Quantum Computing: Foundations to Frontier Fall 2018

Lecture 11

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1 Overview

We would like to see how quantum information and computation can be physically realized. While certain quantum technologies have been realized, such as quantum key distribution via satellites, we are still far from building a fully programmable, universal quantum computer. Several candidate architectures include: ion traps, superconductors, photonics, and topological quantum computing.

2 DiVincenzo Criteria

The DiVincenzo Criteria is a list of engineering requirements for building a universal quantum computer. They are listed below:

- **Long-lived qubits**: a two-level system that can maintain a coherent quantum state for a long time. "A long time" is relative to how quickly gates can be implemented.
- **Universal gates**: a system where qubits can interact with each other in a controlled way, to implement gates from a universal gate set.
- **Initialization**: must be able to reliably set qubits to the $|0\rangle$ state.
- **Measurement**: must be able to measure qubits in the standard $\{ |0\rangle, |1\rangle \}$ basis.

Current systems often target a subset of this criteria, as it is difficult to achieve all at once.

3 Trapped Ion Quantum Computers

Trapped ion quantum computers are cooled to very low temperatures using lasers, and magnetic fields are rotated (at high rates) to keep ions "floating" in free space. Groups developing trapped ion quantum computers include: the University of Maryland/NIST, IonQ (startup), the University of Innsbruck, Austria, and Harvard (who are developing trapped neutral atoms).

- **Qubits**: charged atomic nuclei (atoms) kept in a magnetic containment.
- **State**: encoded into electronic energy states of the ion, specifically in hyperfine energy levels (slight variations in energy levels). As there is a spectrum of energy levels, one challenge is addressing only 2 energy levels.

- **Single qubit gates**: microwave pulses at specific frequencies and durations. One challenge is that it is difficult to only address a single qubit.
- **Entanglement gates**: ions act like pendulums connected by springs. Using specific microwave pulses, entangling gates can be implemented.
- **Measurement**: done using lasers. State $|1\rangle$ emits fluorescence when shined on by a laser, State $|0\rangle$ emits no fluorescence.

- **Pros**:
  - Very clean system to store quantum information; a Be+ ion is the same everywhere.
  - Very high fidelity, the best gate fidelities (up to 99.9%).
  - Very stable: trapped ions can stay coherent for tens of seconds.
- **Cons**:
  - Gates are very slow (microseconds).
  - Hard to scale up. Trapped ion quantum computers require a very sophisticated manufacturing process, and an ion trap can only store about 20 qubits.
    * Older proposal: maze of ion traps, physically move ions between traps using lasers.
    * Newer proposal: connect modules of 30-40 trapped ions using photonics, e.g. using the quantum teleportation protocol.

4 Superconducting Qubits

Superconducting quantum computers must also be cooled to low temperatures (10 mK). They are attractive because they can be fabricated on chips using existing integrated circuit technology. Groups developing superconducting qubit quantum computers include Google, IBM, Regetti (startup), Dwave (startup), and Yale.

- **Qubits**: superconducting coils.
- **State**: encoded in the direction of current flow, or the amount of flux going through a loop.
- **Gates**: implemented using microwaves/RF pulses. Two-qubit gates can only be performed with the nearest-neighbour qubits.
- **Measurement**: also implemented using microwaves/RF pulses.

- **Pros**:
  - Can be manufactured using existing technology.
  - In principle, it is possible to pack millions of qubits onto a single chip.
  - Extremely fast gates (nanoseconds).

  - Coherence times have improved by an order of magnitude of a million in the last 15+ years.

- **Cons**:
  - Relatively low coherence times (microseconds).
  - Computations can only be performed with nearest-neighbour gates, so algorithms require many swaps.
  - Every qubit is different due to manufacturing defects.
  - Need to cool to 10 mK.

5 Optical Quantum Computing

Optical quantum computers are attractive as they do not require being cooled to extremely low temperatures. Groups developing optical quantum computers include Psi Quantum (startup), Xanadu, and many academic labs (University of Bristol, MIT, University of Toronto).

- **Qubits**: photons.
- **State**: encoded in polarization, position and momentum, or using dual-rail encoding.
- **Gates**: implemented using linear optical elements, phase shifters, and beam splitters (e.g. vertically polarized light split in one direction, horizontally polarized light split in another direction).
- **Measurement**: photon detectors.

- **Pros**:
  - Extremely stable (light doesn't interact with many things).
  - Can operate at room temperature.
  - We have a lot of expertise with photonics.
  - Components such as beam splitters exist classically.
- **Cons**:
  - Light can be too stable (hard to interact with).
  - Light is fast.
  - Difficult to deterministically generate entangled photons (can do it probabilistically).

6 Topological Quantum Computing

In 3 dimensions, we have two fundamental particles: fermions (matter particles, such as electrons, protons, and neutrons), and bosons (force carrying particles, such as photons). When one swaps fermions, the quantum state changes, although this is not the case for bosons. In 2 dimensions, mathematically there exist a new particle called "anyons." There exist experiments that show hints of anyons, but they haven't definitively been proven to exist. However, in principle, they topological quantum computers should be naturally fault tolerant; there will be less or no need for error correction. Microsoft is currently pursuing topological quantum computing.

- **Qubits**: anyons (quasiparticles that exist only in 2 dimensions).
- **State**: encoded into the global topological properties of anyons, such as their relative arrangement.
- **Gates**: computation is performed by moving anyons around in "braiding patterns."

7 Where We Stand

We are currently in the Noisy Intermediate Scale Quantum (NISQ) era, and likely will be for a while. This is a primitive stage, and we are taking rudimentary steps towards having fine, exquisite control of quantum properties of matter. We are sometimes refered to as being in the "vacuum tube" era of quantum computing. There are several milestones along the way to develop large scale quantum computers, though it is hard to predict the future, i.e. exactly when they will arrive.

1. **Quantum supremacy/advantage**. We would like to show (and implement) something that no classical computer can do efficiently.
2. **Physics and chemistry applications**. Hopefully, there will be clever ways to use NISQ devices to do science experiments, even though they are primitive and noisy.
3. **Fault tolerant, universal quantum computing**. Eventually, we hope to have devices that satisfy all of the DiVincenzo criteria.