qLearn Week 9: Distributed Quantum Computing

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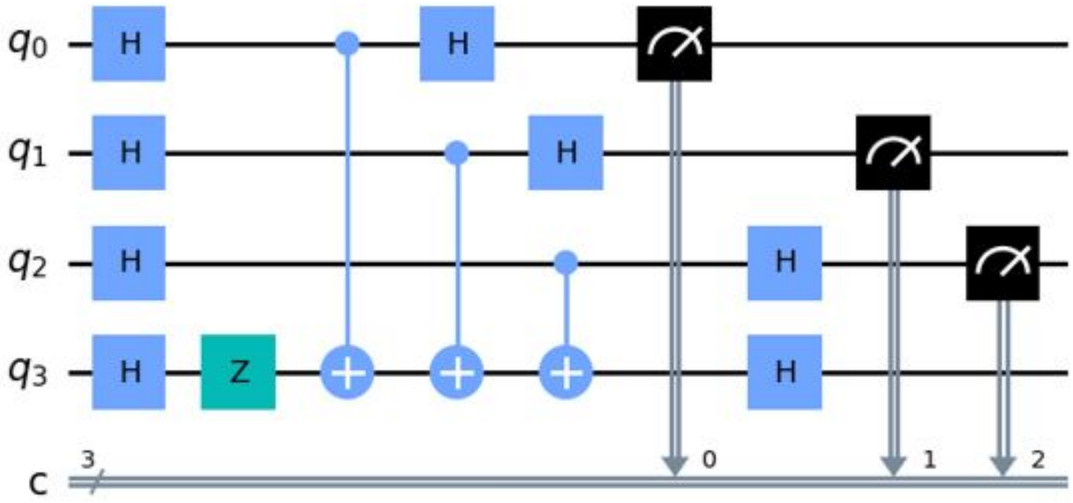
Last Semester...

- Why Quantum?
  - Classical scaling limits
    - Transistor sizes becoming atomic scale
    - Power, heat, fabrication constraints
    - Certain problems exhibit exponential resources classically
    - Simulating natural systems - *nature is quantum; simulate it with quantum systems*
  - Quantum computing principles
    - Superposition: parallel evaluation of amplitudes
    - Interference: ability to amplify correct outcomes and suppress incorrect ones
    - Entanglement: non-classical correlations between quantum bits (qubits!)
- Building hardware is difficult!
  - Noise constraints, decoherence, scalable architecture

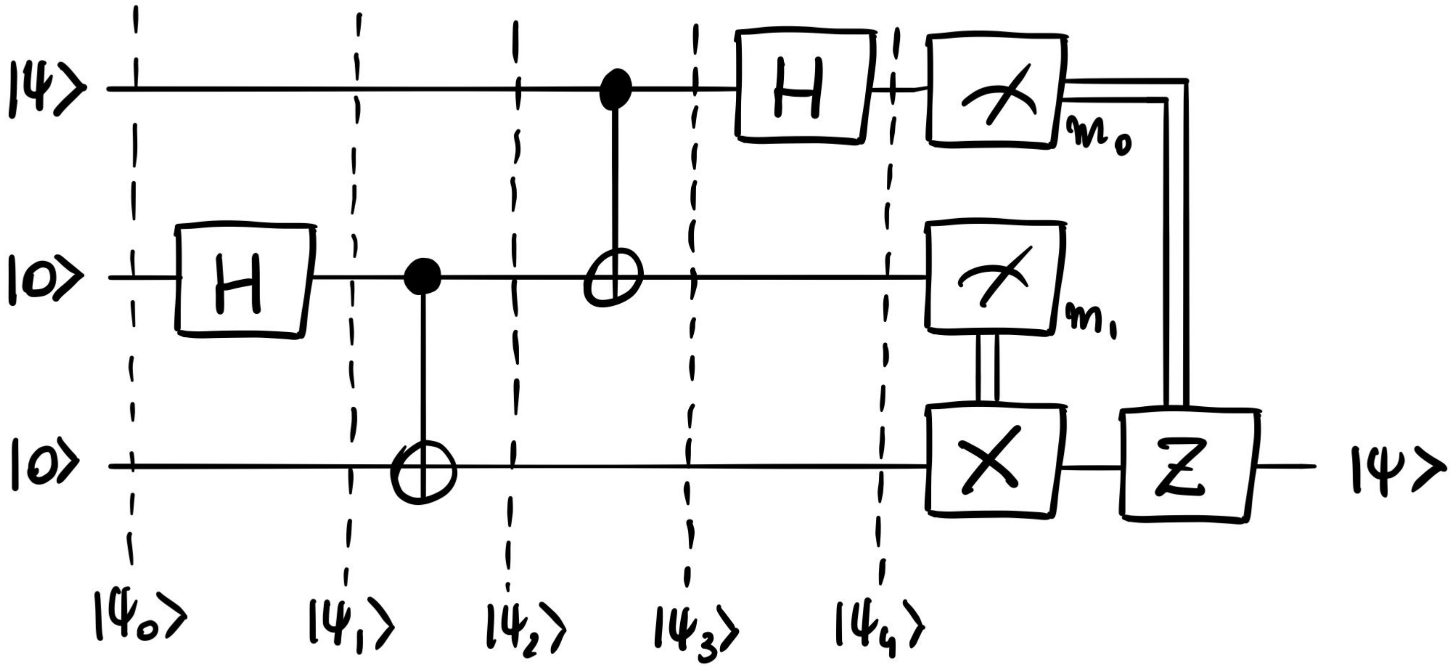
Last Semester

- Quantum Circuit Model



Today: Scaling Quantum Computers!

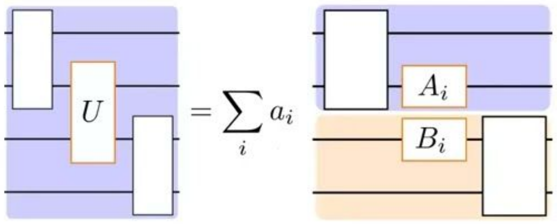
Background: Quantum Teleportation Circuit



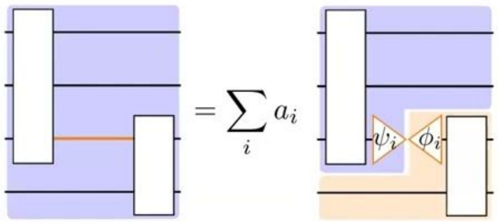
Note: measurement destroys quantum states; we treat them as resources, call them ‘e-bits’, ask me about this!

Near-Term ‘Distribution’: Local Operations

- Without quantum networks, we rely on classical ways to distribute circuits on monolithic hardware: Circuit Cutting!
    - Circuit Cutting: Run several smaller circuits made of the ‘parts’ of the larger circuit and recombine results classically
    - Gate Cutting: distributing multi-qubit gates; decompose gates into single-qubit operations and run for each possible ‘other qubit’ interaction
    - Wire Cutting: distributing qubits; ending one subcircuit with a measurement and using multiple inputs for the other subcircuit



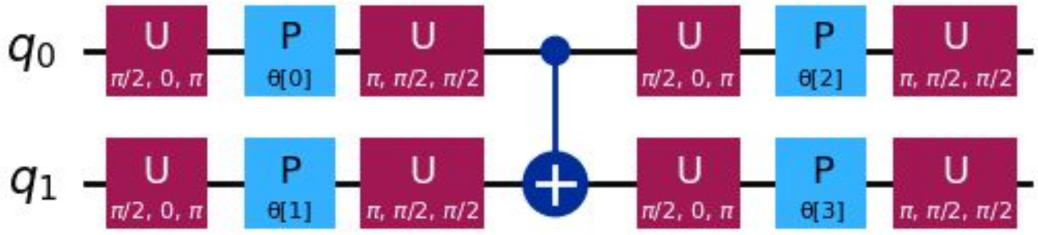
Gate cutting



Wire cutting

LO Schemes

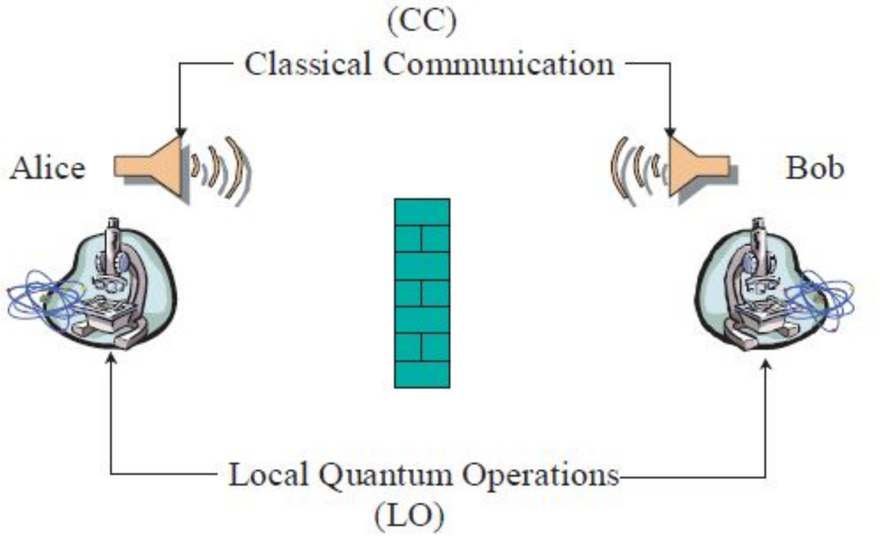
- Exponential overhead; have to run multiple circuits many times (for each ‘pretend’ state possible in a single cut)
- Large (classical) postprocessing; need to combine many results together
- Rapidly growing statistical noise
- **However**, end result allows us to run large circuits on ‘small’ hardware
  - Ideal schemes use as few cuts as possible -> low overhead
  - EX. Variational Quantum Eigensolver (solves for ground state energy of Hamiltonian)



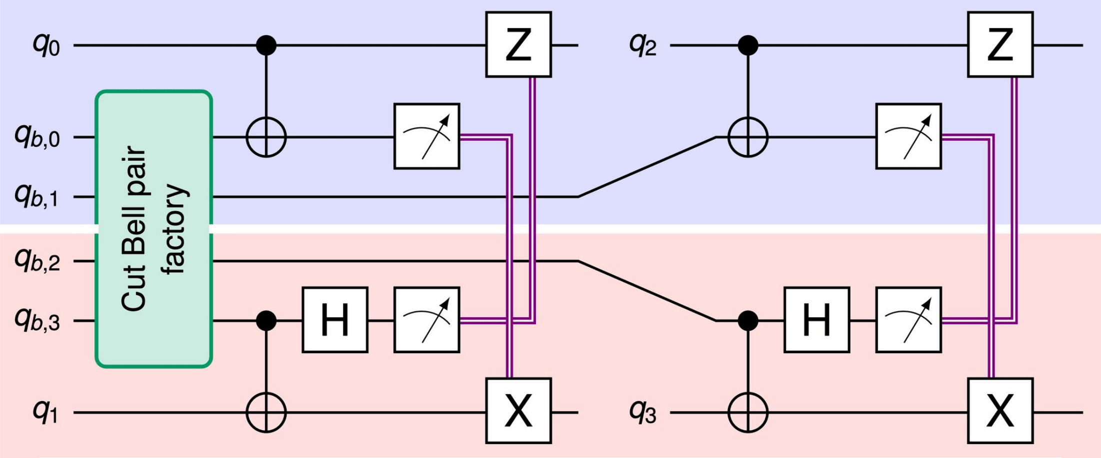
[IBM Circuit Cutting Library]

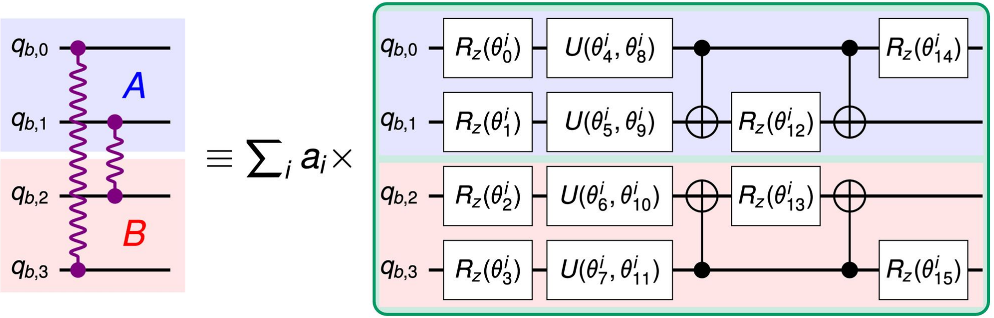
Closer-Term: Local Operations with Classical Communications (LOCC)

- Now we add a (classical) communication channel in between computers (copper wire, etc)
- This allows us to actually run distributed algorithms, but without true entanglement it's a bit more difficult



Cutting Edge Research: LOCC Scheme

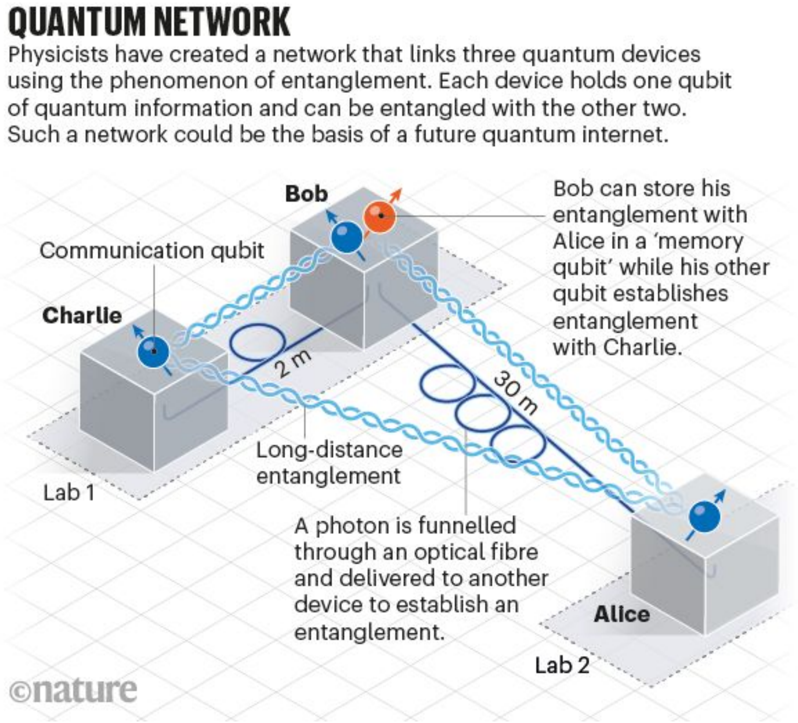




[Combining quantum processors with real-time classical communication]

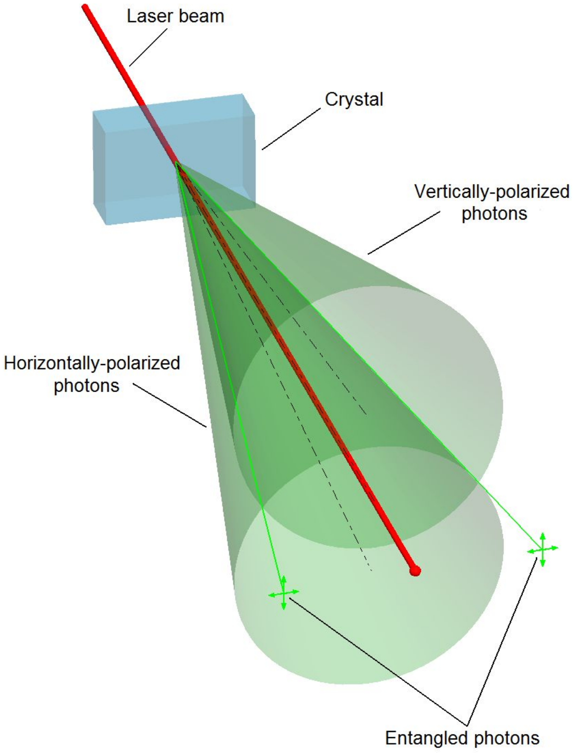
Creating Real Quantum Networks

- Modern communications use fibre optic for its speed and efficiency
- Quantum networks will ideally use a similar resource, since encoding quantum information into light is already a common practice
- Will be discussed further in quantum photonics lecture later in the semester



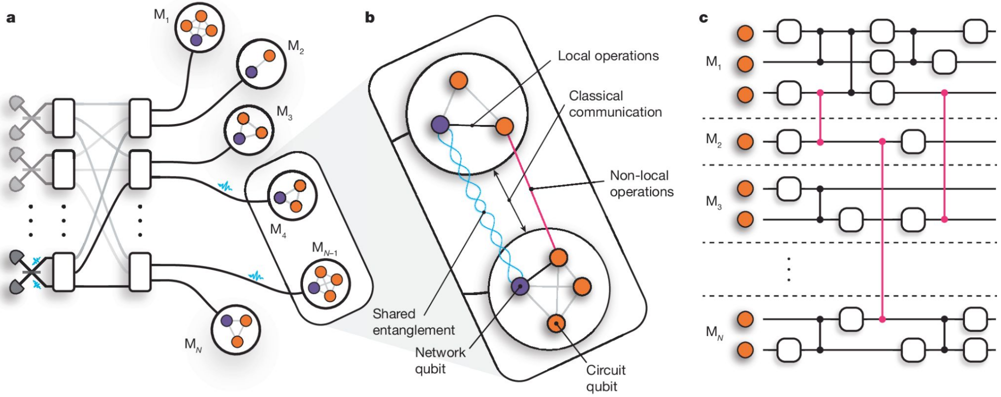
BASICS: Photonic Entanglement Generation

- We can ‘split’ photons using a nonlinear crystal, into two lower-energy entangled photons
  - Nonlinear crystal: essentially a beam splitter, interaction with light independent of light intensity, can change its properties
- These photons are inherently interfered and therefore entangled
- EX. we can entangle two trapped ions by having them both emit a photon, then interfere said photons (entanglement swapping)
- Interested? Nonlinear optics (PHY2208, ECE1450)



True Quantum Networks

- We use everything we've learned so far to connect and use multiple quantum computers!
- When networked correctly, we can make multiple act as one large quantum computer!
- Note: nonlocal entanglement is a bottleneck, in distributed algorithms we attempt to minimize our e-bit count/entanglement resources used



Distributed quantum computing across an optical network link

Appendix: State Vs Gate Teleportation

Which one is a state teleportation? Which one is a gate teleportation? Can you notice anything interesting about the two circuits?