ITIS 6260/8260 Quantum Computing

Lecture 8: Practical Aspects of QC

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Outline

Quantum simulation

Take a Hamiltonian of a reaul quantum systme, Trotterize it, and simulate it on a quantum computer

- Do a chemical reaction without physically performing it: revolutionalize the materials science
- Non-fully-error-corrected quantum computers with a few hundred qubits might be enough to start seeing advantages for quantum simulation
- Microsoft (2016) argues that 100-200 logical qubits would already be enough to let us simulate nitrogen fixation in the Haber process, the chemical reaction that the world uses to make fertilizer (a market for billions of dollars)

Adiabatic optimization

- might produce speedups better than Grover's algorithm for special classes of optimization problems

Code breaking

- the sexiest application from quantum computing though not interesting for the industry to invest in quantum computers for this purpose
- this is not the commercial application of quantum computers

- squre-root speedup of database search

Machine learning

Machine learning seems a good match for quantum computing because many machine-learning tasks boil down to performing linear algebra on extremely high-dimensional real vectors.

The HHL algorithm (Harrow, Hassidim, Lloyd)

For a linear equation $A\mathbf{x} = \mathbf{b}$:

- Suppose I have a $(\log n)$-qubit quantum state $|b\rangle$ whose amplitudes encode (a normalized version of) the vector $\mathbf{b}$. Suppose also that I'm able to efficiently apply a Hamiltonian H that corresponds to A. Then assuming one further condition (about the matrix A being far from singular), in logarithmic time, I can prepare a $(\log n)$-qubit quantum state $|x\rangle$ whose amplitudes encode a normalized version of the solution vector $\mathbf{x}$
- **Challenges**: how can we convert this into and out of a quantum system?
- For example: when you get $|x\rangle = \sum_{i=1}^{n} \alpha_i |i\rangle$. How can you get α_i out? You need to measure n times which is exponential again

DiVincenzo Criteria

- Long-lived qubits
- Universal gates
- Initialization
- Measurement

Build a qubit

- trapped Ions (the oldest techiniques back to 1995)
- superconducting qubits
- photonics
- nonabelian Anyons

Ions

- manipulate the magnetic field to get ions in a like
- once we fix a direction, each atomic nucleus has a spin state that can be up, down, or a superposition of both
- If bring two ions close together, the natural Coulomb interaction between can be used to design CNOT gate
- manipulate the ions by using a laser to pick them up and move them around
- in order to scale up, people proposed to use many traps: with quantum teleportation to entangle qubits in different traps
- experimental ion-trap groups: NIST, UMD, and Innsbruck (Austria)

Superconducting qubits

- all the action happens on coils on a chip, (like an ordinary computer chip), which is placed in a dilution refrigerator and cooled down enough for the coils to superconduct (the temperature is around 10 milliKelvin)
- Superconductivity (current flows with zero resistance) is a famous quantum effect. The superconducting qubits are "LARGE" (naked eyes can see them)
- a qubit: one example is whether the current is flowing clockwise, counterclockwise, or in a superposition of two
- Between two of the coils, one can place a thin layer called a Josephson junction, which lets electrons tunnel from one coil to the other, and can result in a 2-qubit gate being implemented.

Superconducting qubits

- advantages of superconducting qubits: easy to make a lot coils, gate operations are fast (nanoseconds), chip fabrication technology mature
- disadvantages of superconducting qubits: coherence times are shorter (tens of microseconds compared to seconds for ions), superconducting qubits cannot be moved around. They can only talk to their near neighbors. In most of our algorithms, we assumes gates between any pair of qubits. We can only do this via simulation in superconducting qubits by swapping qubits
- experimental superconducting groups: D-Wave, Google, IBM, Intel, Rigetti (a start up: ex-IBM-employees), etc.
- John Martinis's group (Google) is leading. Trying to get 72-qubit chip. IBM is developing 50 qubits

Photonics

- We have discussed this in Lecture 1 already
- The advantages of optical QC is that photons can maintain their quantum coherence for extremely long times—as long as they travel in straight lines
- The photons in the cosmic microwave background (CMB) radiation may have maintained their quantum coherence for billions of years
- The challenge: these photons are flying at the speed of light, so hard to control them
- Aaronson's Boson Sampling quantum computer model uses photons

Topological QC with non-abelian anyons

- two types of fundamental particle in the universe: Bosons and Fermions
- difference: If we swap two identical bosons, nothing happens. If we swap two identical fermions, then the amplitude get multiplied by -1.
- photons are bosons while “matter” particles, like electrons, quarks, and neutrinos, are all fermions
- Difference in behavior: fermions “take up space”—the Pauli exclusion principle prevents two fermions from occupying the exact same state—whereas bosons can “pile up on top of each other” (e.g., lasers and Bose-Einstein condensates)

Topological QC with non-abelian anyons

- in the 3-dimensional space, every particle must be either a fermion or a boson
- in 2 dimensions, one can have particles that are neither bosons nor fermions. These particles are anyons. Physically, they could arise as "quasiparticles"–that is, particle-like excitations in a 2-dimensional medium.
- (Freedman, Kitaev, Wang) if you could make such quasiparticles in a two-dimensional surface, then just moving the particles around each other in a suitable sequence would be enough to do a universal quantum computation

Topological QC with non-abelian anyons

- in order to affect the quantum computation's output, one needs to change the topology of the braiding pattern formed by the particles' worldlines
- Due to this "topological" property, this setup might be naturally much more robust to decoherence than more traditional approaches to building a QC, and might require much less error-correction
- Microsoft is the leader in the topological approach to quantum computer

Q&A?