

Quantum Computer Prototypes

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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]

TU Delft control and measurement processors

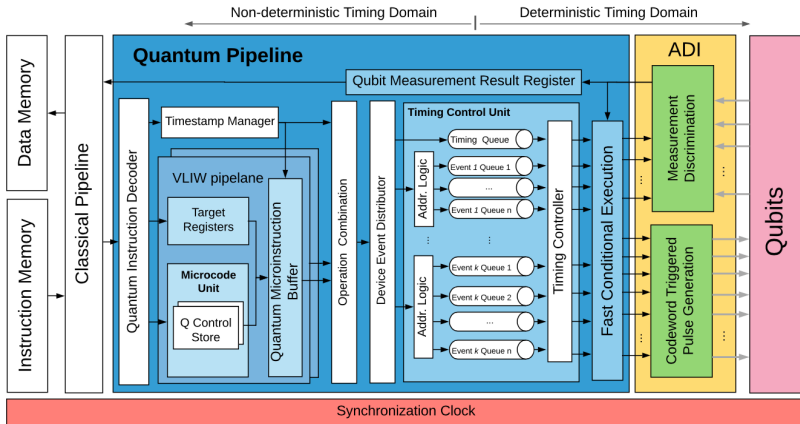


Fig. 9. Quantum microarchitecture implementing the instantiated eQASM for the seven-qubit superconducting quantum processor.

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

This is an example for superconducting qubits.

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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 $|000\rangle$
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 (1–100 S) gate operation times

Examples

Research groups: University of Maryland, IonQ, Honeywell

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

DiVincenzo's criteria

1. A scalable physical system with well characterized qubits
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7. The ability to transmit faithfully flying qubits between specified locations

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.

Hyper ne 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, Engin

Ion traps: A scalable physical system with well characterized qubits

Optical qubits

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Figure:

Credit: [Nielsen and Chuang, 2011]

Ion traps: Long relevant decoherence times, much longer than the gate operation time

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

Figure: Credit: NAP.

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 $|000\rangle$

Cooling the ions down to ground state

Continuous wave lasers carry away momentum from system.

Ion traps: A “universal” set of quantum gates

Coherent qubit control
system

Single qubit gates

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

Figure: Credit: [Häffner et al., 2008]

Ion traps: A “universal” set of quantum gates

Two qubit gates

1. State-dependent force.
2. Ignacio Cirac and Peter Zoller two qubit gate in 1995.
3. Molmer-Sorensen 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.
2. Mössbauer effect / state-dependent fluorescence.
3. Photon detectors.

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

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 qubits between specified locations

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

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Superconductors: A scalable physical system with well characterized qubits

Linear resonator

Superconducting resonator

$$H = \frac{Q^2}{2L} + \frac{Q^2}{2C} \quad H = \hbar \omega_0 \left(n + \frac{1}{2} \right)$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

C acts as mass

Inductance acts as spring

[Devoret et al., 2004]

Superconductors: A scalable physical system with well characterized qubits

Nonlinear resonator

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

Figure: Credit: wikimedia.org

Superconductors: A scalable physical system with well characterized qubits

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, $T_c = 1.2\text{K}$).

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 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. 5GHz microwaves stimulate transition, with standard deviation 150MHz.

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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Other technologies

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 (hyper ne) 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/ ux qubit.

All are in infancy.

Hard to bet on long term winner.

Other technologies

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

Other technologies

Figure: Credit: [Nielsen and Chuang, 2011]

Other technologies

Figure: Credit: [Resch and Karpuzcu, 2019]



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