Why should you pay attention to Distributed Quantum Computing?

Maria Gragera Garces, University of Edinburgh

A little bit about myself

UNIVERSITY OF BATH PHYSICS → THE UNIVERSITY of EDINBURGH informatics

A little bit about myself

IBM Quantum

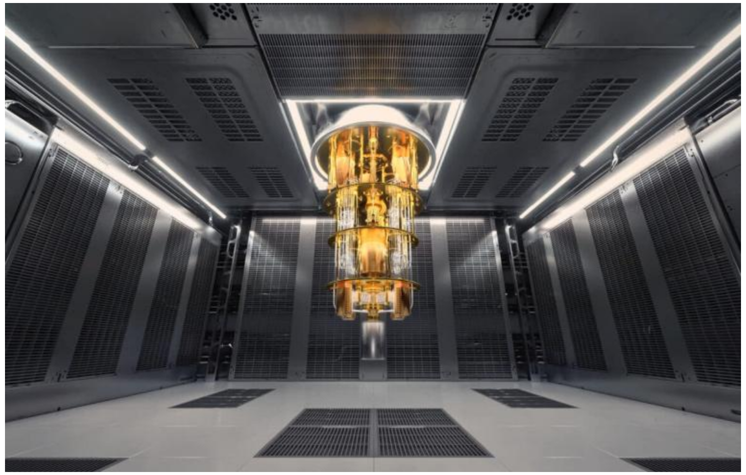
R&D 2021 – 2022
Feltham

Software & Education 2023-2024
Zurich Lab

Internship 2025
Cambridge

A little bit about myself

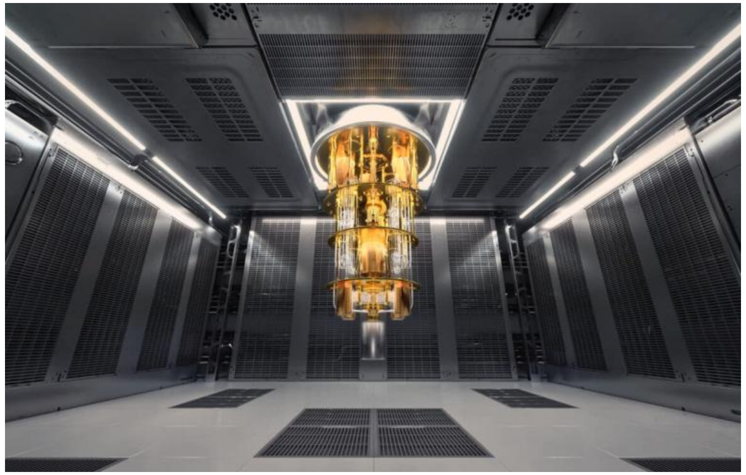
QUANTUM



THE UNIVERSITY of EDINBURGH
informatics

A little bit about myself

QUANTUM



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QUANTUM NETWORKS + QUANTUM COMPUTERS

=

DISTRIBUTED QUANTUM COMPUTING

Scaling quantum computers

is

a **distributed-systems & networking problem**,

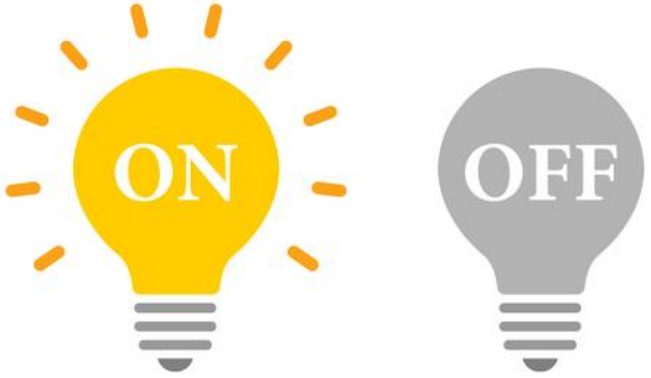
where the **hardest** unsolved parts

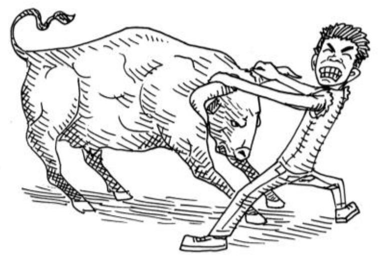
are the kind of thing **we are good at.**

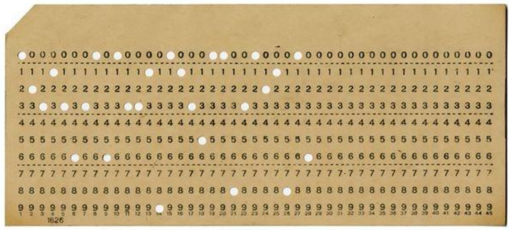
What is Quantum?

- **Qubits vs Bits**

BITS

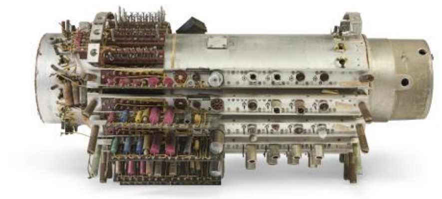




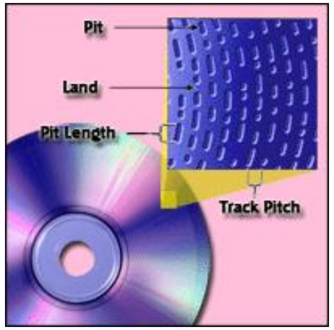


Punch card

Vacuum tube

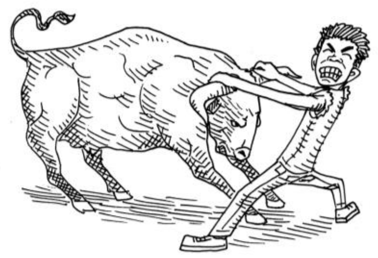


Mercury delay-line memory



DVDs

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

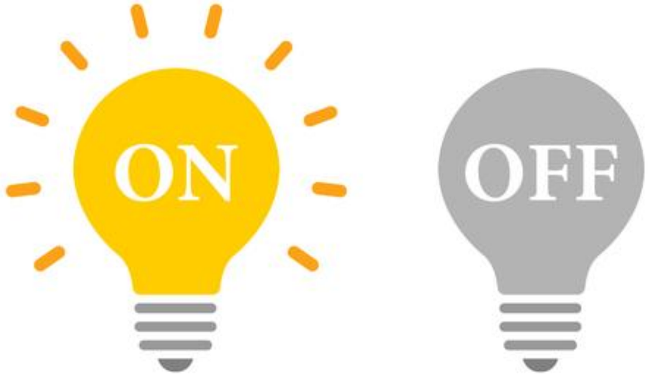


What is Quantum?

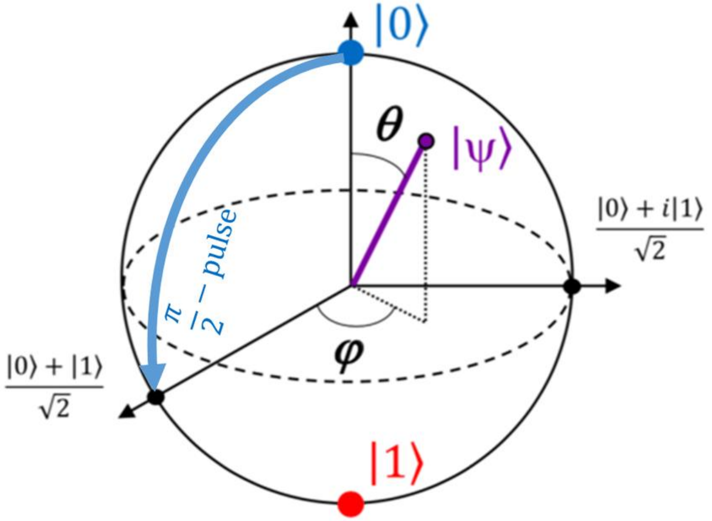
two-dimensional complex vector space (Hilbert space)

- **Qubits vs Bits**

BITS



QUBITS



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

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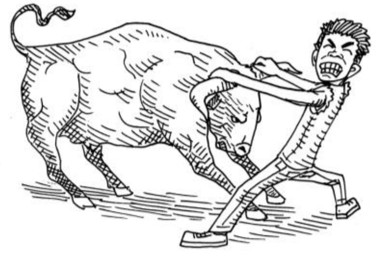
What is Quantum?



- Qubits vs Bits
- **Qubits are physical**

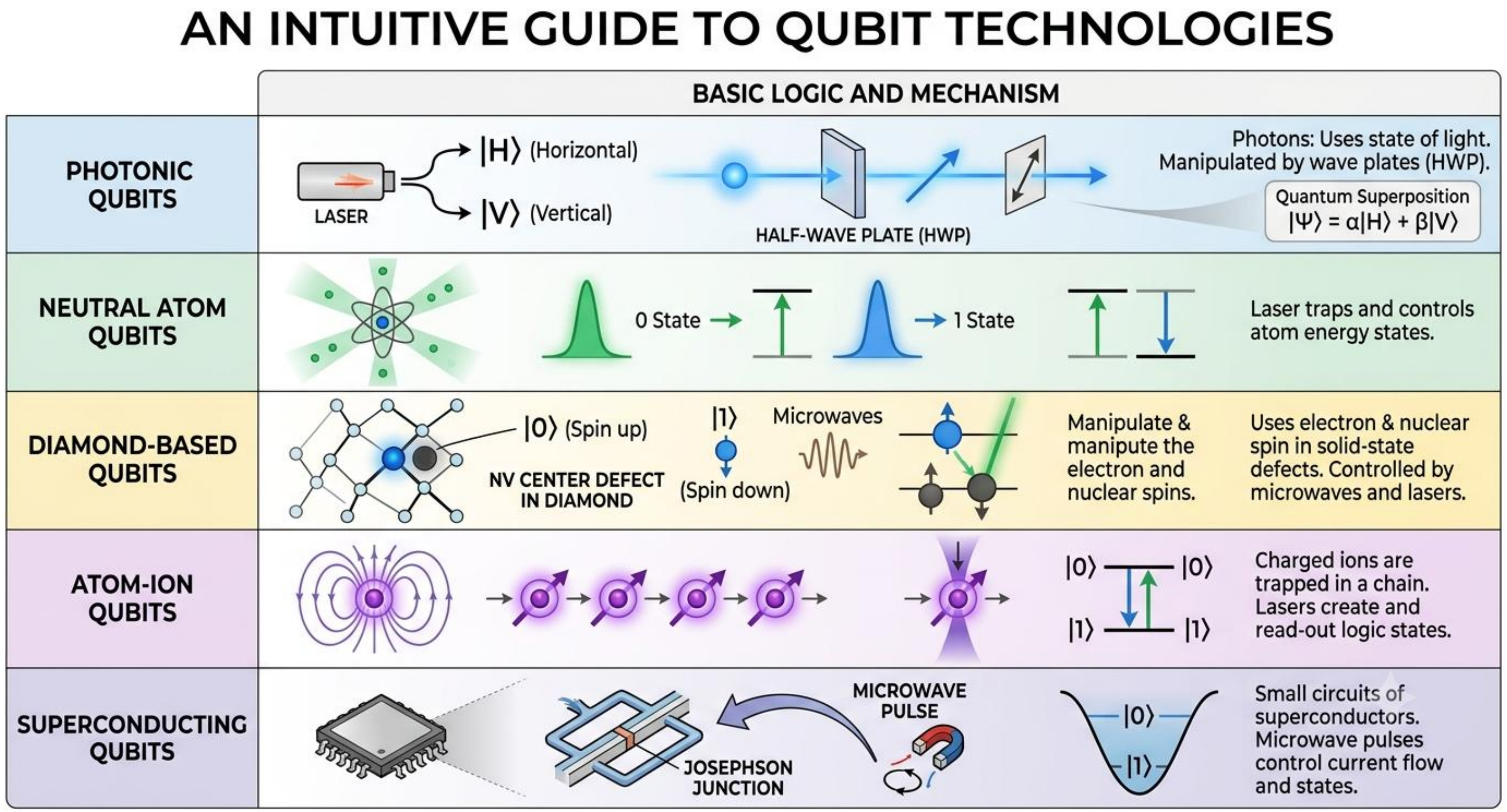


Image created with AI (Gemini)

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

What is Quantum?

- Qubits vs Bits
- Qubits are physical
- **Qubits offer complexity advantages**

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, ... John M. Martinis + Show authors

Sampling

Simulating physics with computers

Published: June 1982

Volume 21, pages 467–488 (1982) Cite this article

Simulating quantum systems

Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer

Author: Peter W. Shor | AUTHORS INFO & AFFILIATIONS

https://doi.org/10.1137/S0097539795293172

Factoring

A fast quantum mechanical algorithm for database search

Author: Lov K. Grover | Authors Info & Claims

STOC '96: Proceedings of the twenty-eighth annual ACM symposium on Theory of Computing • Pages 212 - 219
https://doi.org/10.1145/237814.237866

Unstructured search

FEATURED IN PHYSICS | EDITORS' SUGGESTION

Quantum Algorithm for Linear Systems of Equations

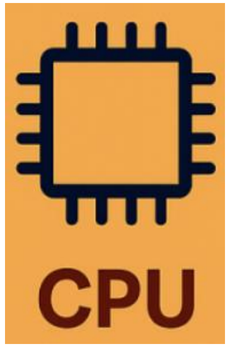
Aram W. Harrow[1], Avinatan Hassidim[2], and Seth Lloyd[3]

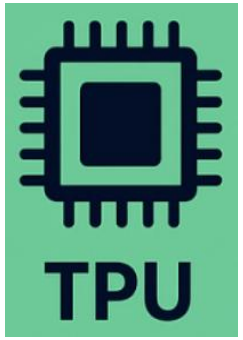
Optimization & ML

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

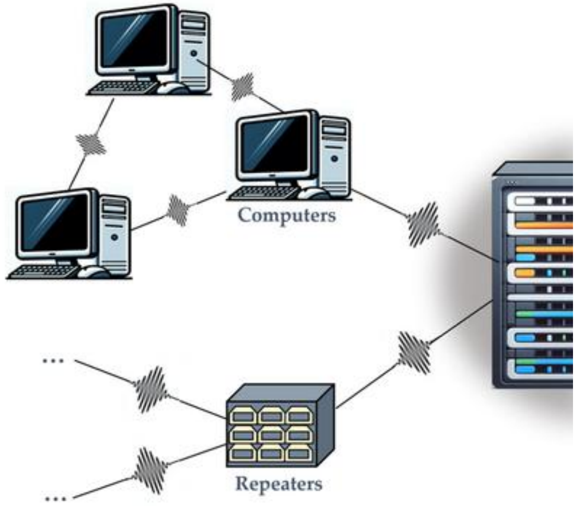
What quantum advantage ***desires***

COMPUTE





COMMUNICATION



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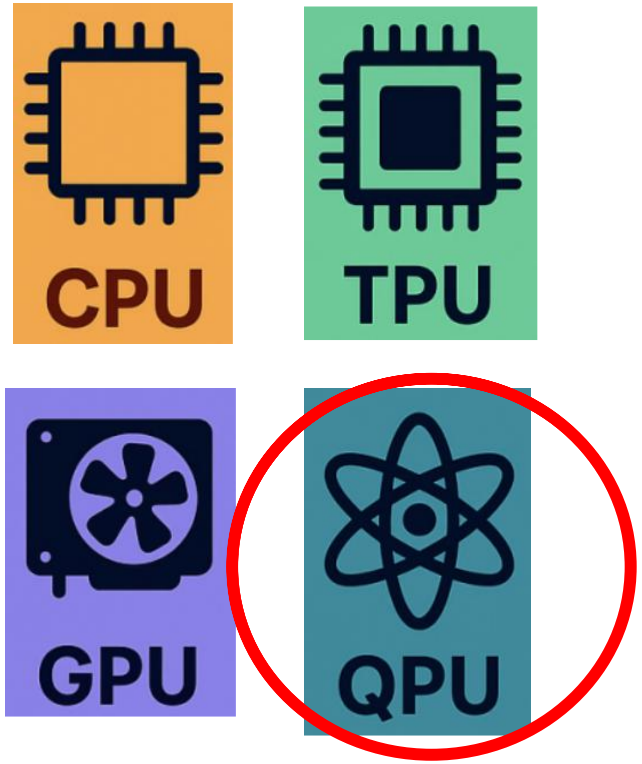
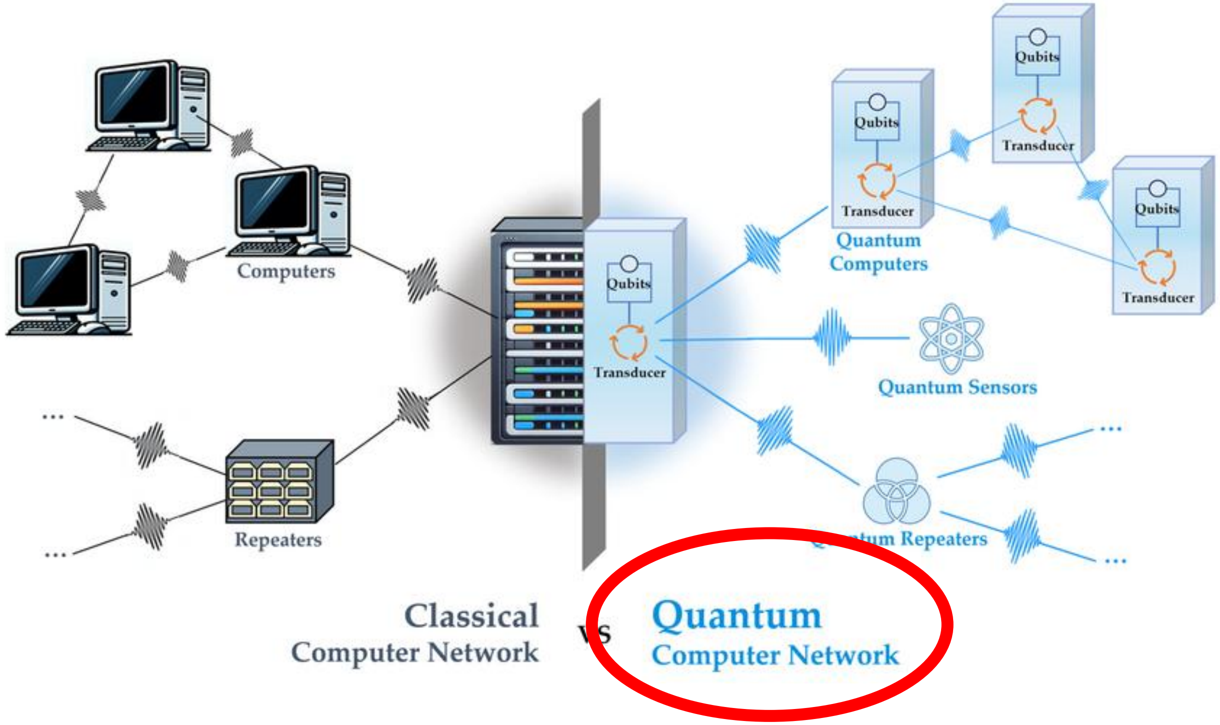


COMMUNICATION



Xu, Xinyao, et al. "Optomechanical microwave-to-optical photon transducer chips: Empowering the quantum internet revolution." Micromachines 15.4 (2024)

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

What quantum advantage ***needs***

[Submitted on 21 May 2025]

How to factor 2048 bit RSA integers with less than a million noisy qubits

Craig Gidney

Planning the transition to quantum-safe cryptosystems requires understanding the cost of quantum attacks on vulnerable cryptosystems. In Gidney+Ekerå 2019, I co-published
an estimate stating that 2048 bit RSA integers could be factored in eight hours by a qu
number of qubits required. I estimate that a 2048 bit RSA integer could be factored in
same assumptions as in 2019: a square grid of qubits with nearest neighbor connectio
control system reaction time of 10 microseconds.
The qubit count reduction comes mainly from using approximate residue arithmetic (C
surface codes (Gidney+Newman+Brooks+Jones 2023), and from allocating less space
The longer runtime is mainly due to performing more Toffoli gates and using fewer ma
by over 100x compa

[Submitted on 23 May 2019 (v1), last revised 13 Apr 2021 (this version, v3)]

How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits

Craig Gidney, Martin Ekerå

We significantly reduce the cost of factoring integers and computing discrete logarithms in finite fields on a quantum computer by combining techniques from Shor 1994, Griffiths-Niu 1996, Zalka 2006, Fowler 2012, Ekerå-Håstad 2017, Ekerå 2017, Ekerå 2018, Gidney-Fowler 2019, Gidney 2019. We estimate the approximate cost of our
construction using plausible physical assumptions for large-scale superconducting qubit platforms: a planar grid of qubits with nearest-neighbor connectivity, a characteristic
e normally ignored such as
spacetime volume is a
In the abstract circuit model
n Toffolis, and
mes based on the DLP in

~10^5–10^7 *physical* qubits

[Submitted on 14 Nov 2022]

Assessing require

Michael E. Beverland, Prakas
Sundaram, Alexander Vaschillo

While quantum computers promise to solve some scientifically and commercially valuable problems thought intractable for classical machines, delivering on this promise will require a large-scale quantum machine. Understanding the impact of architecture design choices for a scaled quantum stack for specific applications, prior to full realization of the quantum system, is an important open challenge. To this end, we develop a framework for quantum resource estimation, abstracting the layers of the stack, to estimate
resources required across these layers for large-scale quantum applications. Using a tool that implem
that hundreds of thousands to millions of physical qubits are needed to achieve practical quantum ad
controllability, that are critical at scale to rendering these applications practical. A goal of our work is
the broader community to explore design choices across the stack, from algorithms to qubits.

[Submitted on 11 May 2016 (v1), last revised 25 May 2016 (this version, v2)]

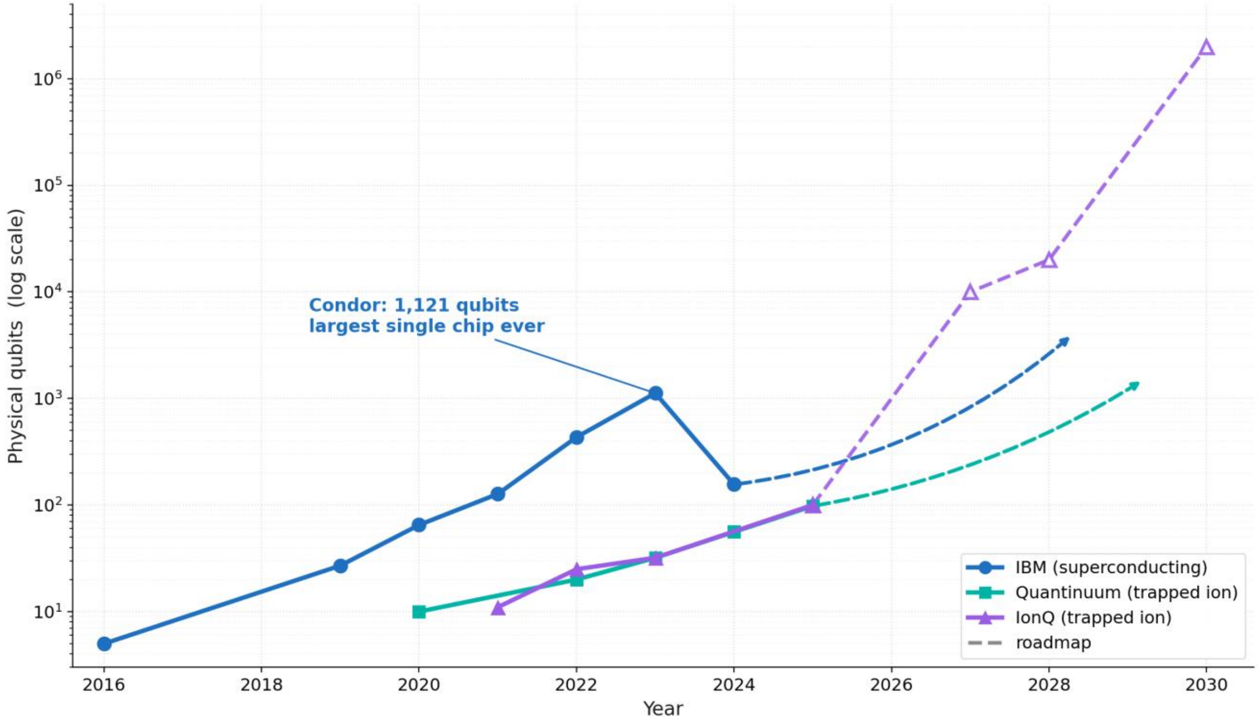
Elucidating Reaction Mechanisms on Quantum Computers

Markus Reiher, Nathan Wiebe, Krysta M Svore, Dave Wecker, Matthias Troyer

We show how a quantum computer can be employed to elucidate reaction mechanisms in complex chemical systems, using the open problem of biological nitrogen fixation in nitrogenase as an example. We discuss how quantum computers can augment classical-computer simulations for such problems, to significantly increase their accuracy and enable hitherto intractable simulations. Detailed resource estimates show that, even when taking into account the substantial overhead of quantum error correction, and the need to compile into discrete gate sets, the necessary computations can be performed in reasonable time on small quantum computers. This demonstrates that quantum computers will realistically be able to tackle important problems in chemistry that are both scientifically and economically significant.

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

What quantum advantage needs



We ran out of room on the chip, so ... **we plugged in a network**

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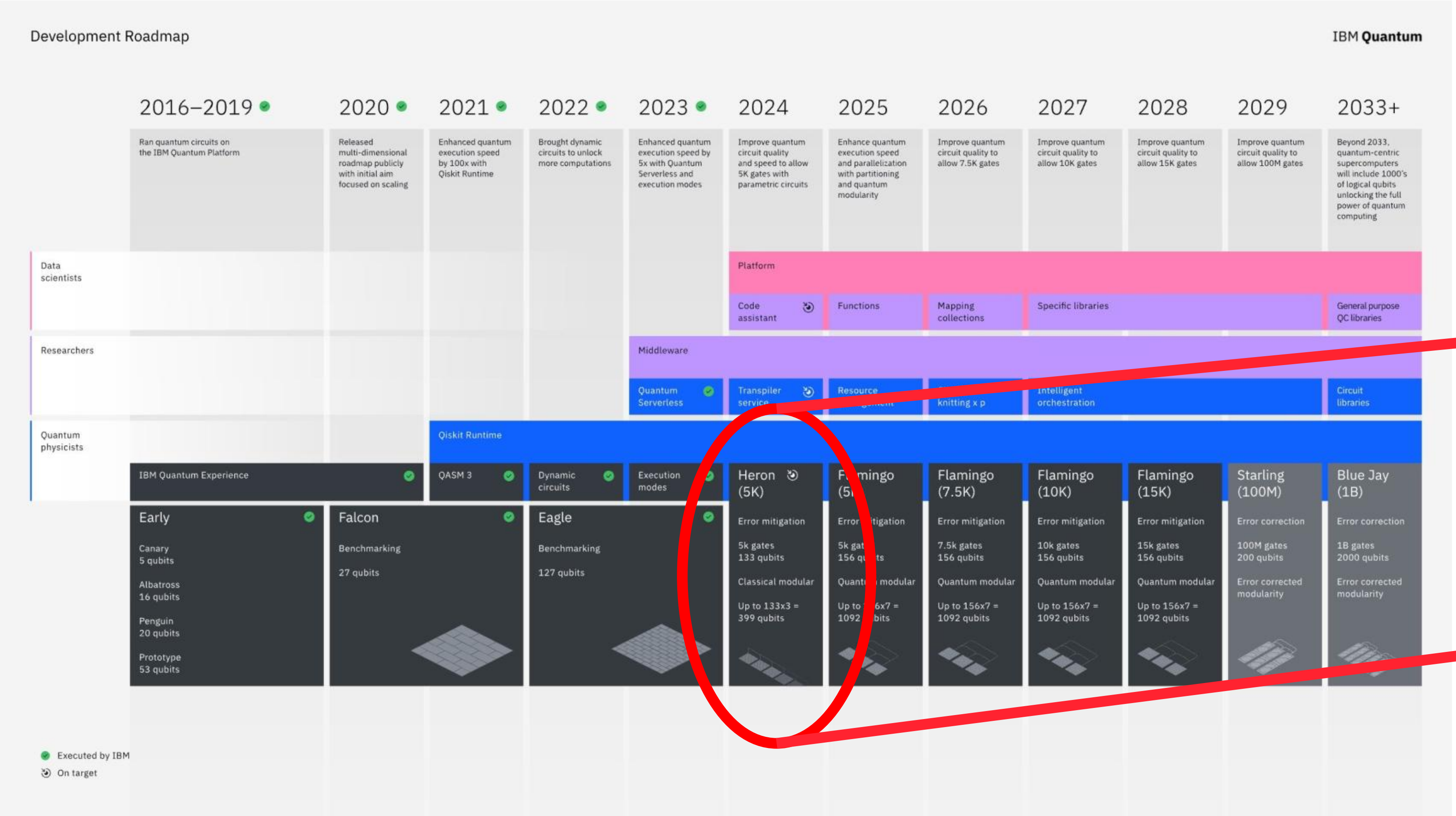
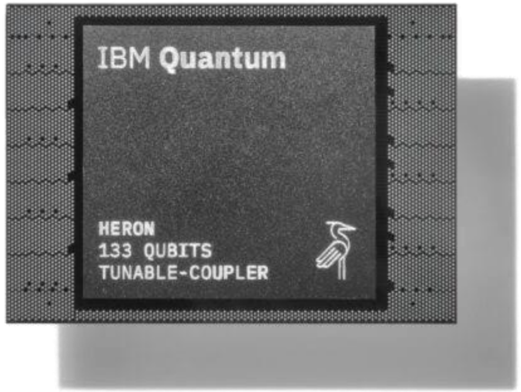
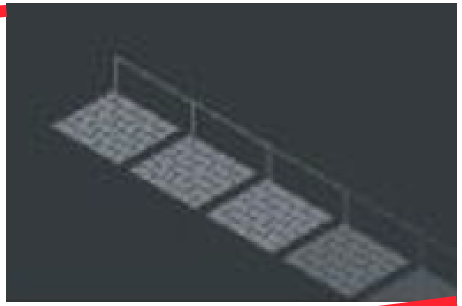
Classical Networks

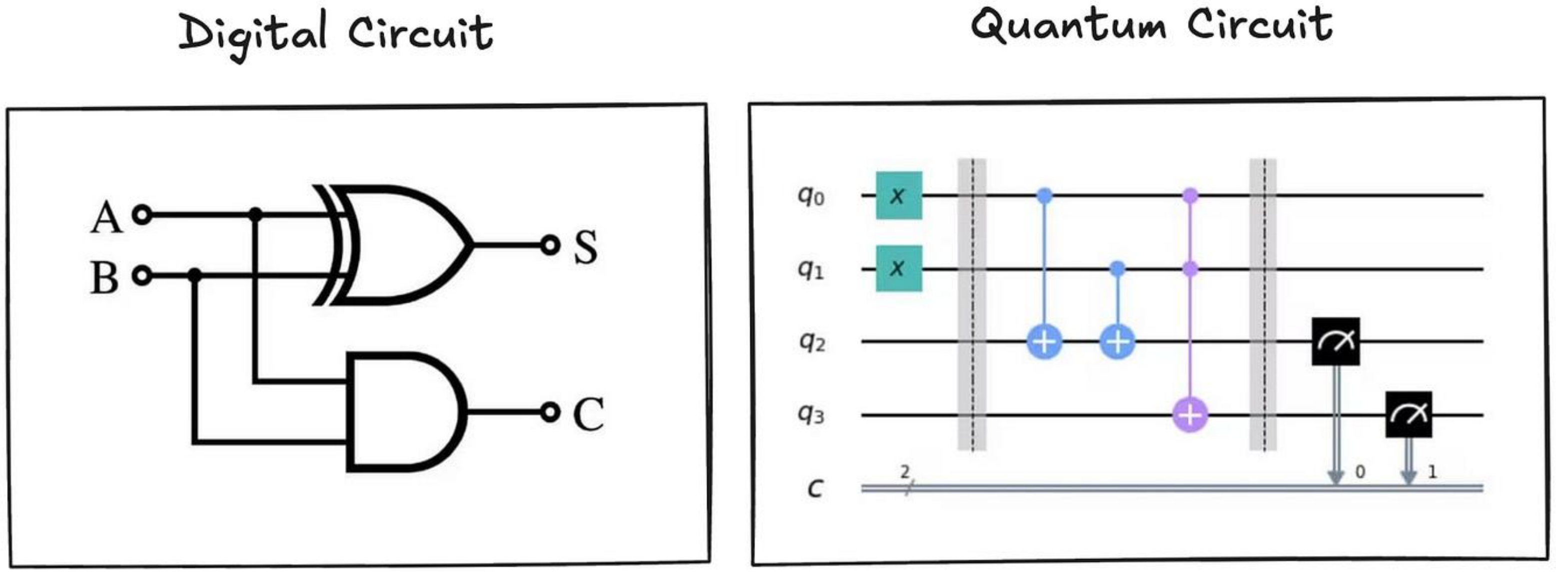






Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

Quantum computing



Source: IBM. Redesigned by Jennifer Tran from Realmscape

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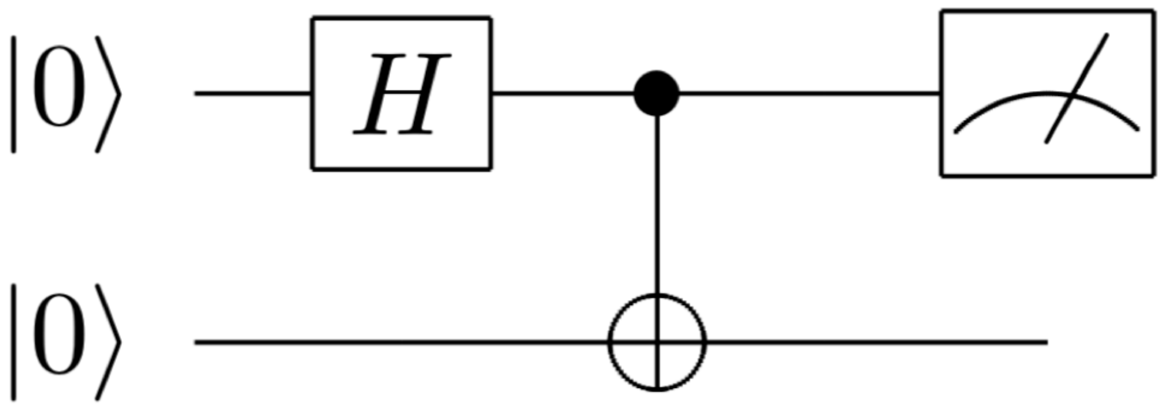
Quantum computing



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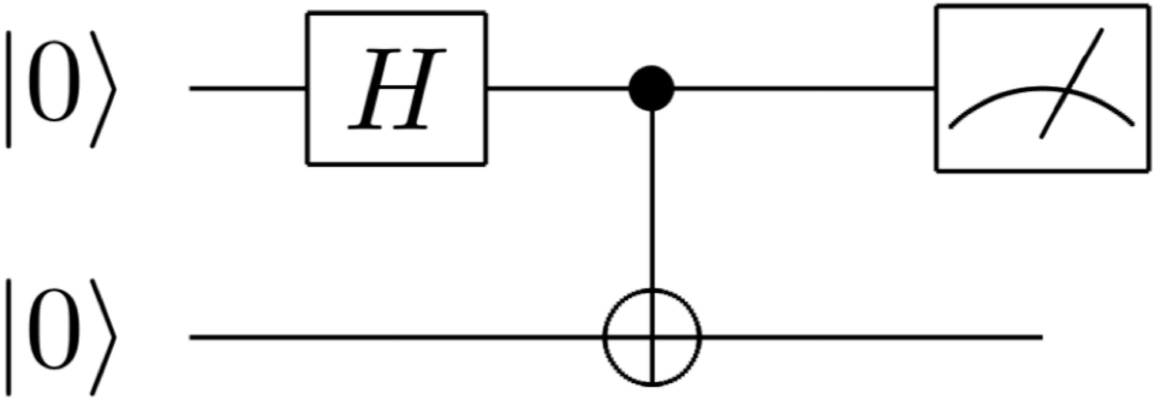

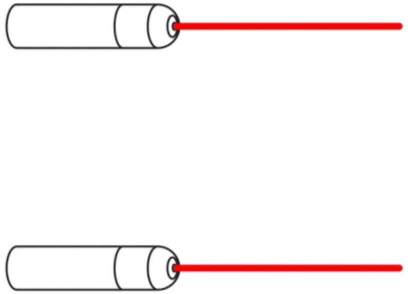

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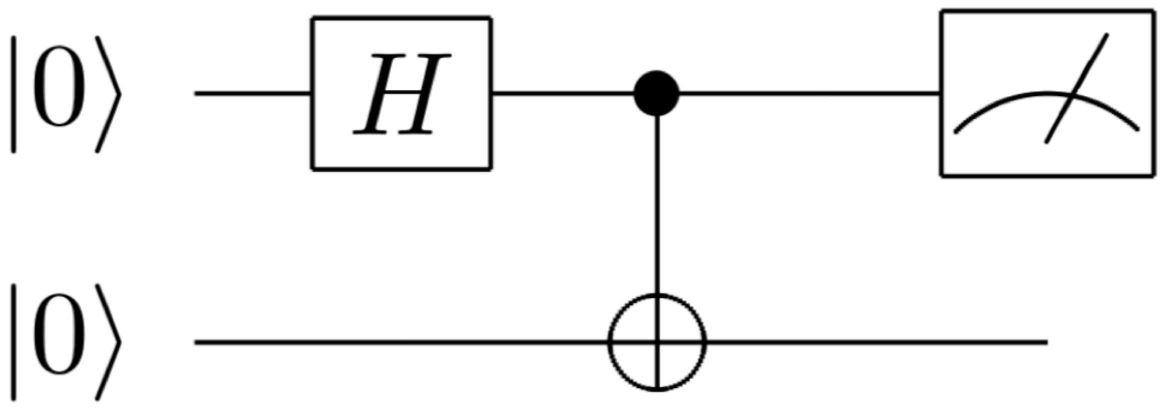
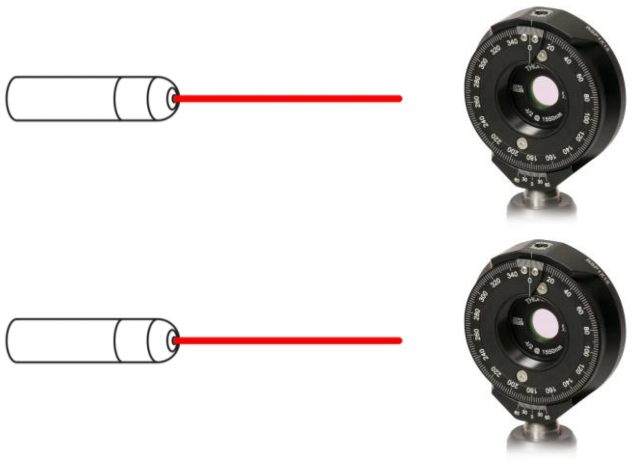
Quantum computing





Thor labs: wave plate

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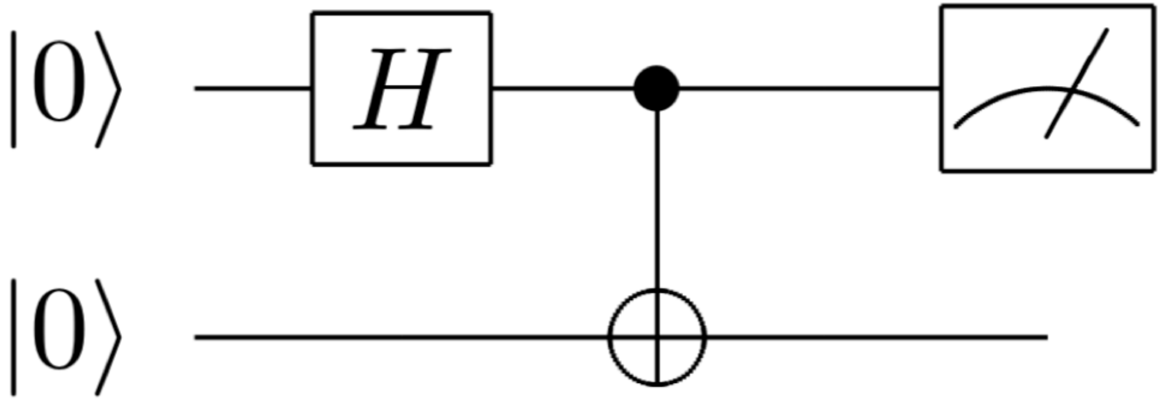
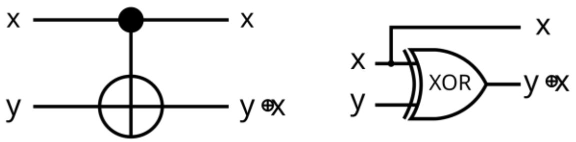
Quantum computing



Thor labs: wave plate

Reversible XOR



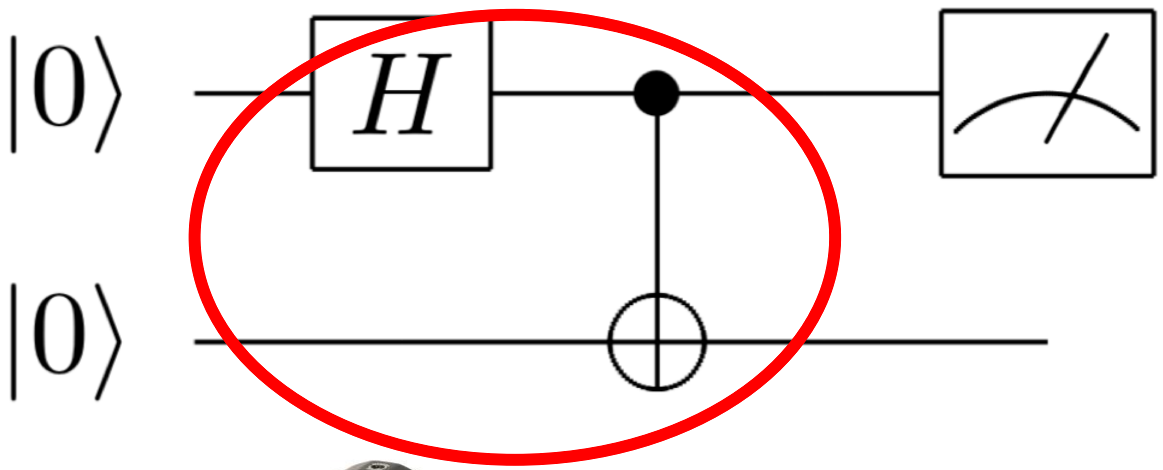
input		output	
x	y	x	y+x
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

input		output	
x	y	x	y+x
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Taken from Wikipedia

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

Quantum computing



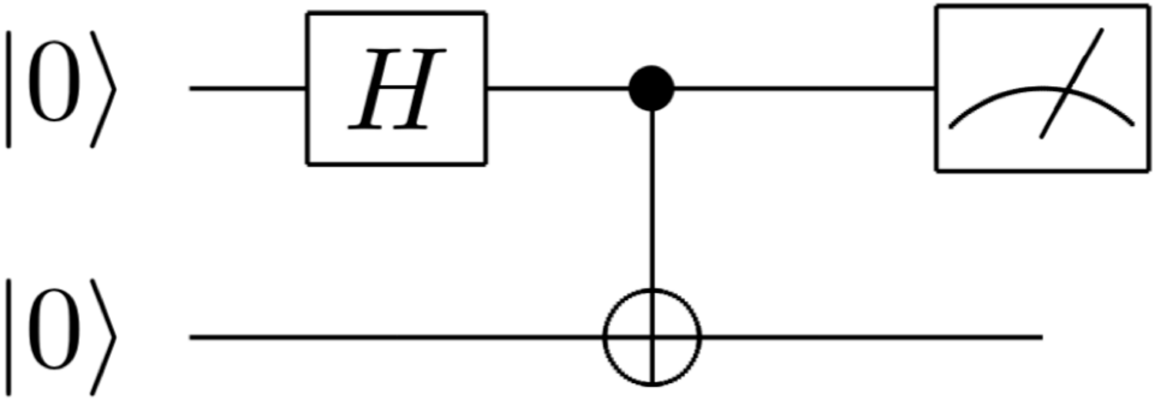
Entanglement!

Thor labs: wave plate

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

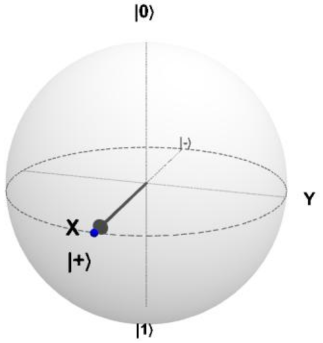
Entanglement?

$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

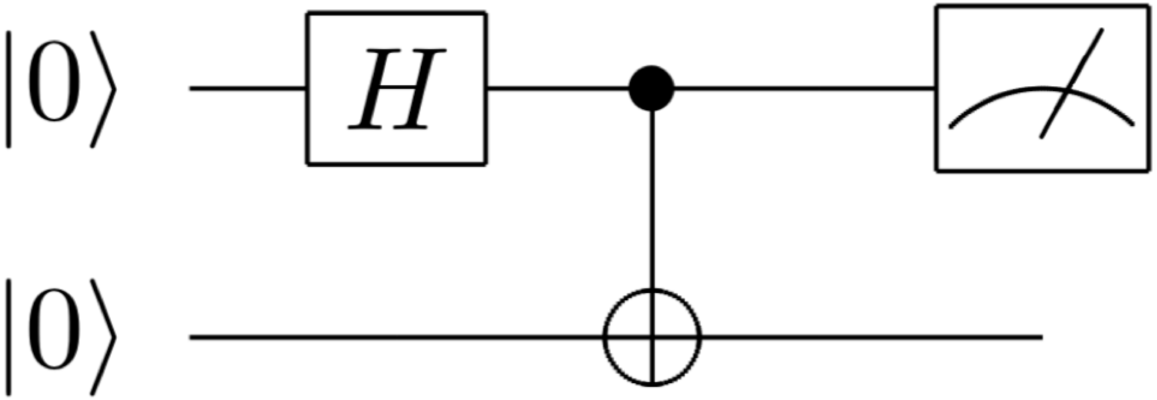


$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

Entanglement?



$|0\rangle$ $|+\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} / \sqrt{2}$



$|0\rangle$ $|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

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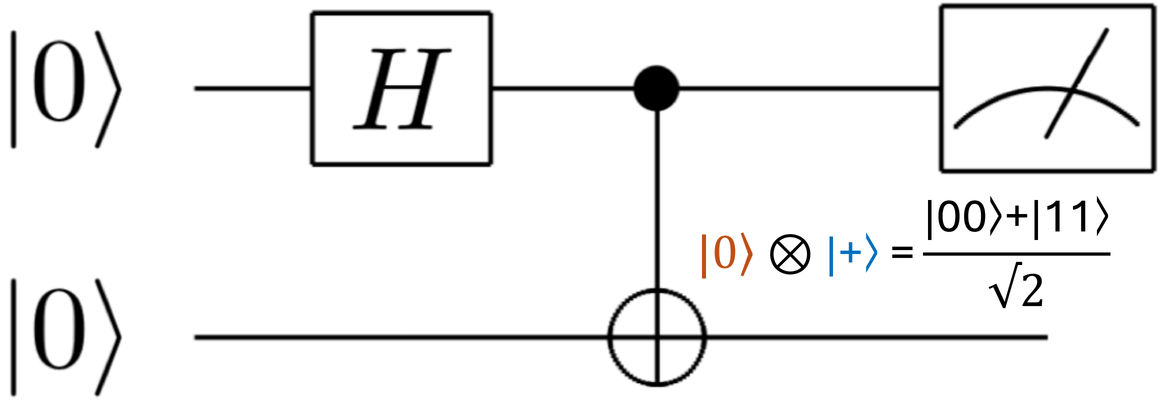
Entanglement?

$|0\rangle$ $\quad |+\rangle = \begin{pmatrix}1\\0\end{pmatrix}/\sqrt{2}$

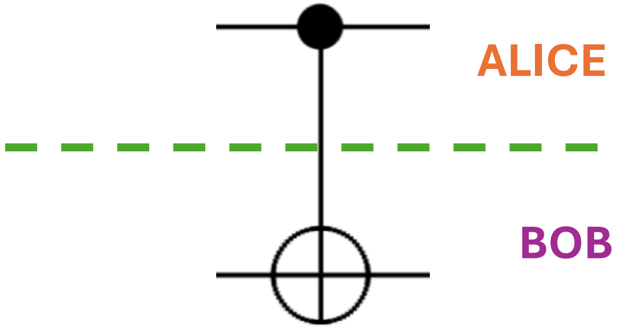


$|0\rangle \otimes |+\rangle = \frac{|00\rangle+|11\rangle}{\sqrt{2}}$

$|0\rangle$ $\quad |0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$

We cannot separate these states

Entanglement



- Entangled pair (**pre-established**) would have to be consumed
- These are networks **resources**, and it's **exponentially expensive** to attempt to circumvent their consumption using classical networks.

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

Quantum Networks

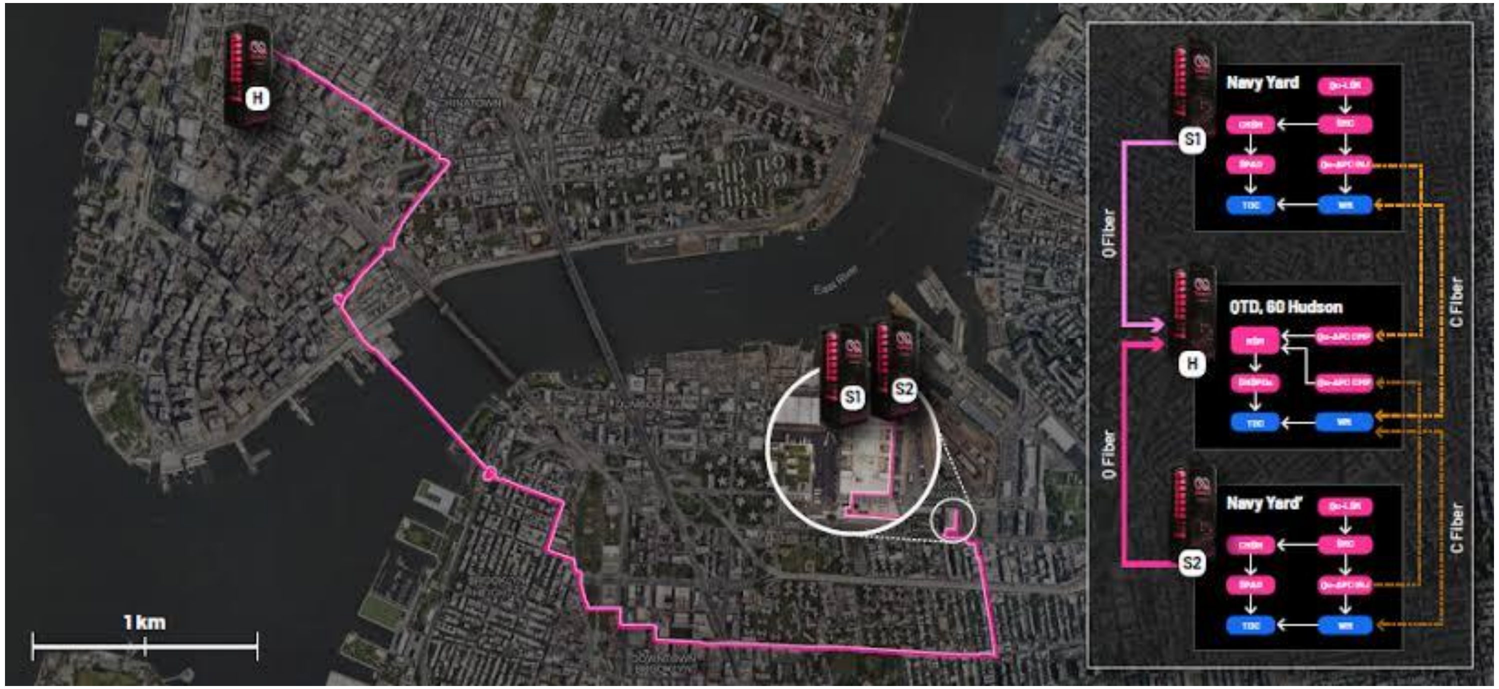
Offer entanglement as a new resource!

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

Quantum Networks

REAL & WORKING

Offer entanglement as a new resource!

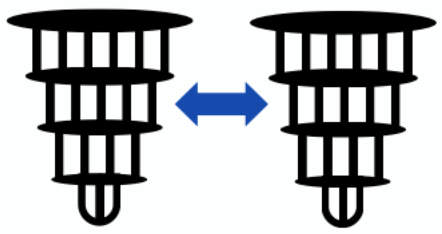


Qunnet's & Cisco's New York metropolitan quantum network

Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

Entanglement is super nice!

Enables DQC



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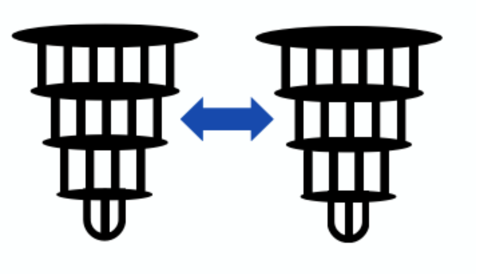
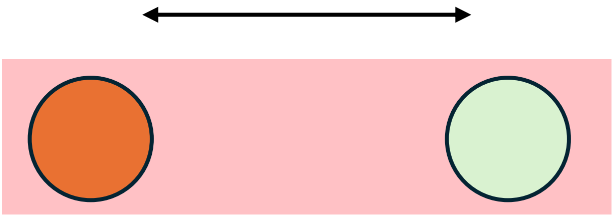


Can correlate at any distance



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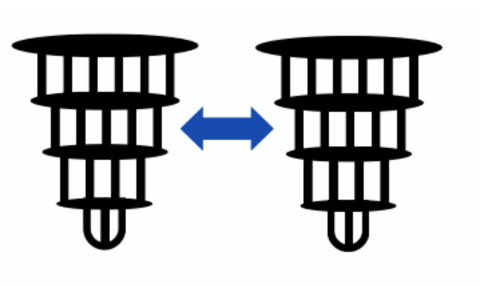

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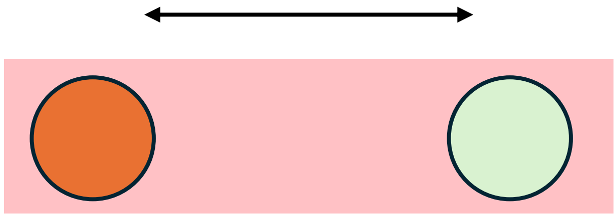


Communication savings

<u>SUPERDENSE ENCODING</u>

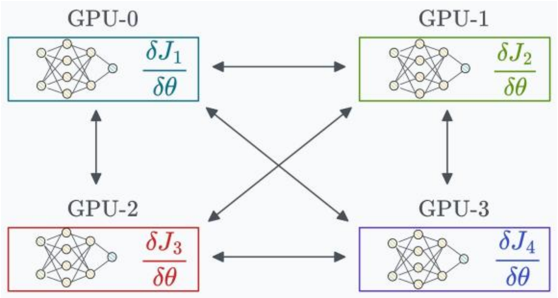
2 online bits

=

1 pre-shared qubit

+

1 online bit



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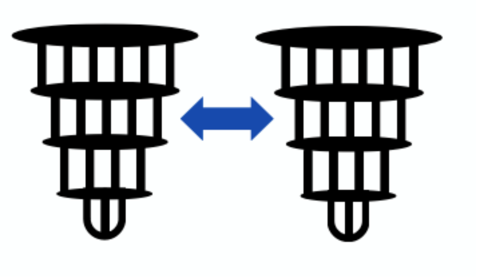

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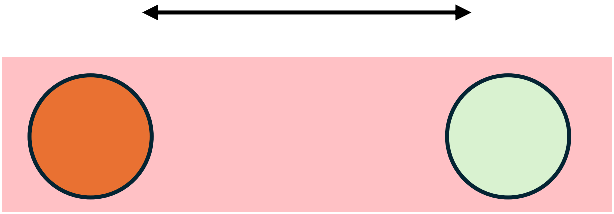

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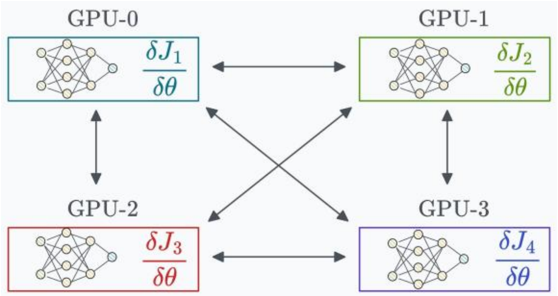
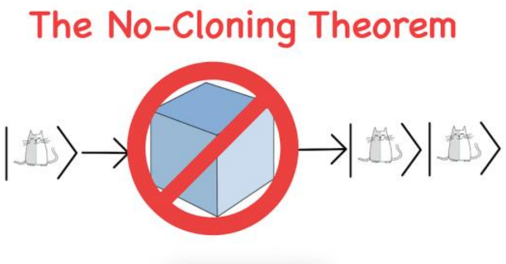
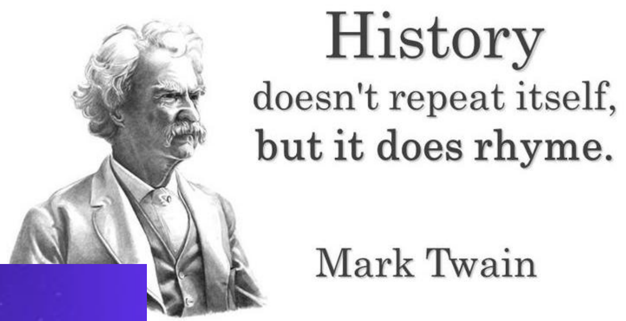


Security guarantees



Scaling quantum computers is a **distributed-systems & networking problem,** where the **hardest** unsolved parts are the kind of thing **we are good at.**

The promise of a Quantum internet



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Open problems galore **in DQC**

ENTANGLEMENT DISTRIBUTION (resource management)

- **Generation rate vs decoherence:** entanglement is probabilistic + slow to make; the whole system is rate-limited
- **Routing:** routing a *consumable* with *probabilistic delivery* under a *decoherence deadline*; no classical analogue
- **Swapping at repeaters:** multi-hop paths via entanglement swapping, itself probabilistic; multipath to boost success
- **Purification / distillation:** burn many noisy pairs to forge one good one; a quality-vs-throughput knob
- **Quantum memory:** a buffer with a burning fuse: store entanglement while the protocol catches up, but it decoheres

QUANTUM vs CLASSICAL COMMUNICATION

- **Circuit knitting / wire cutting:** skip the quantum link, stitch results classically & pay exponential sampling overhead in # cuts
- **Where's the crossover?** when is a slow, noisy quantum link worth more than exponential classical shots?
- **Provable comm. Advantage:** which workloads actually need quantum communication? (communication-complexity results)

COMPILATION & MAPPING

- **Circuit partitioning across QPUs**: graph/hypergraph min-cut + qubit mapping; NP-hard; minimize non-local gates
- **Telegate vs teledata**: teleport the gate, or move the qubit? a per-operation cost decision
- **Entanglement-aware cost models:** every non-local gate spends a scarce, decaying Bell pair; objective unlike classical placement

PROGRAMMING MODEL & TOOLING

- **Right abstraction?:** one transparent virtual machine vs explicit nodes + links (shared-memory vs MPI, reborn)
- **Verification & debugging:** no breakpoints: you can't inspect state without collapsing it
- **Benchmarking:** no agreed metrics for a DQC system

QUANTUM vs CLASSICAL COMMUNICATION

- **"NUMA for qubits"** : intra-chip ≪ chip-to-chip ≪ rack ≪ datacenter, by orders of magnitude in latency & fidelity
- **Heterogeneous QPU clusters** : different sizes, topologies, error rates; placement across a quantum memory hierarchy
- **Microwave→optical transduction:** the physical bottleneck; why you can't just run a fiber between two fridges today

REAL-TIME CLASSICAL CONTROL

- **Feedforward within the coherence window:** teleportation needs classical bits acted on *before* decoherence
- **The deadline is physics, not an SLA:** classical scheduler/network latency coupled directly to qubit lifetime (μs)
- **Clock / phase synchronization:** sub-ns timing across nodes for photon interference

FAULT TOLERANCE ACROSS THE NETWORK

- **Distributed QEC:** syndrome extraction over links orders-of-magnitude noisier than on-chip
- **Networked codes & lattice surgery:** surface-code logical qubits spanning QPUs; thresholds for modular architectures
- **Reliability without copies:** it's replication/consensus, except no-cloning forbids backups

SYSTEMS / HPC INTEGRATION

- **QPU as accelerator:** how does a QPU cluster slot into a supercomputer's job scheduler? (like GPUs, but with deadlines)
- **Hybrid workflows:** classical pre/post-processing tightly coupled to quantum kernels; data movement & orchestration
- **Standardization:** no stack, no interfaces, no portability yet

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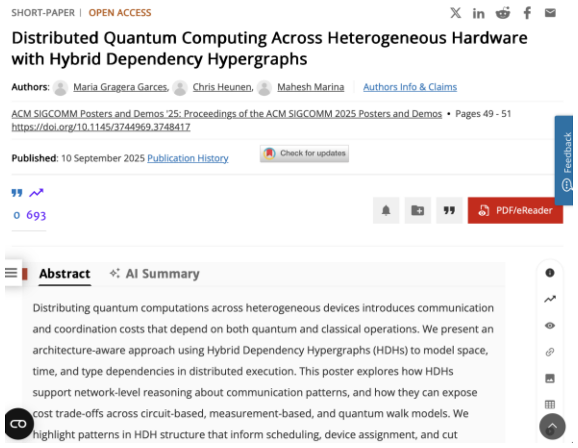
Circuit partitioning


SHORT-PAPER | OPEN ACCESS

Distributed Quantum Computing Across Heterogeneous Hardware with Hybrid Dependency Hypergraphs

Authors: Maria Gragera Garces, Chris Heunen, Mahesh Marina Authors Info & Claims

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PDF/eReader

Abstract AI Summary

Distributing quantum computations across heterogeneous devices introduces communication and coordination costs that depend on both quantum and classical operations. We present an architecture-aware approach using Hybrid Dependency Hypergraphs (HDHs) to model space, time, and type dependencies in distributed execution. This poster explores how HDHs support network-level reasoning about communication patterns, and how they can expose cost trade-offs across circuit-based, measurement-based, and quantum walk models. We highlight patterns in HDH structure that inform scheduling, device assignment, and cut

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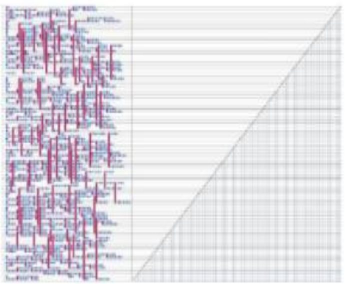
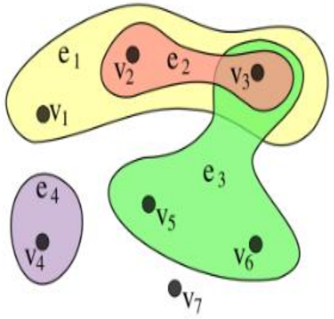
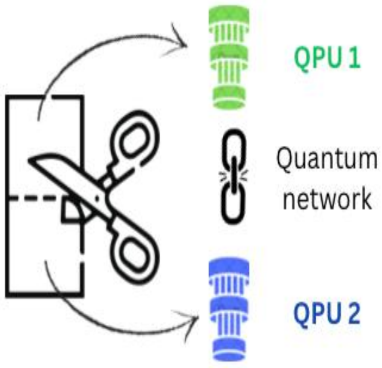


Large computation



Abstraction

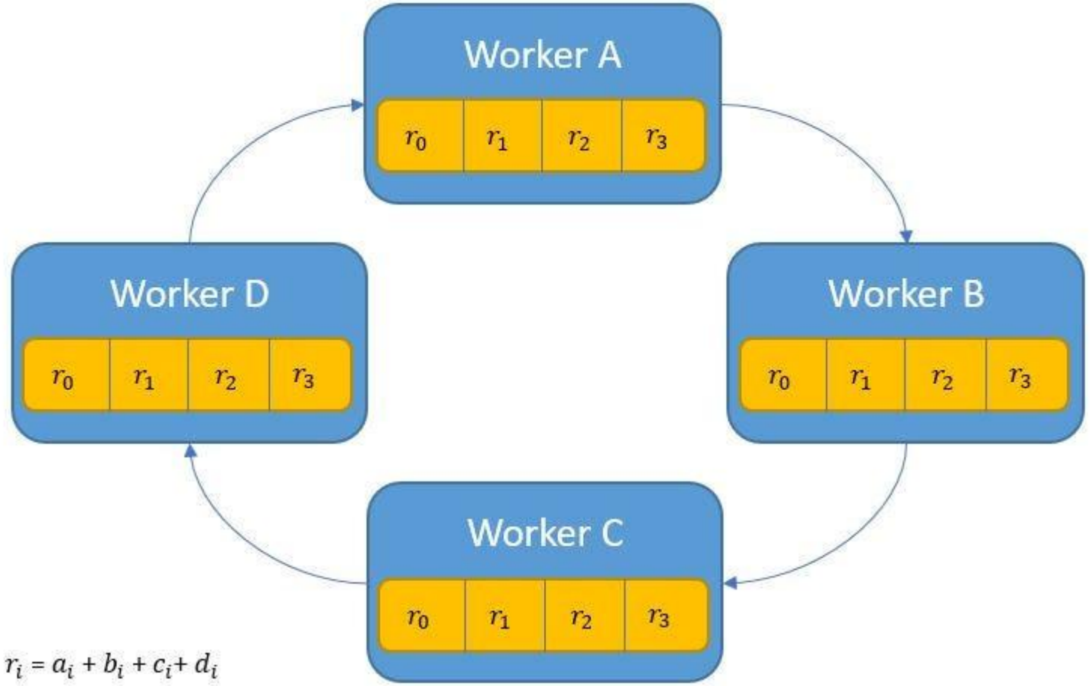


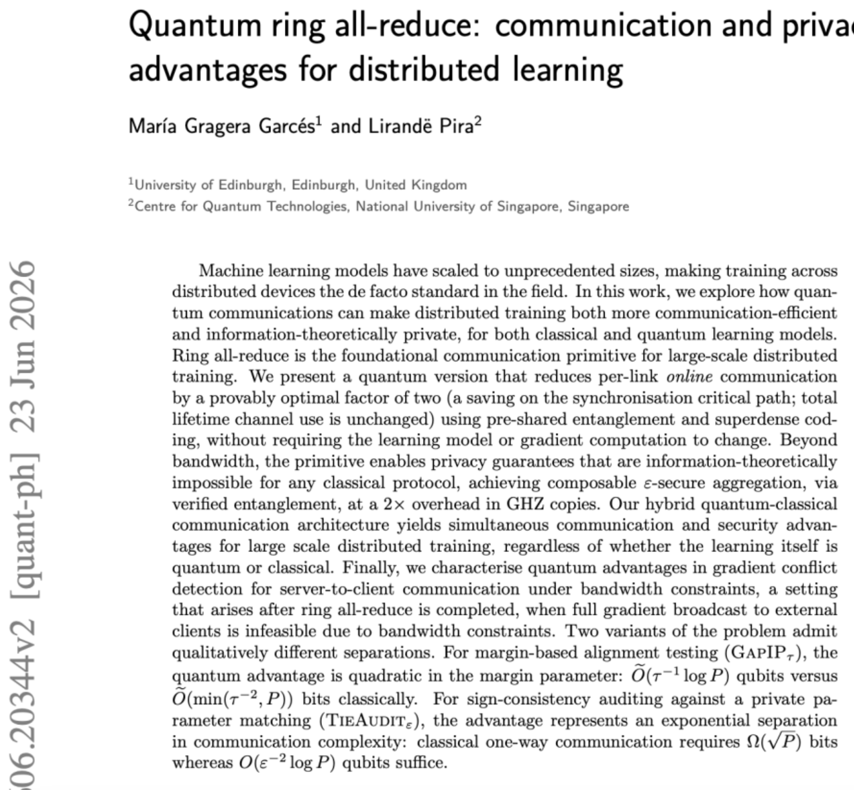
Partition for Assignment to QPUs in the network

~ Hypergraph partitioning problem

Communication advantages

Reductions in communication for key classical & quantum applications (e.g. Ring all reduce)





Quantum ring all-reduce: communication and privacy advantages for distributed learning

María Gragera Garcés[1] and Lirandë Pira[2]

[1]University of Edinburgh, Edinburgh, United Kingdom
[2]Centre for Quantum Technologies, National University of Singapore, Singapore

06.20344v2 [quant-ph] 23 Jun 2026

Machine learning models have scaled to unprecedented sizes, making training across distributed devices the de facto standard in the field. In this work, we explore how quantum communications can make distributed training both more communication-efficient and information-theoretically private, for both classical and quantum learning models. Ring all-reduce is the foundational communication primitive for large-scale distributed training. We present a quantum version that reduces per-link *online* communication by a provably optimal factor of two (a saving on the synchronisation critical path; total lifetime channel use is unchanged) using pre-shared entanglement and superdense coding, without requiring the learning model or gradient computation to change. Beyond bandwidth, the primitive enables privacy guarantees that are information-theoretically impossible for any classical protocol, achieving composable ε-secure aggregation, via verified entanglement, at a $2\times$ overhead in GHZ copies. Our hybrid quantum-classical communication architecture yields simultaneous communication and security advantages for large scale distributed training, regardless of whether the learning itself is quantum or classical. Finally, we characterise quantum advantages in gradient conflict detection for server-to-client communication under bandwidth constraints, a setting that arises after ring all-reduce is completed, when full gradient broadcast to external clients is infeasible due to bandwidth constraints. Two variants of the problem admit qualitatively different separations. For margin-based alignment testing (GAPIP_τ), the quantum advantage is quadratic in the margin parameter: $\widetilde{O}(\tau^{-1} \log P)$ qubits versus $\widetilde{O}(\min(\tau^{-2}, P))$ bits classically. For sign-consistency auditing against a private parameter matching ($\text{TIEAUDIT}_\varepsilon$), the advantage represents an exponential separation in communication complexity: classical one-way communication requires $\Omega(\sqrt{P})$ bits whereas $O(\varepsilon^{-2} \log P)$ qubits suffice.

Securing quantum secrets

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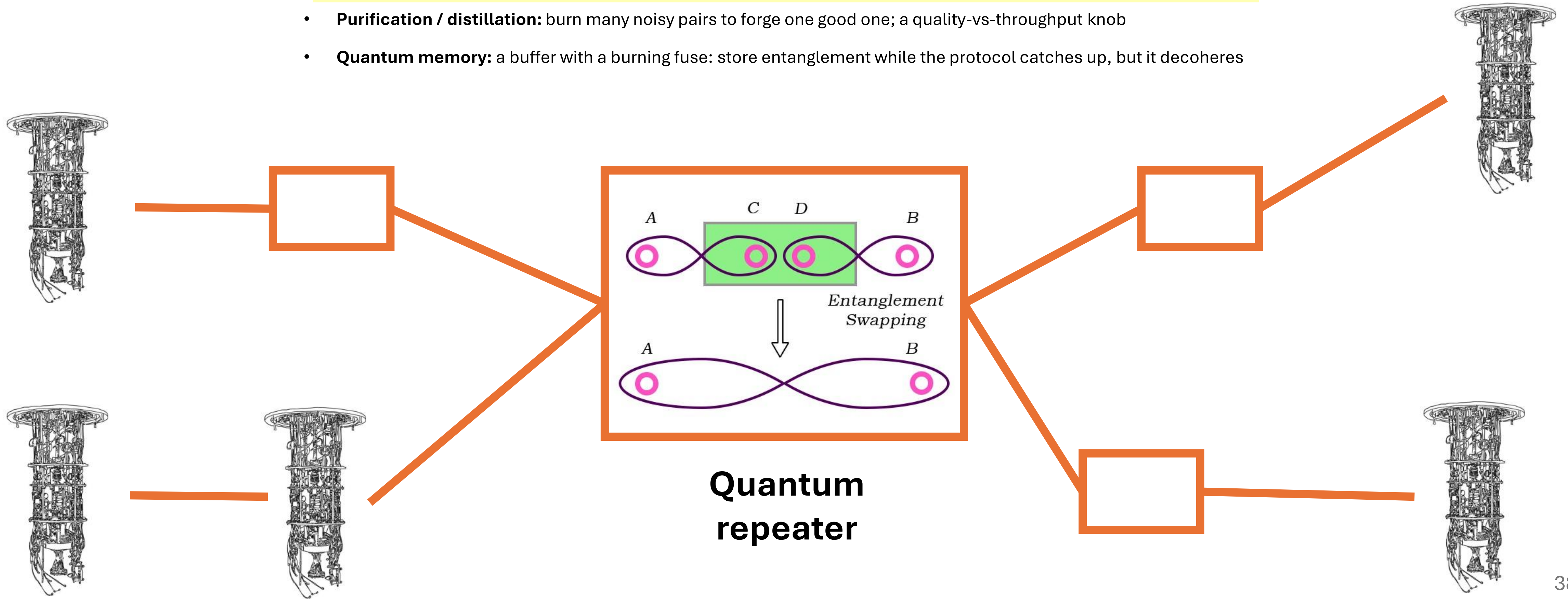

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MORE NEXT YEAR!

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