Quantum Computer Prototypes

Yipeng Huang

Rutgers University

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Where we are in the semester

Full stack quantum computer engineering

1. Algorithms: QAOA & VQE
2. Programming languages, assertions, stabilizers
3. Google Cirq, IBM Qiskit
4. Quantum circuit simulation and quantum supremacy
5. Extracting success: quantum computer architecture
6. Prototypes: quantum computer microarchitecture

- Programming assignments (2 × 25 points)
- Seminar presentations (2 × 25 points)
Course evaluation

https://sirs.ctaar.rutgers.edu/blue Very important to help develop next iteration of this course.
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Anatomy of a quantum computer
   Essential hardware components of a quantum computer
   DiVincenzo’s criteria

Device technologies
   Trapped ion quantum computers
   Superconducting quantum computers
   Other technologies
Essential hardware components of a quantum computer

Host processor plane

Control processor plane
digital processing, non-deterministic timing

Control and measurement plane
analog processing, deterministic timing

Quantum data plane

[National Academies of Sciences, Engineering, and Medicine, 2019, Chapter 5]
This is an example for superconducting qubits.

**Figure:** Credit: [Fu et al., 2019]
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DiVincenzo’s criteria

The central challenge
Keeping qubits weakly coupled to external decoherence forces, while keeping them strongly coupled to each other.

Examples
The requirements are often conflicting: single nuclear spin can remain in a superposition state for days, but because it couples so weakly with the world, control and measurement is hard.
DiVincenzo’s criteria

1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $|000\ldots\rangle$
3. Long relevant decoherence times, much longer than the gate operation time
4. A “universal” set of quantum gates
5. A qubit-specific measurement capability
6. The ability to interconvert stationary and flying qubits
7. The ability to transmit faithfully flying qubits between specified locations
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Trapped ion quantum computers

**Strengths**
Long coherence, high inter-connectivity

**Weaknesses**
Rely on multiple interacting technologies, relatively slow (1–100µS) gate operation times

**Examples**
Research groups: University of Maryland, IonQ, Honeywell

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**Figure:** Credit: [Ladd et al., 2010]

**FIG. 2:** Schematic of ion trap apparatus. Electric potentials are applied to appropriate electrodes in order to confine a 1-D crystal of individual atomic ions. Lasers affect coherent spin-dependent forces to the ions that can entangle their internal qubit levels through their Coulomb-coupled motion. Resonant lasers can also cause spin-dependent fluorescence for the efficient detection of the trapped ion qubit states. The inset shows a collection of atomic Ca⁺⁺ ions fluorescing (courtesy R. Blatt, University of Innsbruck).
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Ion traps: A scalable physical system with well characterized qubits

Optical qubits
Ground electronic state and a metastable excited electronic state. Large gap, higher frequency, optical laser for control.

Hyperfine qubits
Pair of energy states resulting from nucleus with non-zero spin with smaller energy difference. Small gap, lower frequency, microwave sources for control.

Figure:
Credit: [National Academies of Sciences, Engineering, and Medicine, 2019]
Ion traps: A scalable physical system with well characterized qubits

**Optical qubits**
Ground electronic state and a metastable excited electronic state. Large gap, higher frequency, optical laser for control.

**Hyperfine qubits**
Pair of energy states resulting from nucleus with non-zero spin with smaller energy difference. Small gap, lower frequency, microwave sources for control.

*Figure:*
Credit: [Nielsen and Chuang, 2011]
Ion traps: Long relevant decoherence times, much longer than the gate operation time

Figure: Credit: NAP.

High vacuum

Radio frequency Paul trap
Like a rotating saddle. RF at 20–200 MHz. Voltage amplitudes 30–400 V.

Direct current axial trap
DC axial trap 0-30V
Ion traps: Long relevant decoherence times, much longer than the gate operation time

An artificial 1 dimensional crystal

Once ions are settled in trap, confined in two dimensions with more freedom to move axially. They repel and interact with each other due to Coulomb repulsion.

Figure: Credit: NAP.
Ion traps: The ability to initialize the state of the qubits to a simple fiducial state, such as $|000\ldots\rangle$

Cooling the ions down to ground state

Continuous wave lasers carry away momentum from system.
Coherent qubit control system

Single qubit gates
Rabi oscillations between the two qubit levels with resonant laser pulses.

Fig. 6. Rabi oscillations of a single Ca\(^+\) ion. Each dot represents 1000 experiments, each consisting of initialization, application of laser light on the qubit transition and state detection.

Figure: Credit: [Häffner et al., 2008]
Ion traps: A “universal” set of quantum gates

Two qubit gates

2. Ignacio Cirac and Peter Zoller two qubit gate in 1995.
3. Mølmer-Sørensen gate.
4. Global entangling gate, or pair-wise control signals.
5. 2–5% error rates for two-qubit gates.

Figure: Credit: [Häffner et al., 2008]
Ion traps: A qubit-specific measurement capability

1. Continuous wave lasers for read out illumination.
3. Photon detectors.

Figure: Credit: [Ladd et al., 2010]

FIG. 2: Schematic of ion trap apparatus. Electric potentials are applied to appropriate electrodes in order to confine a 1-D crystal of individual atomic ions. Lasers affect coherent spin-dependent forces to the ions that can entangle their internal qubit levels through their Coulomb-coupled motion. Resonant lasers can also cause spin-dependent fluorescence for the efficient detection of the trapped ion qubit states. The inset shows a collection of atomic Ca" ions fluorescing (courtesy R. Blatt, University of Innsbruck).
Ion traps: The ability to interconvert stationary and flying qubits

1. Each trap may scale to over 50 qubits.
2. Proposals to couple distant traps via photonics or via entangled ions.
Ion traps: The ability to transmit faithfully flying qubits between specified locations

Figure 4.2: (a) The physical structure of an ion-trap quantum computer. An optimistic size of the trapping electrodes is in the order of tens of micrometers [193]. The data ion is kept together with a cooling ion and cooled before and after each movement step or logic gate. The ion-group can move to any of the 6 adjacent trapping regions for interaction with another ion-group. (b) A two-qubit gate sequence where the ion-group in the top left junction moves to the middle for a two-qubit gate. The gate is implemented with an external laser beam acting on the two ion-groups.

Figure: Ion shuttling. Credit: [Metodi and Chong, 2006]
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Superconducting quantum computers

**Strengths**

Solid state, lithographically defined (single mask, single metal layer), relatively fast (10–100nS) gate operation times

**Weaknesses**

Variability, cryogenic

**Examples**

Research groups: IBM, Google (Bristlecone, Sycamore), Rigetti
DiVincenzo’s criteria

1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $\vert 000 \ldots \rangle$
3. Long relevant decoherence times, much longer than the gate operation time
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Superconductors: A scalable physical system with well characterized qubits

Figure: Credit: [Krantz et al., 2019]

**Linear resonator**

Superconducting resonator

\[ H = \frac{\Phi^2}{2L} + \frac{Q^2}{2C} \]

\[ \omega_0 = \frac{1}{\sqrt{LC}} \]

C acts as mass

Inductance acts as spring

[Devoret et al., 2004]

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**FIG. 1.** (a) Circuit for a parallel LC-oscillator (quantum harmonic oscillator, QHO), with inductance \( L \) in parallel with capacitance, \( C \). The superconducting phase on the island is denoted \( \phi \), referencing ground as zero. (b) Energy potential for the QHO, where energy levels are equidistantly spaced \( \hbar \omega_r \) apart. (c) Josephson qubit circuit, where the nonlinear inductance \( L_J \) (represented with the Josephson-subcircuit in the dashed orange box) is shunted by a capacitance, \( C_s \). (d) The Josephson inductance reshapes the quadratic energy potential (dashed red) into sinusoidal (solid blue), which yields non-equidistant energy levels. This allows us to isolate the two lowest energy levels \( |0\rangle \) and \( |1\rangle \), forming a computational subspace with an energy separation \( \hbar \omega_{01} \), which is different than \( \hbar \omega_{12} \).
Superconductors: A scalable physical system with well characterized qubits

**Nonlinear resonator**

1. Nonlinear inductor: Josephson junction.
2. Al-AlOx-Al.
3. Josphson junction introduces nonlinearity.

*Figure: Credit: wikimedia.org*
Superconductors: A scalable physical system with well characterized qubits

FIG. 1. (a) Circuit for a parallel LC-oscillator (quantum harmonic oscillator, QHO), with inductance $L$ in parallel with capacitance, $C$. The superconducting phase on the island is denoted $\phi$, referencing ground as zero. (b) Energy potential for the QHO, where energy levels are equidistantly spaced $\hbar \omega$, apart. (c) Josephson qubit circuit, where the nonlinear inductance $L_I$ (represented with the Josephson-subcircuit in the dashed orange box) is shunted by a capacitance, $C_s$. (d) The Josephson inductance reshapes the quadratic energy potential (dashed red) into sinusoidal (solid blue), which yields non-equidistant energy levels. This allows us to isolate the two lowest energy levels $|0\rangle$ and $|1\rangle$, forming a computational subspace with an energy separation $\hbar \omega_{01}$, which is different than $\hbar \omega_{12}$.

Artificial atoms with atom-like spectra
Superconductors: Long relevant decoherence times, much longer than the gate operation time

Superconductors and cryogenic temperatures needed for qubit coherence

1. Superconductivity eliminates heat dissipation with current.

2. Cryogenic temperatures eliminate state transitions due to thermal excitation (5GHz microwave corresponds to thermal energy of 250mK).

3. Cryogenic temperatures also needed for superconductivity (for aluminium, $T_c = 1.2K$).
Superconductors: Long relevant decoherence times, much longer than the gate operation time

Dilution refrigerator

1. Dry refrigerator cools to 50K and 3K. Here, thermal budget is 1W.
2. Liquid helium cools to 700mK, 50mK, 10mK. Here, thermal budget is 30\(\mu\)W–1mW.

Cryogenic signal processing stage-by-stage

1. Thermally resistive will necessarily imply electrically lossy.
2. Filter out the noise.
3. Attenuate to send to next stage.

Takes 2 days to cool down to operating temperature.
Superconductors: A "universal" set of quantum gates

Single qubit gates

1. JJ reshapes the parabolic energy well so that gap between lower energy levels is wider.

2. Creates a $f_{01}$ transition frequency.

3. Then you can change the state $(I,V)$ by injecting microwaves at the right frequency.

4. $\approx 5$GHz microwaves stimulate transition, with standard deviation $\sigma \approx 150$MHz.

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**Figure**: Credit: [Krantz et al., 2019]
Superconductors: A “universal” set of quantum gates

Two qubit gates

1. Single junction nontunable
2. Two-junction tunable

Examples
OpenPulse.
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Trapped ions and superconductors are currently the only technologies with full-stack integration.

In fact, it is quite remarkable that both are at comparable maturity level, given the wildly different technologies involved.

Outside of TI and SC, other technologies are demonstrating single and two qubit gates.
Other technologies

Atomic, molecular, and optical physics
Trapped optical ion, trapped (hyperfine) microwave/RF ion, trapped neutral atoms, liquid nuclear magnetic resonance.

Solid-state
GaAs quantum dot, optically active defects, diamond defects, nitrogen vacancy centers, superconducting phase/charge/flux qubit.

All are in infancy.
Hard to bet on long term winner.
### Other technologies

<table>
<thead>
<tr>
<th>Type of Matter Qubit</th>
<th>Coherence</th>
<th>Benchmarking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\omega_0/2\pi$</td>
<td>$T_2$</td>
</tr>
<tr>
<td><strong>AMO</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trapped Optical Ion</td>
<td>400 THz</td>
<td>1 ms</td>
</tr>
<tr>
<td>(40 Ca$^+$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trapped Microwave Ion</td>
<td>300 MHz</td>
<td>10 sec</td>
</tr>
<tr>
<td>(9 Be$^+$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trapped Neutral Atoms</td>
<td>7 GHz</td>
<td>3 sec</td>
</tr>
<tr>
<td>($^{87}$Rb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Molecule Nuclear Spins</td>
<td>500 MHz</td>
<td>2 sec</td>
</tr>
<tr>
<td><strong>Solid-State</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e$^-$ Spin in GaAs Quantum Dot</td>
<td>10 GHz</td>
<td>3 $\mu$s</td>
</tr>
<tr>
<td>(31P:Si)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e$^-$ Spins Bound to (31P:Si)</td>
<td>300 MHz</td>
<td>60 ms</td>
</tr>
<tr>
<td>Nuclear Spins in Si</td>
<td>60 MHz</td>
<td>25 sec</td>
</tr>
<tr>
<td>NV$^-$ Center in Diamond</td>
<td>3 GHz</td>
<td>2 ms</td>
</tr>
<tr>
<td>Superconducting Phase Qubit</td>
<td>10 GHz</td>
<td>350 ns</td>
</tr>
<tr>
<td>Superconducting Charge Qubit</td>
<td>10 GHz</td>
<td>2 $\mu$s</td>
</tr>
<tr>
<td>Superconducting Flux Qubit</td>
<td>10 GHz</td>
<td>4 $\mu$s</td>
</tr>
</tbody>
</table>

Table comparing the current performance of various matter qubits. The approximate resonant frequency of each qubit is listed as $\omega_0/2\pi$; this is not necessarily the speed of operation, but sets a limit for defining the phase of a single qubit. Therefore, $Q = \omega_0 T_2$ is a very rough quality factor. Benchmarking values show approximate error rates for single or multi-qubit gates. Values marked with * are found by state tomography, and give the departure of the fidelity from 100%. Values marked with † are found with randomized benchmarking. Other values are rough experimental gate error estimates.

**Figure:** Credit: [Ladd et al., 2010]
Other technologies

<table>
<thead>
<tr>
<th>System</th>
<th>$\tau_Q$</th>
<th>$\tau_{op}$</th>
<th>$n_{op} = \lambda^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear spin</td>
<td>$10^{-2} - 10^8$</td>
<td>$10^{-3} - 10^{-6}$</td>
<td>$10^5 - 10^{14}$</td>
</tr>
<tr>
<td>Electron spin</td>
<td>$10^{-3}$</td>
<td>$10^{-7}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Ion trap (In$^+$)</td>
<td>$10^{-1}$</td>
<td>$10^{-14}$</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>Electron – Au</td>
<td>$10^{-8}$</td>
<td>$10^{-14}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Electron – GaAs</td>
<td>$10^{-10}$</td>
<td>$10^{-13}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Quantum dot</td>
<td>$10^{-6}$</td>
<td>$10^{-9}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Optical cavity</td>
<td>$10^{-5}$</td>
<td>$10^{-14}$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Microwave cavity</td>
<td>$10^0$</td>
<td>$10^{-4}$</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

Figure 7.1. Crude estimates for decoherence times $\tau_Q$ (seconds), operation times $\tau_{op}$ (seconds), and maximum number of operations $n_{op} = \lambda^{-1} = \tau_Q / \tau_{op}$ for various candidate physical realizations of interacting systems of quantum bits. Despite the number of entries in this table, only three fundamentally different qubit representations are given: spin, charge, and photon. The ion trap utilizes either fine or hyperfine transitions of a trapped atom (Section 7.6), which correspond to electron and nuclear spin flips. The estimates for electrons in gold and GaAs, and in quantum dots are given for a charge representation, with an electrode or some confined area either containing an electron or not. In optical and microwave cavities, photons (of frequencies from gigahertz to hundreds of terahertz) populating different modes of the cavities represent the qubit. Take these estimates with a grain of salt: they are only meant to give some perspective on the wide range of possibilities.

**Figure:** Credit: [Nielsen and Chuang, 2011]
Other technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Coherence Time (s)</th>
<th>1-Qubit Gate Latency (s)</th>
<th>2-Qubit Gate Latency (s)</th>
<th>1-Qubit Gate Fidelity (%)</th>
<th>2-Qubit Gate Fidelity (%)</th>
<th>Mobile</th>
</tr>
</thead>
</table>

Table 1. Metrics for various quantum technologies. * Nuclear/Electron Hybrid

Figure: Credit: [Resch and Karpuzcu, 2019]
Primary sources

▶ [National Academies of Sciences, Engineering, and Medicine, 2019, Chapter 5, Appendix B, Appendix C]
▶ [DiVincenzo, 2000]
▶ [Nielsen and Chuang, 2011, Chapter 1.5]
▶ [Nielsen and Chuang, 2011, Chapter 7]
▶ [Marinescu, 2011, Chapter 6]
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