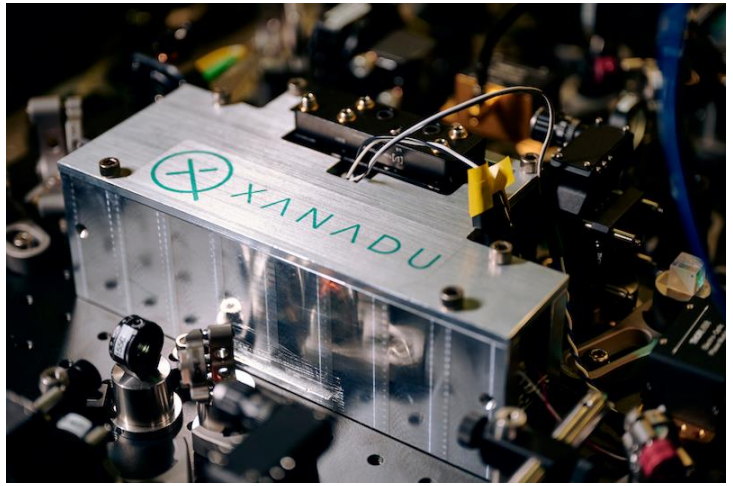
DEPT. OF ELECTRICAL AND COMPUTER ENGINEERING

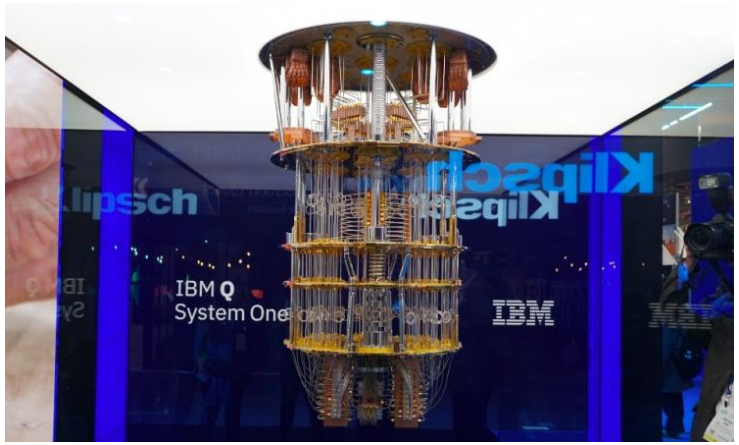
UNIVERSITY OF ARIZONA

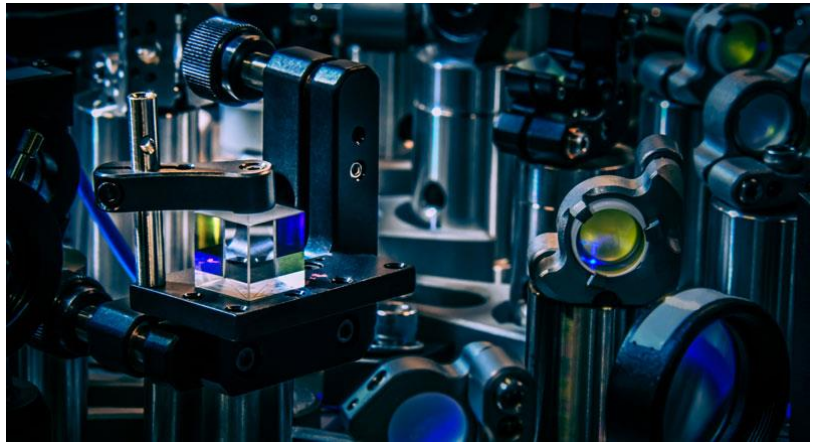
Quantum Technologies

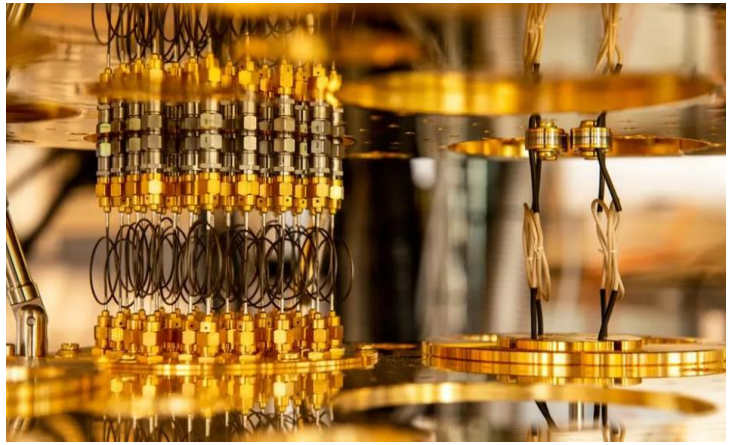












Superconducting

Trapped Ions

Photonic

Quantum Applications

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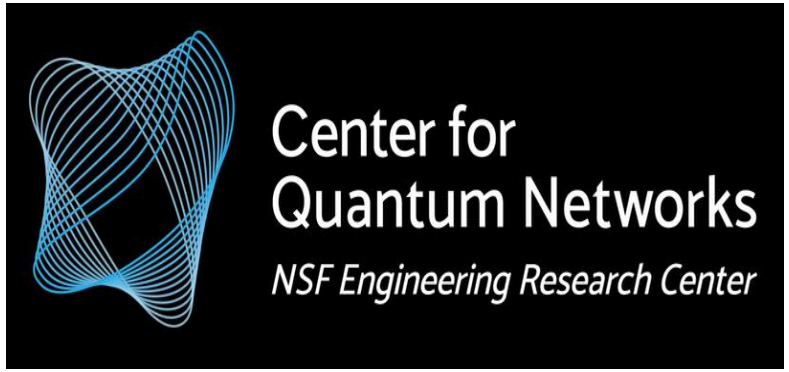
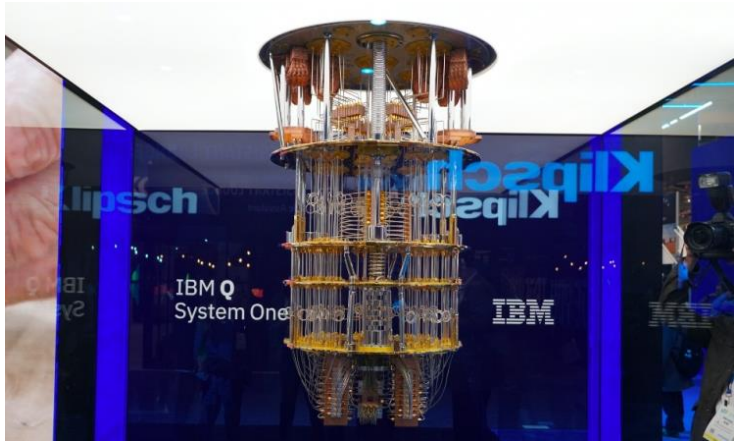
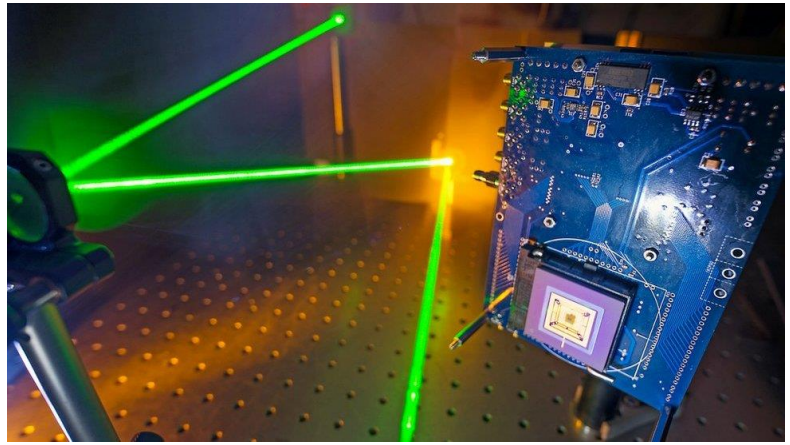




Computing

Networking



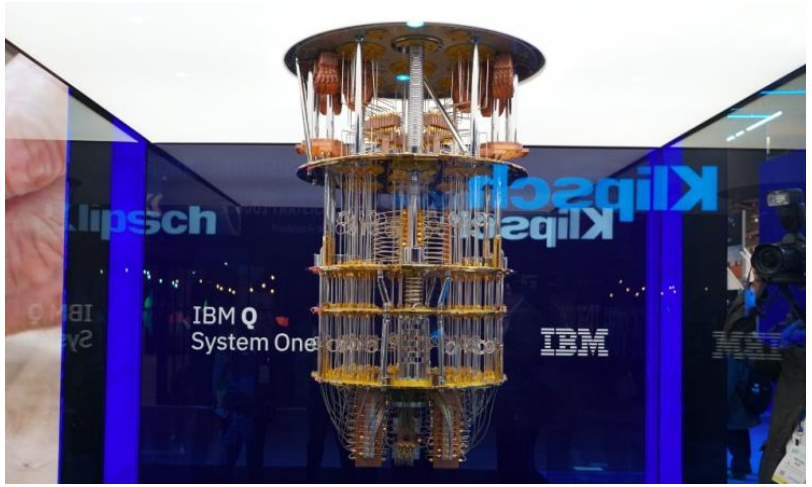
Sensing

How to SCALE in the presence of noise?

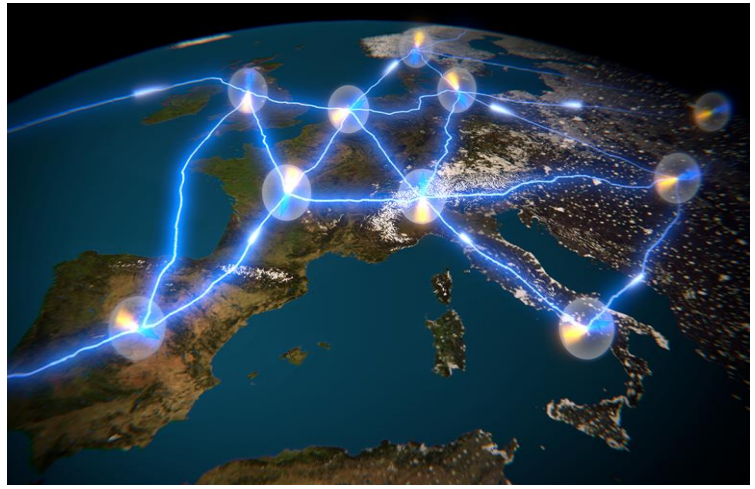
World Challenges

- Green energy
- Drug discovery
- Digital security

Computing



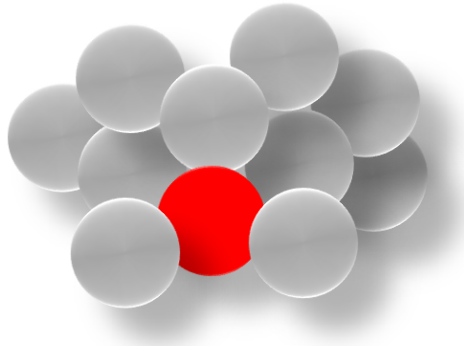
Networking



Qubits are very fragile → **Quantum error correction to the rescue!**

ERRORS

Sophisticated math to solve quantum noise!



United We Stand, Divided We Fall!

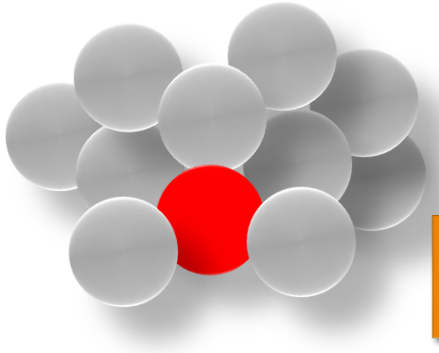
Error Correction in our Cellphones

Communication Channel

1 0 0 … → Channel → 1 1 0 …

Error Correction = Add Redundancy

[111][000][000] … → Channel → [111][100][000] …

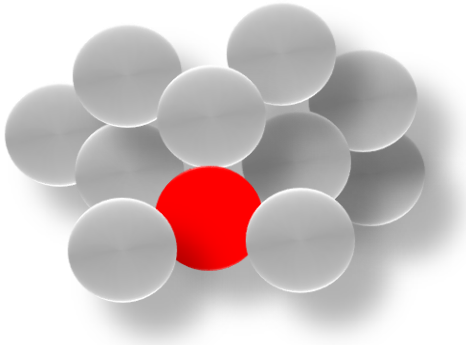


Encode information in correlated bits!

Quantum Error Correction (QEC)

ERRORS

QECC
Encode



United
We Stand,
Divided
We Fall!

Noisy
Logical operation

k qubits $|\psi\rangle_L$ → $|\phi\rangle_L$

QECC
Encode

Translate
(Synthesize)

QECC
Decode

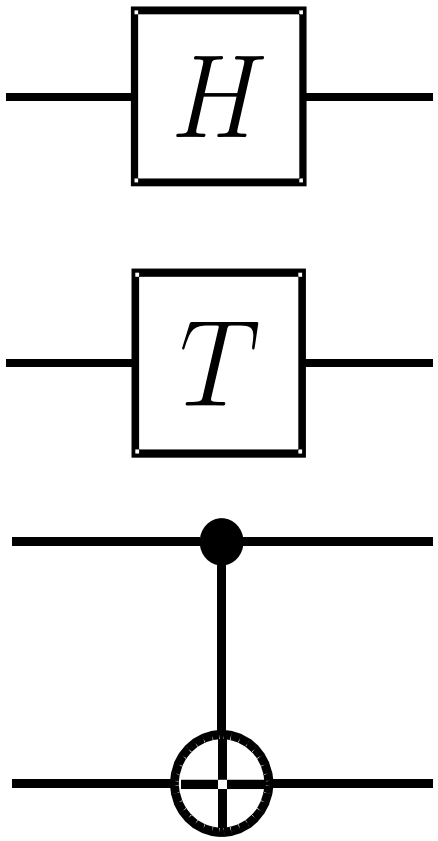
n qubits $\overline{|\psi\rangle}$ → $\overline{|\phi\rangle}$

Physical operation
Fault-tolerant

QECC: Quantum Error Correcting Code

QEC: Universal Fault-Tolerance

Universal set of gates



Noisy

Logical operation

k qubits $|\psi\rangle_L$ → $|\phi\rangle_L$

QECC Encode ↓

Translate (Synthesize)

↑ QECC Decode

n qubits $\overline{|\psi\rangle}$ → $\overline{|\phi\rangle}$

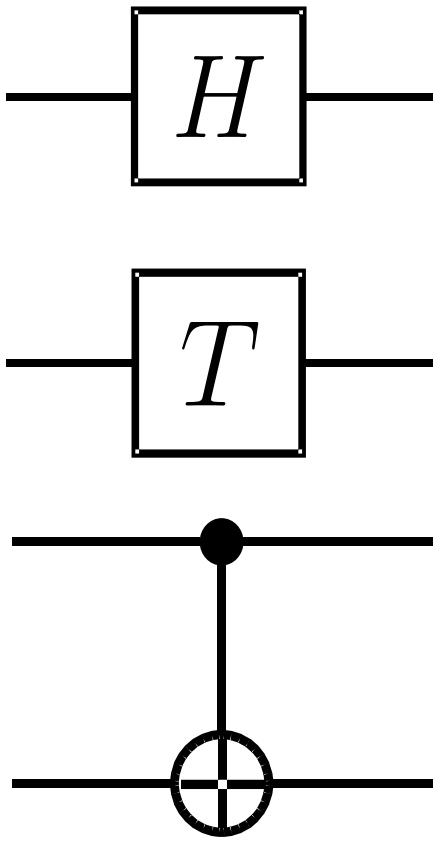
Physical operation

Fault-tolerant

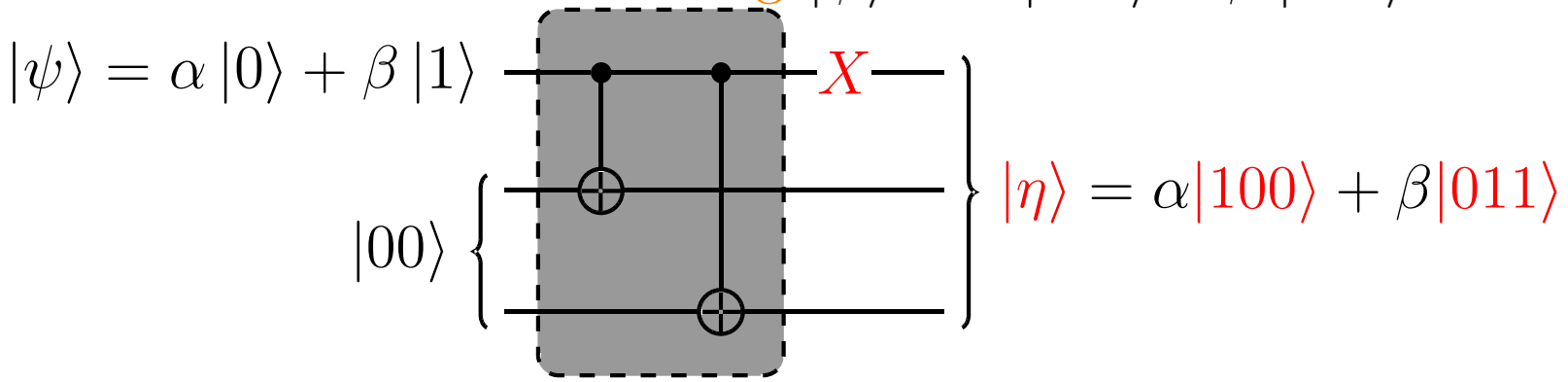
QECC: Quantum Error Correcting Code

QEC: Syndrome Measurement

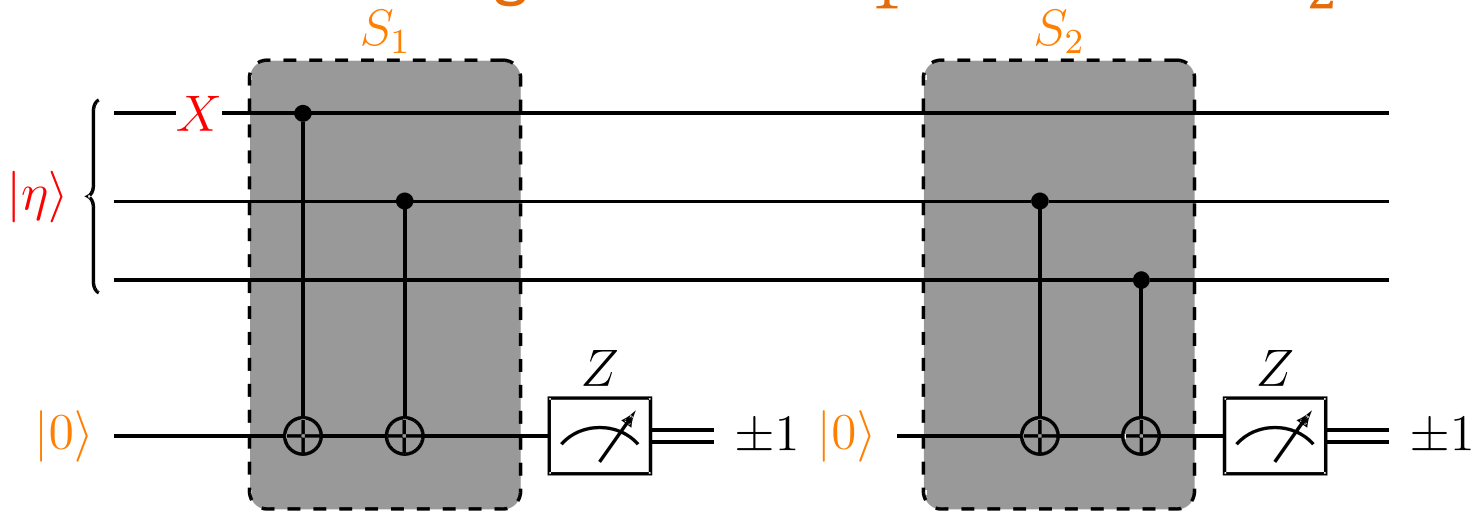
Universal set of gates



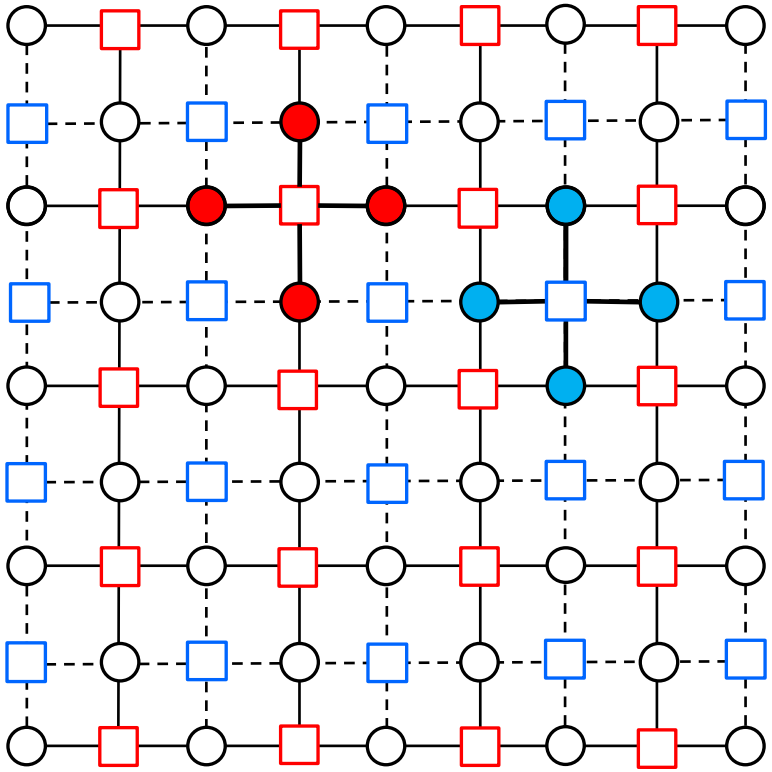
Encoding $\overline{|\psi\rangle} = \alpha\,|000\rangle + \beta\,|111\rangle$



Measure the stabilizer generators $S_1 = ZZI$ and $S_2 = IZZ$:

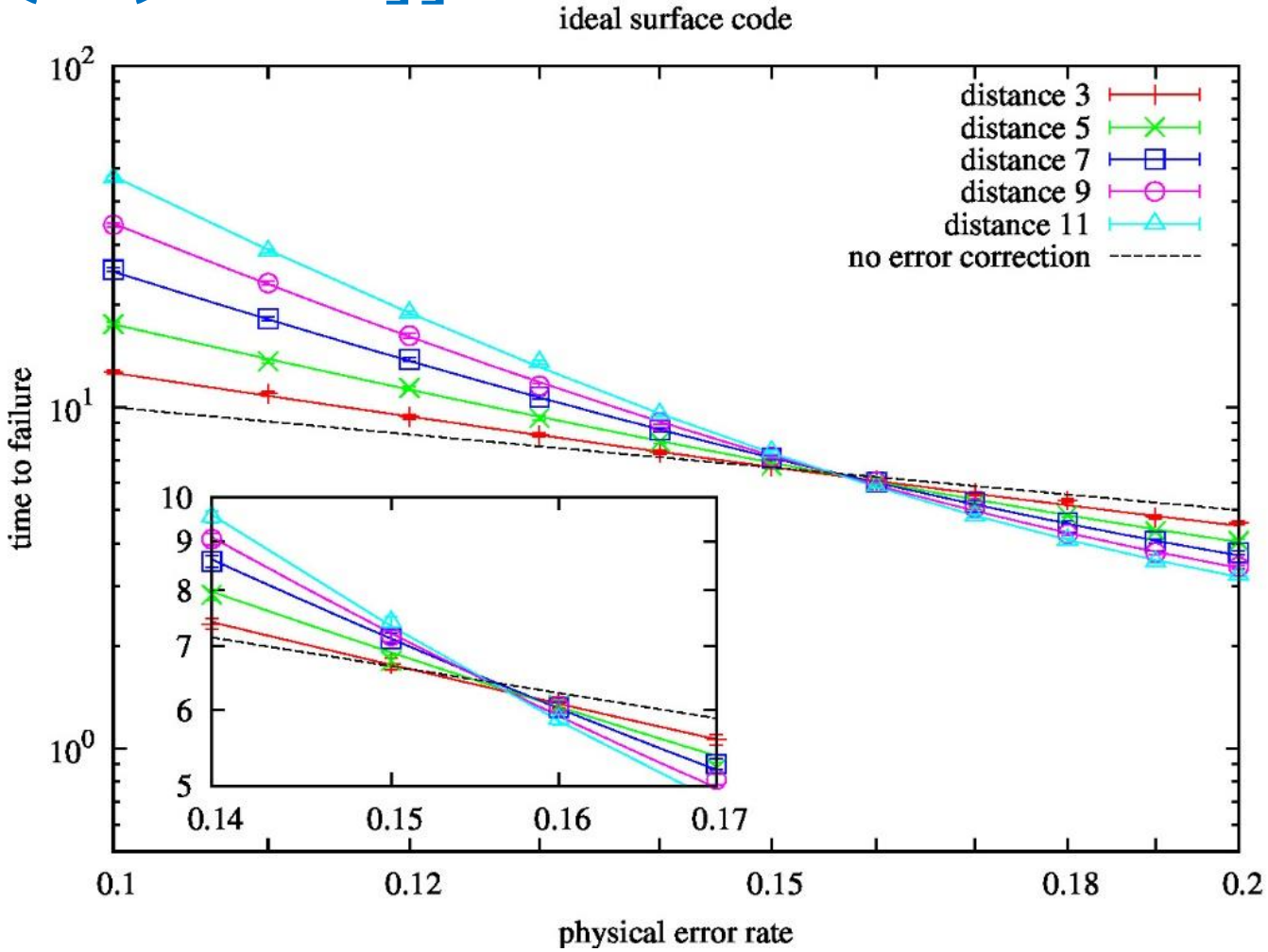


The Surface Code $[[\ O(L^2), 1, L\ ]]$



- vertex checks (H_X)

- plaquette checks (H_Z)



https://arxiv.org/abs/0905.0531

What are “Good” Quantum Codes?

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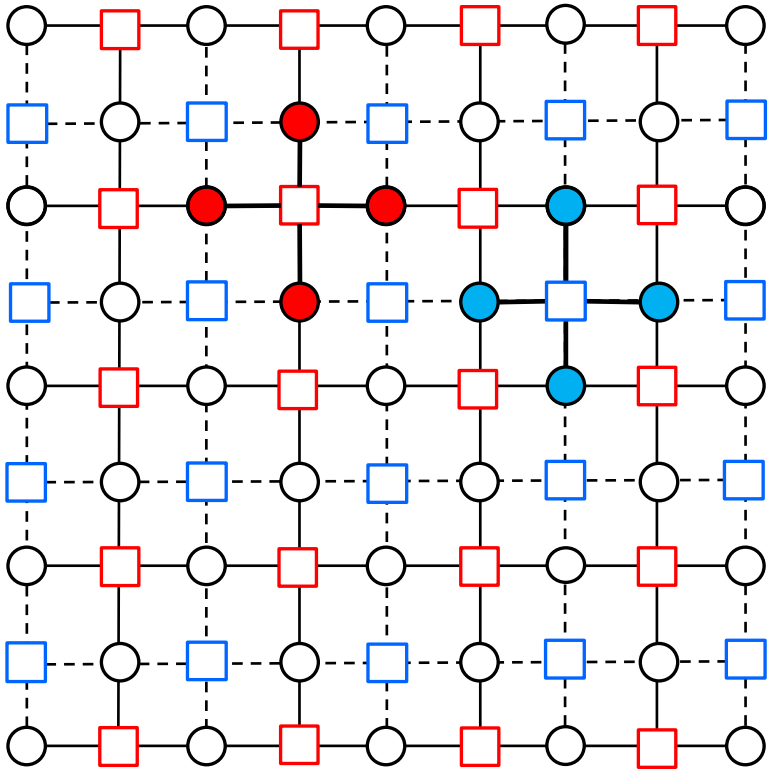

- vertex checks (H_X)

- plaquette checks (H_Z)

Topological Codes	Optimal QLDPC Codes
$[[\, n, 1, O(\sqrt{n}) \,]]$	$[[\, n, O(n), O(n) \,]]$
High error thresholds	Promising thresholds
~ Linear-time decoder	Linear-time decoder
Logical gates done	Very little research
Nearest-neighbor	**Long-range interactions**
Not scalable; large overhead	**Scalable with constant overhead???**

QLDPC: Quantum Low-Density Parity-Check

QEC for Distributed Quantum Computing

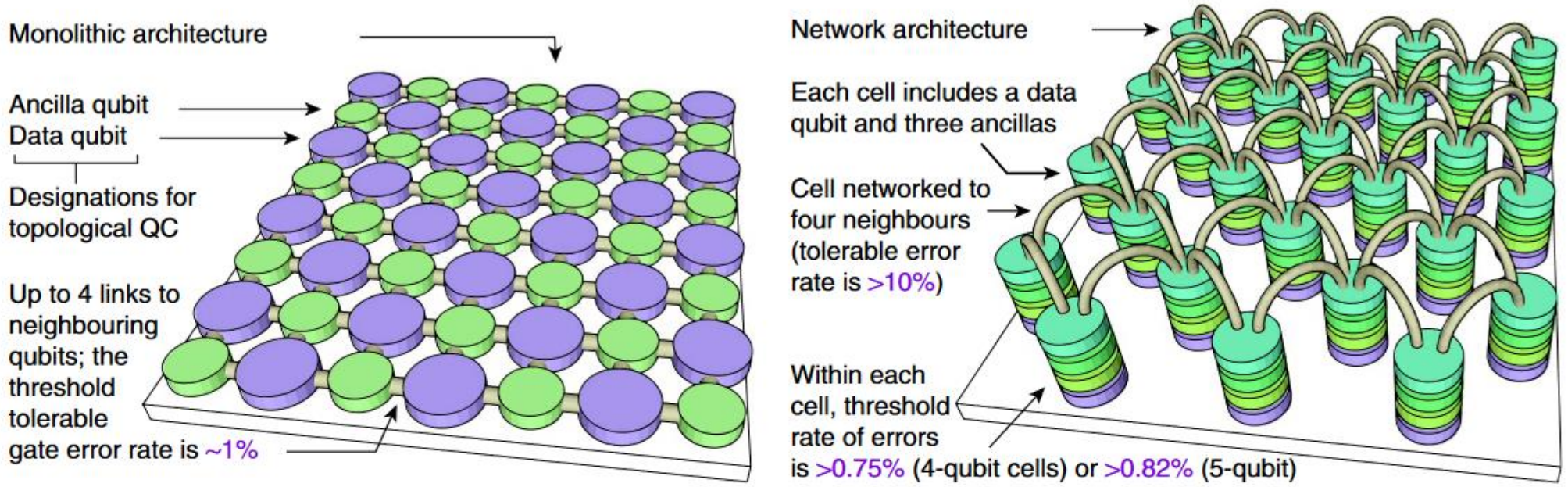

Figure 1 | Quantum architectures. Left: a monolithic grid of qubits with neighbours directly connected to enable high fidelity two-qubit operations. (layout from ref. 5.) Such a structure is a plausible goal for some systems, for example, specific superconducting devices[23]. Right: For other nascent quantum technologies the network paradigm is appropriate. A single nitrogen-vacancy (NV) centre in diamond, with its electron spin and associated nuclear spin(s)[24], would constitute a cell. A small ion trap holding a modest number of ions[10,25] is another example. Noisy network links with error rates $\geq$ 10% are acceptable. For photonic links this goal is realistic given imperfections like photon loss and instabilities in path lengths or interaction strengths. Similarly, with solid state 'wires' formed by spin chains[26], noisy entanglement distribution of this kind is a reasonable goal[27].

N. Nickerson, Y. Li, and S. Benjamin, "Topological quantum computing with a very noisy network and local error rates approaching one percent," *in Nat. Commun.* **4**, 1756 (2013)

QEC for Quantum Networks (Repeaters)

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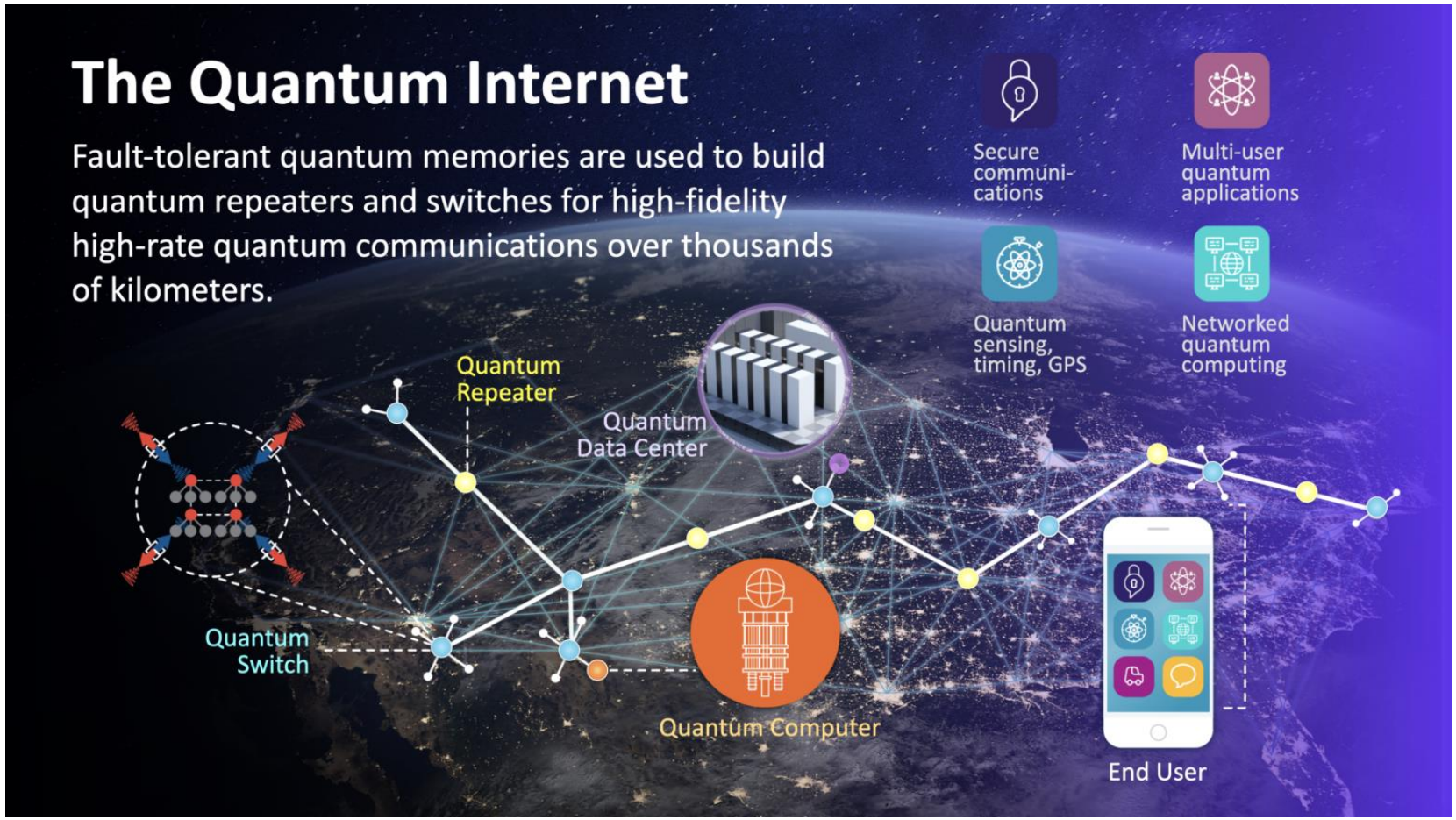

NSF

Center for Quantum Networks
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Thank you!

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