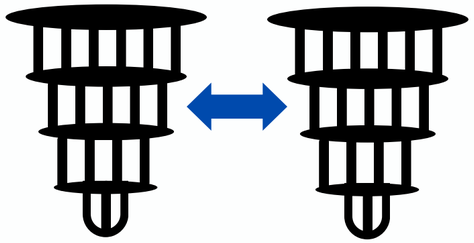
Distributed Quantum Computing

TOMORROW'S GOAL, TODAY'S CHALLENGE



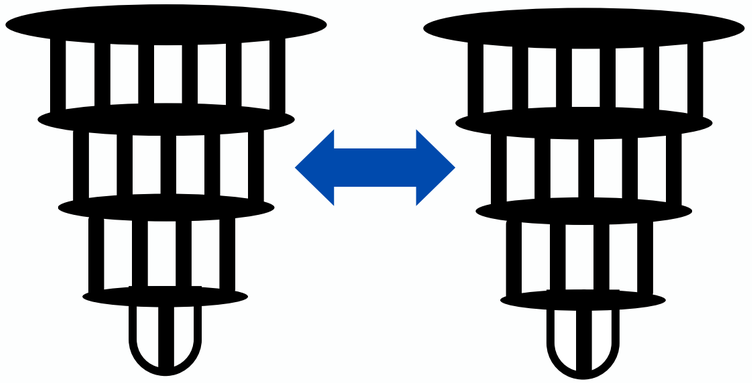
Maria Gragera Garces,
7th of May 2025

Quantum Software Lab

THE UNIVERSITY OF EDINBURGH

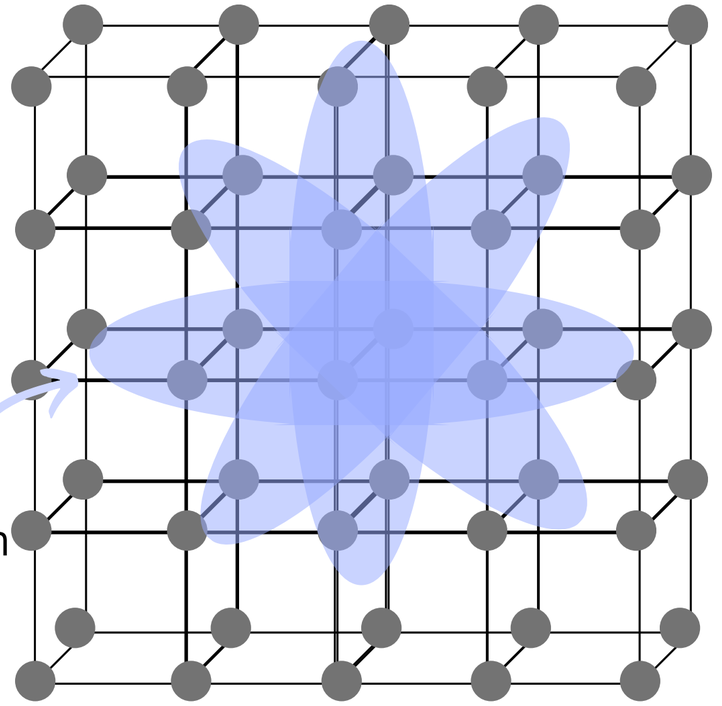
AGENDA

- Quantum Computing: Why? and How?
- The Classical Story
- Distributing: Why?
- The Challenges of Distributed Quantum Computing
- How to Distribute Quantum Workloads
- The Channel Question
- Cutting and Knitting circuits
- If the channel is quantum
- If the channel is classical
- State of the art
- The Hardware conversation



QC: WHY? HOW?

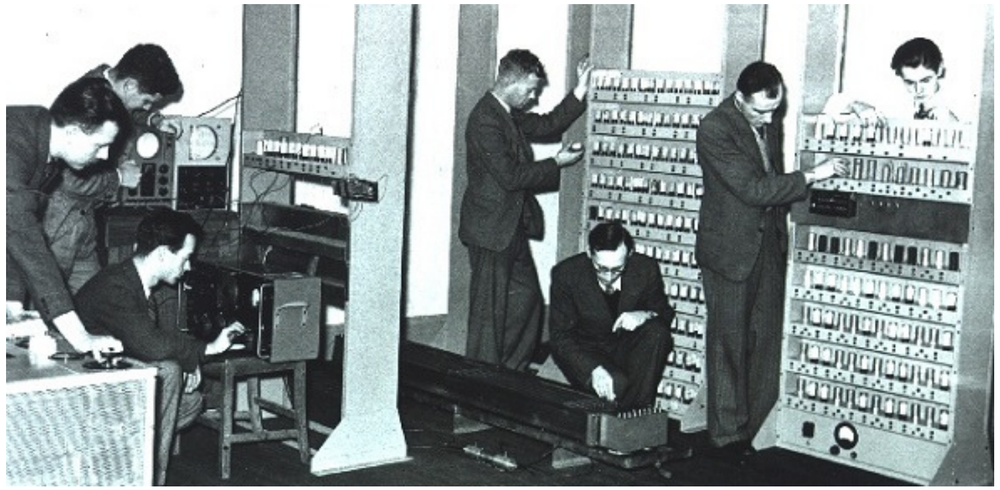
Solving the unsolvable



Hamiltonian Simulation

4 TODOs:

- Identify problems with quantum advantage
- Design efficient quantum algorithms
- Build scalable, error-corrected hardware
- Develop quantum-aware interfaces (compilers,...)



We're lucky. We aren't the first.

THE CLASSICAL STORY

Identify problems with quantum advantage

Cryptography
Enigma, WWII

Business
Post war economy bookkeeping

Build scalable, error-corrected hardware

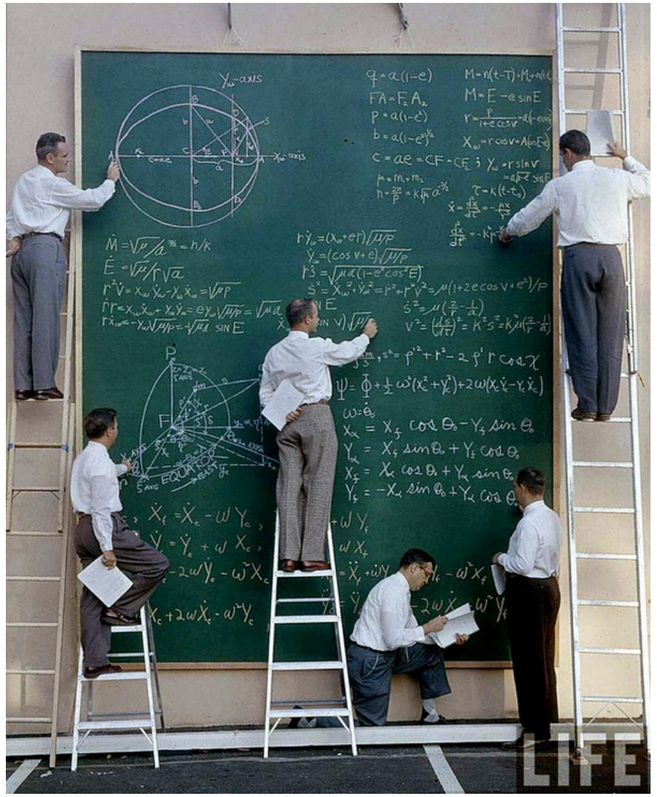
vacuum tubes → transistors → integrated circuits → microprocessor

Error correction became a thing of the past - it's not even taught anymore!

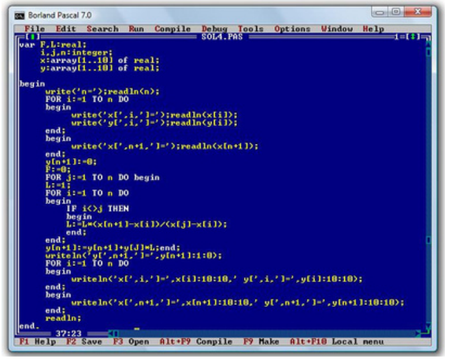
Design efficient quantum algorithms

New toys, new games:
Scientists went back to the blackboard and developed:

- ***Sorting and searching***: Quicksort, Merge Sort, and Binary Search
- ***Pathfinding and scheduling***: Dijkstra's algorithm, critical path methods, and early queuing theory
- ***Linear algebra routines***: LU decomposition, eigenvalue solvers
- ***Numerical stability tools***: avoiding floating-point errors and round-off instabilities
- ***Data structures***: Trees, heaps, hash tables
- ***Cryptographic protocols***: the foundations of public-key cryptography



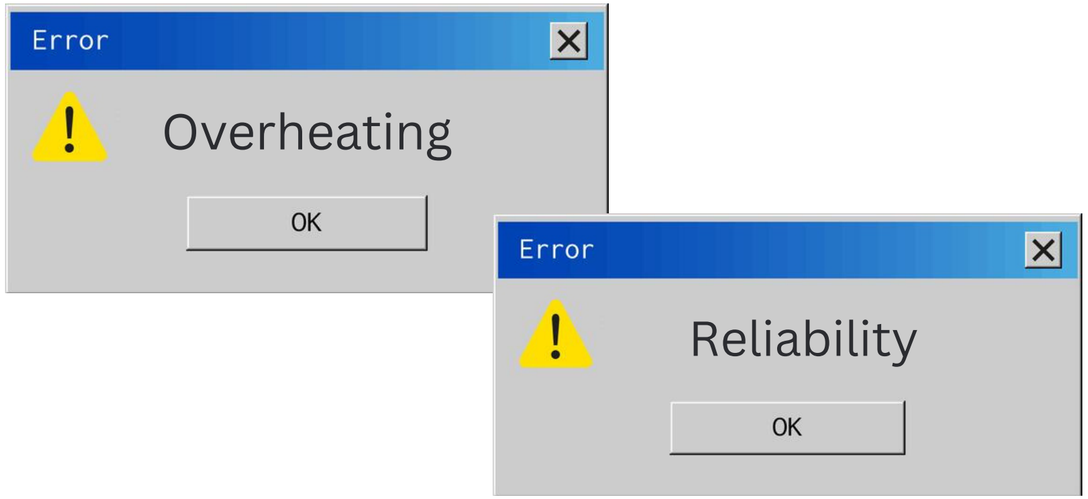
Develop quantum-aware interfaces (compilers,...)



- Programming languages
- Operating Systems
- User Interfaces

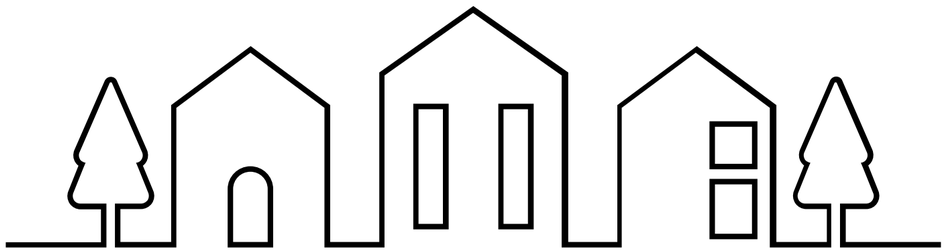
DISTRIBUTING: WHY?

The number of transistors on a microchip roughly doubles every two years, whereas its cost is halved.
~ **Moore's Law:**
Moore 60s



started building tall

stopped building wide



THE CHALLENGES OF DQC

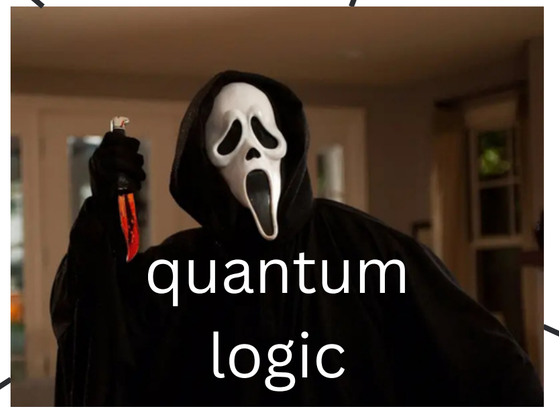
Entanglement entropy of a subsystem often scales with the size of its boundary rather than its volume
~ Area Law: *Bekenstein & Hawking 70s*

Quantum parallelism

erent operational parallelism

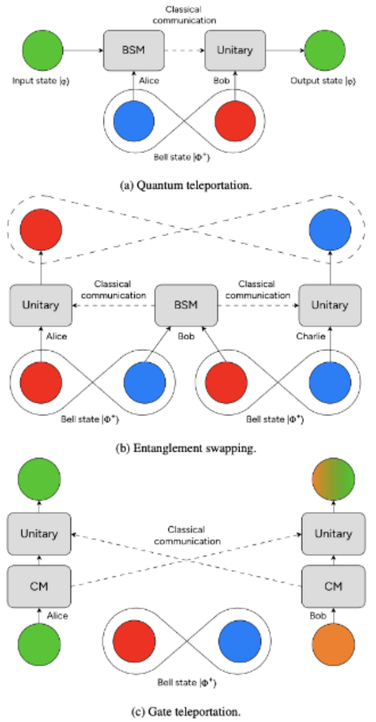
no straightforward speedup when workloads are partitioned across disconnected subsystems

Amdhal's and Gustafson's Laws

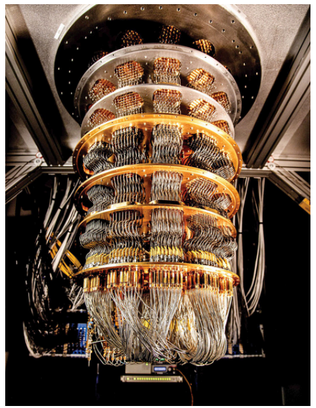


Teleportation

We need new algorithms & to make some choices



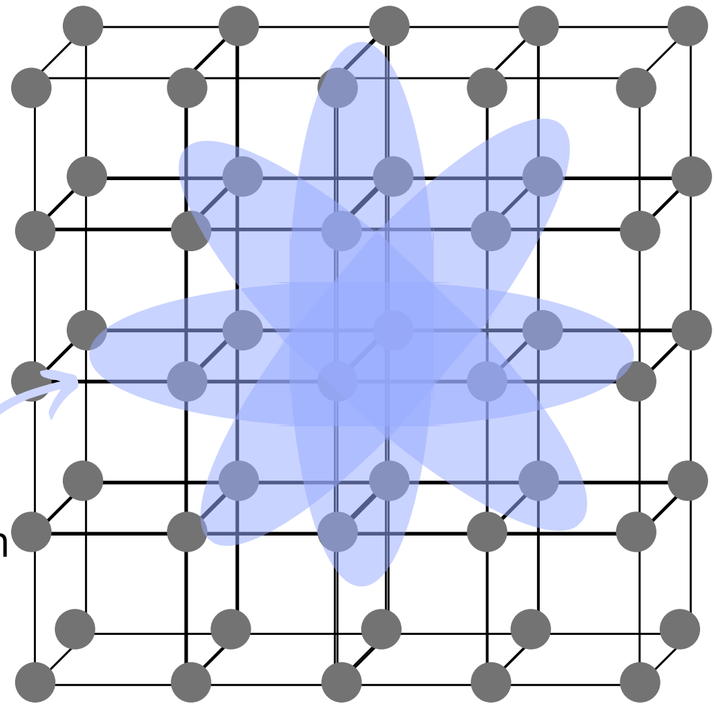
Coherence



No cloning

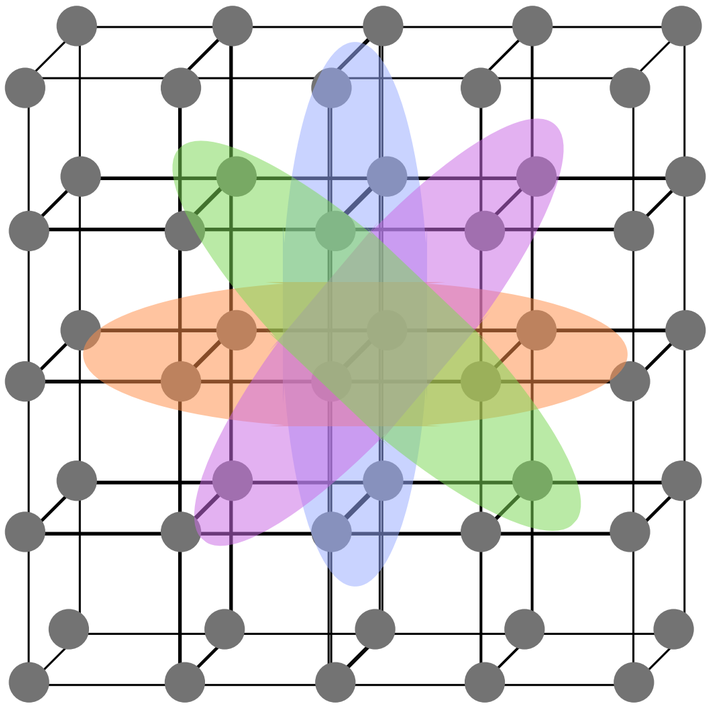
How do we send something that we can't copy?

HOW TO DISTRIBUTE QUANTUM WORKLOADS



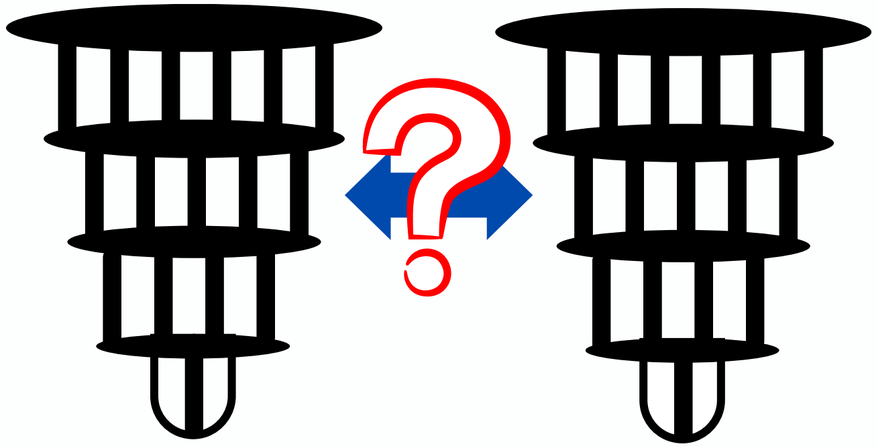
search space

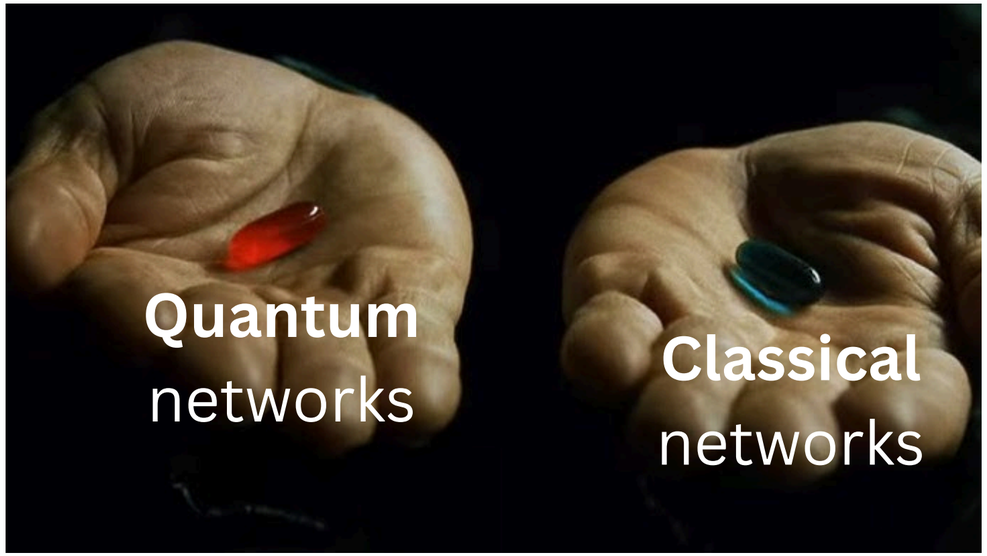
Hamiltonian landscape



$$H = H_{local(i)} + H_{interactions(i,j)}$$

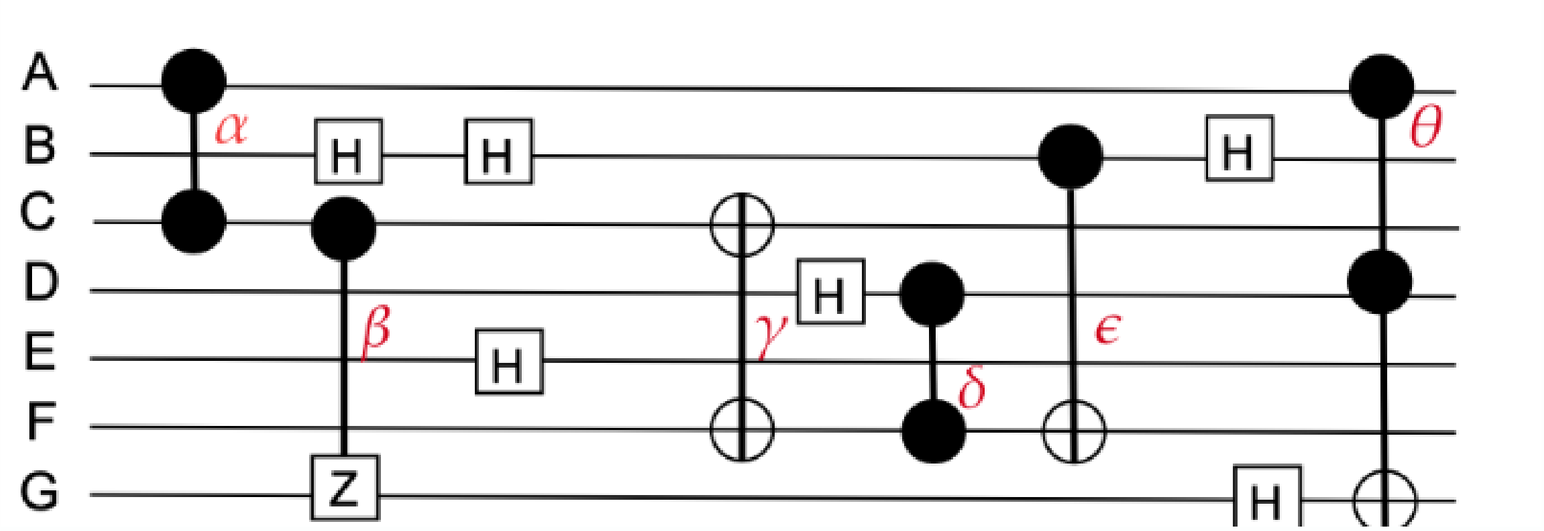
THE CHANNEL QUESTION

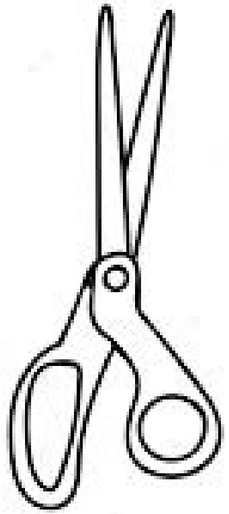


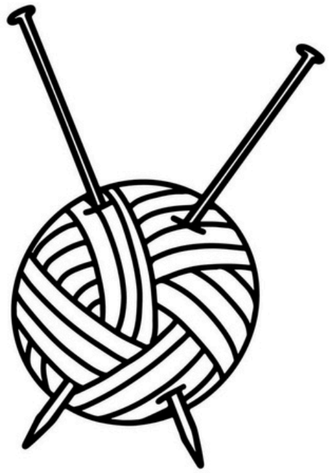


You take the blue pill... the story ends, you wake up in your bed and believe whatever you want to believe. You take the red pill... you stay in Wonderland, and I show you how deep the rabbit hole goes.

CUTTING AND KNITTING CIRCUITS

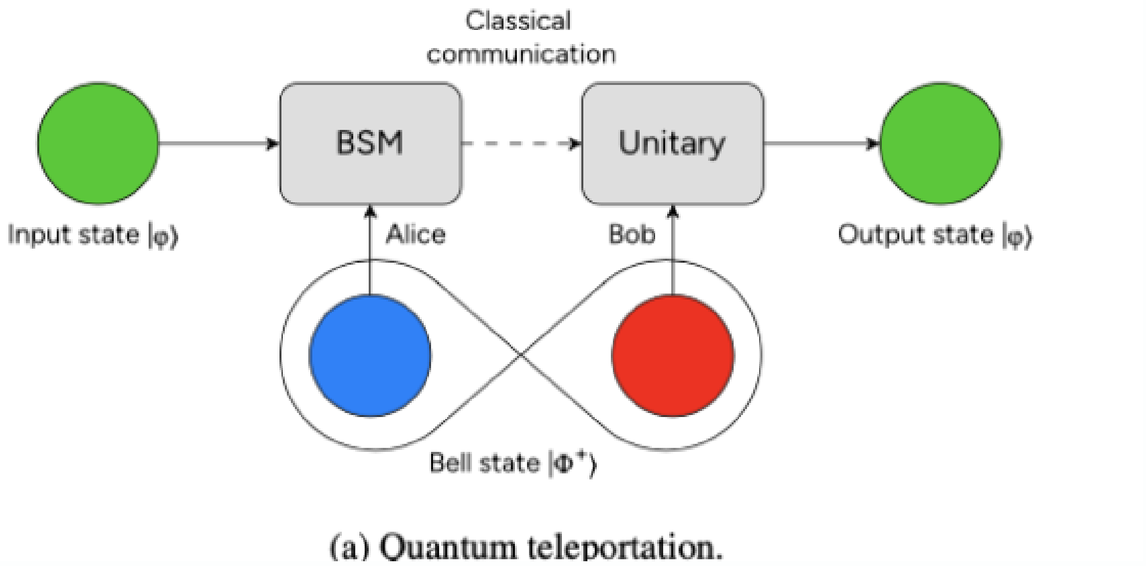




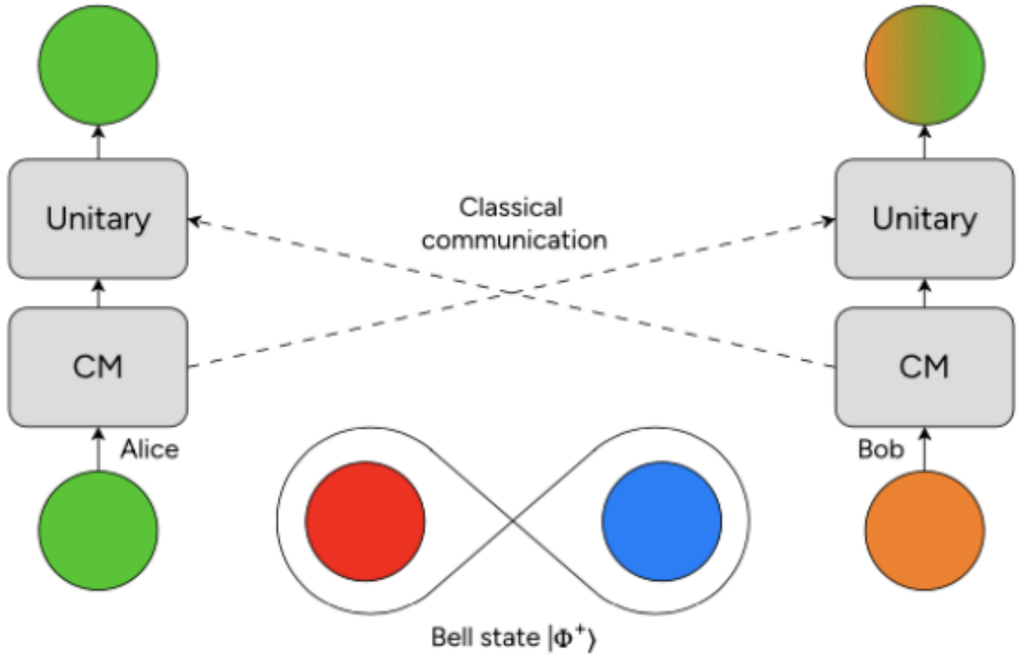


1) Decide how many QPUs we are distributing over
2) Choose if we want to cut through wires of gates
3) Make the relevant hypergraph
4) Cut it!

CUTTING AND KNITTING CIRCUITS



(a) Quantum teleportation.



(c) Gate teleportation.

1) Decide how many QPUs we are distributing over

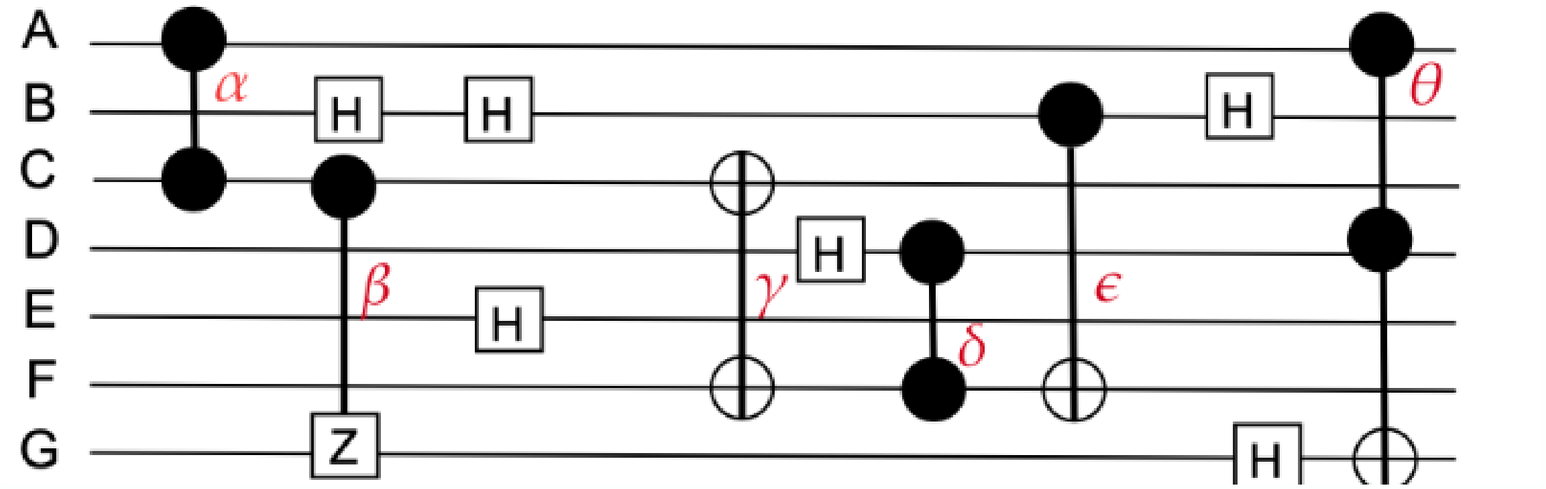
2) Choose if we want to cut through wires of gates

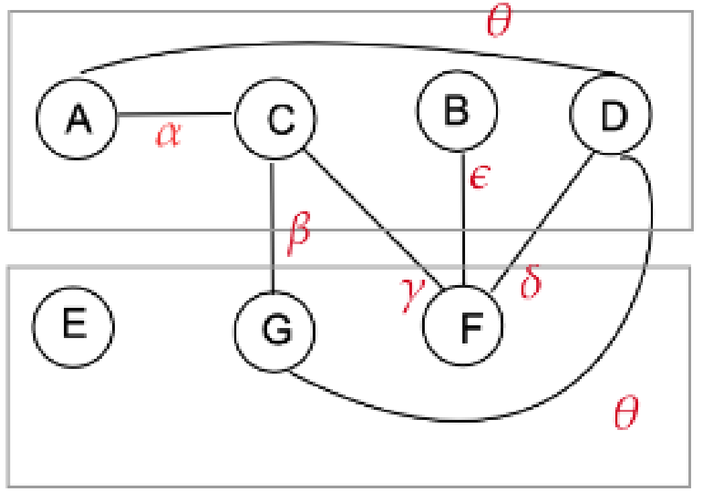
3) Make the relevant hypergraph

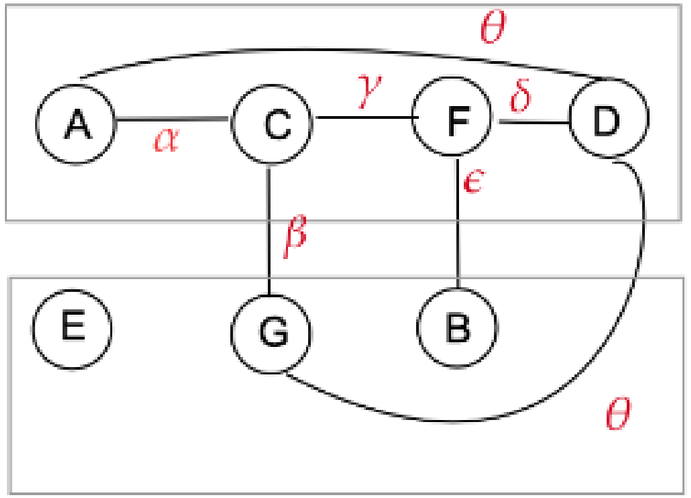
4) Cut it!

Image from arXiv:2404.01265

CUTTING AND KNITTING CIRCUITS







1) Decide how many QPUs we are distributing over
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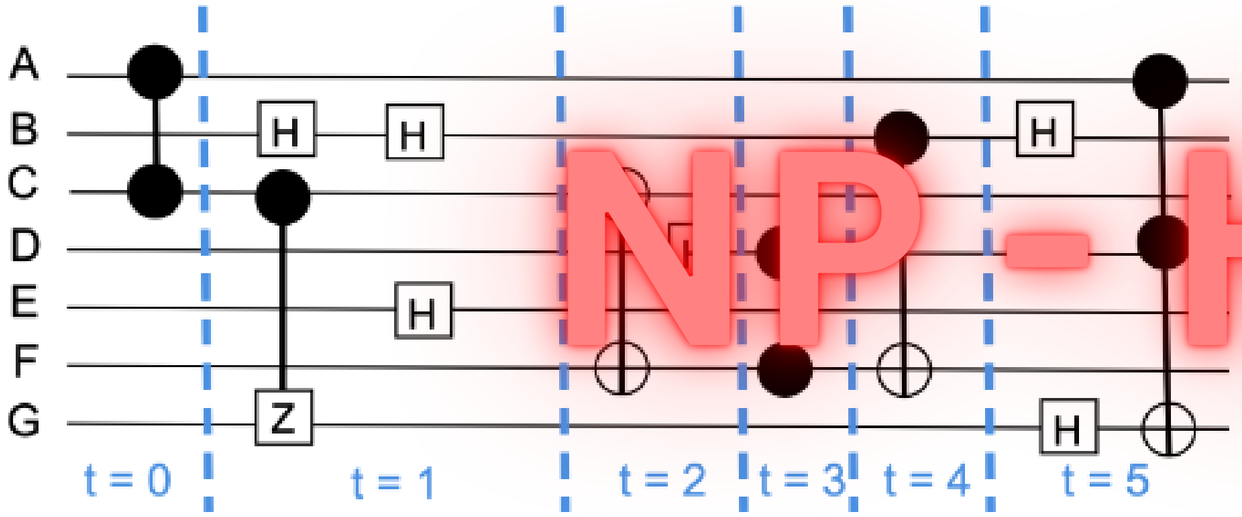
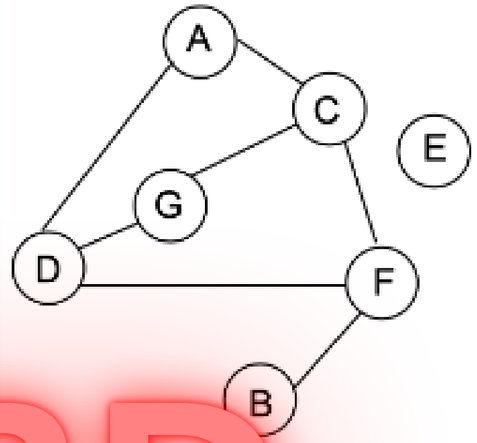
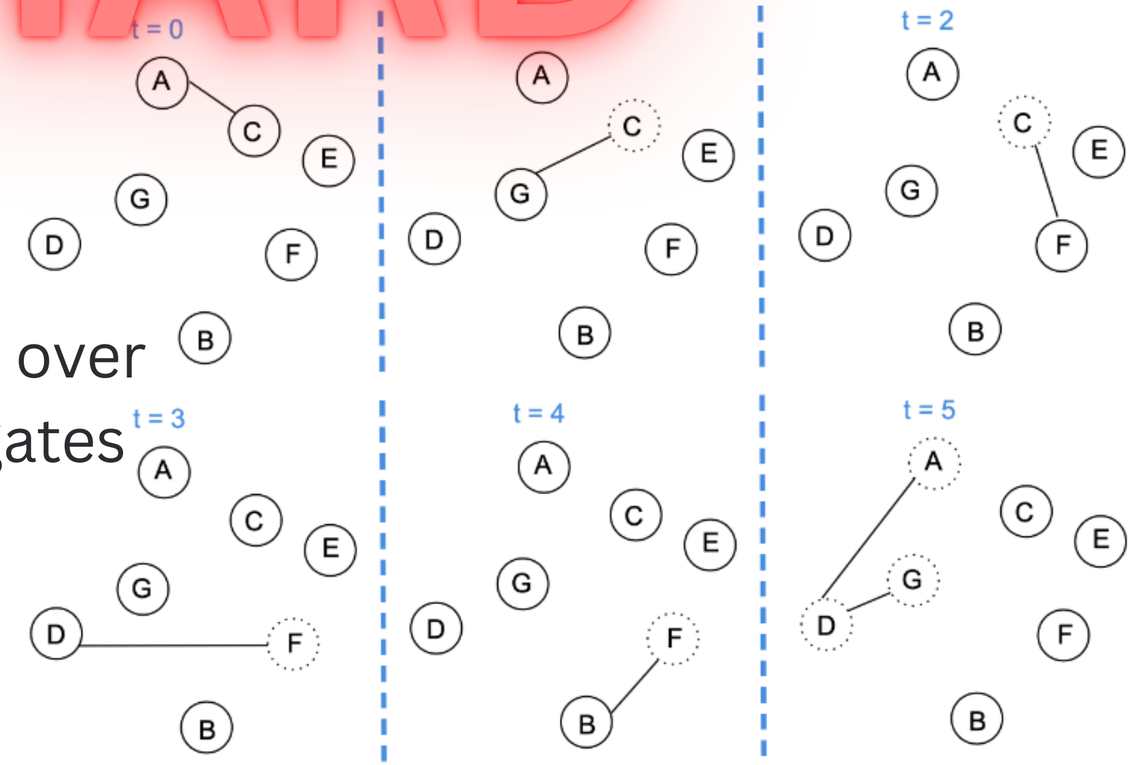
3) Make the relevant hypergraph
4) Cut it!

CUTTING AND KNITTING CIRCUITS





NP-HARD



1) Decide how many QPUs we are distributing over
2) Choose if we want to cut through wires of gates
3) Make the relevant hypergraph
4) **Cut it!**

IF THE CHANNEL IS QUANTUM

Good news we can teleport!

We need to:

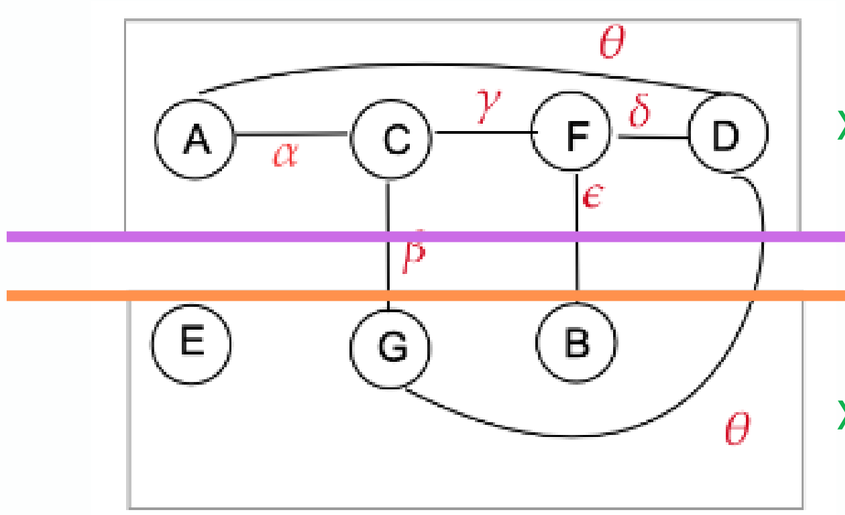
- Establish entanglement between our QPUs
- Deal with new errors introduced by the channel

IF THE CHANNEL IS CLASSICAL ☹

Bad news we can't teleport!

We need to:

- Establish entanglement between our QPUs
- Deal with new errors introduced by measurement
- Probabilistically decompose the channel



x Need to run many shots now

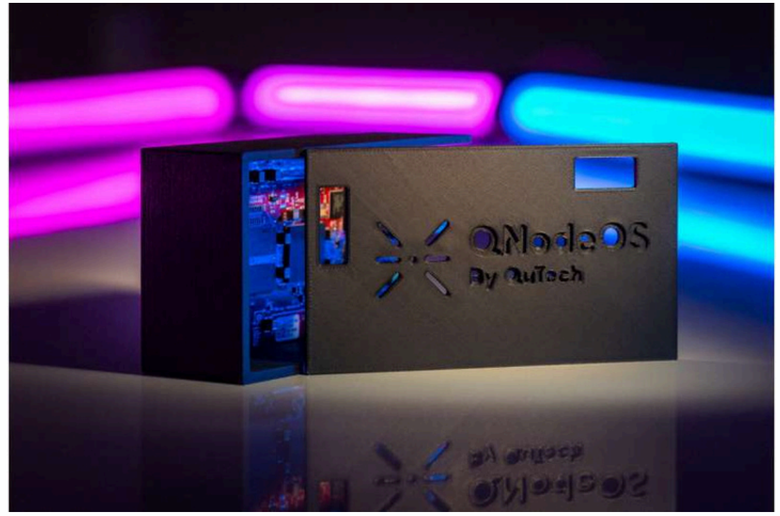
Mid-circuit measurement

Classical feed-forwarding

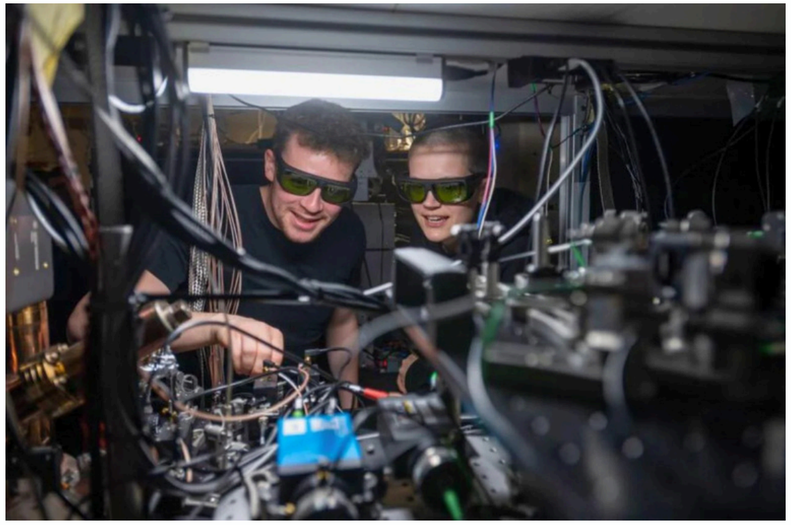
x Need to run many shots now

STATE OF THE ART

Xanadu’s Aurora



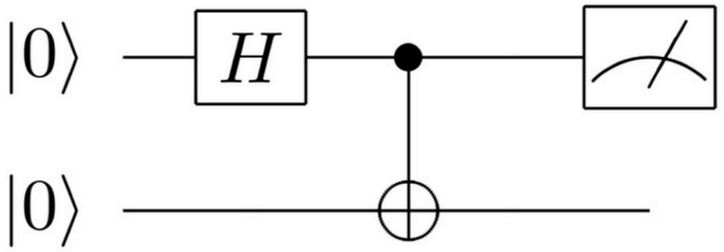
1st Quantum Networking OS system



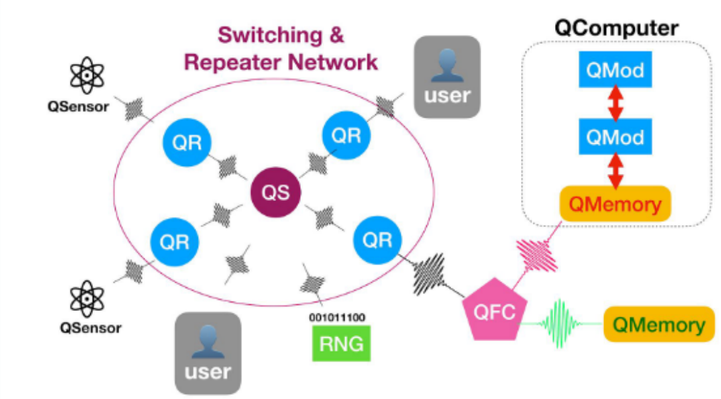
Distributed Grover search

THE HARDWARE CONVERSATION

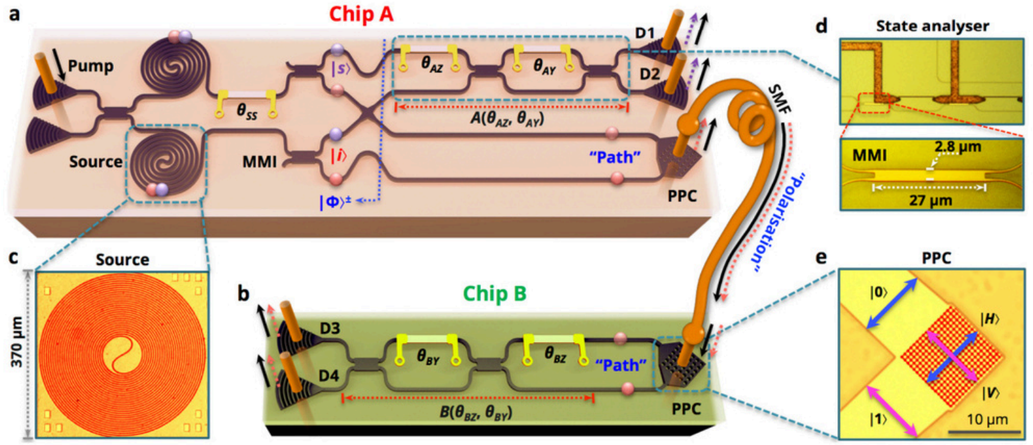
A uni-model perspective



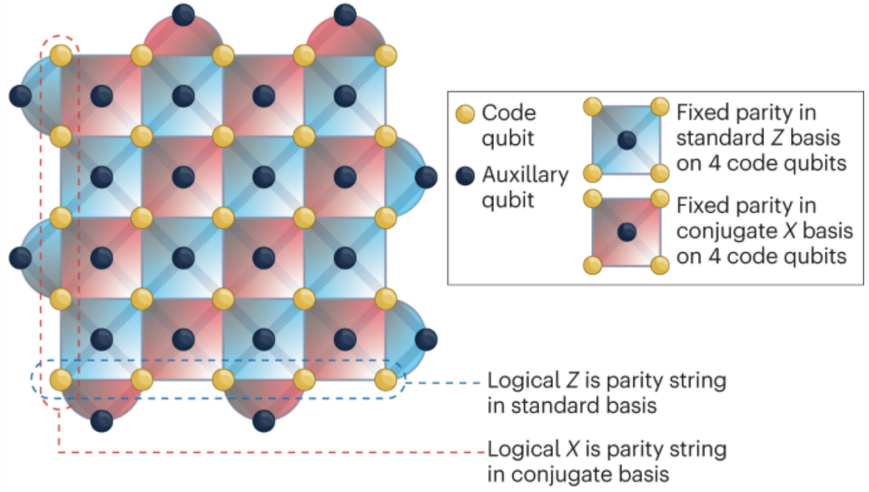
Neither quantum computers nor networks are mature or built to be compatible



Interconnects

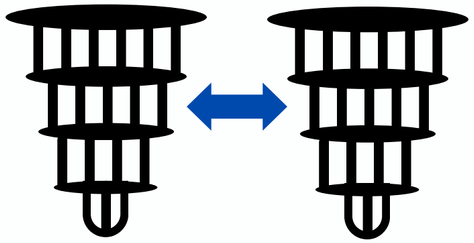


Errors and fidelity



Q&A

THANK YOU!



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