Superconducting qubits for quantum information

Symposium in honor of Paul Benioff’s fundamental contributions to quantum information

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All work from UC Santa Barbara

Argonne National Laboratory
Symposium on Quantum Computing: Beginnings to Current Frontiers
May 26 2016 3:10-4 pm
Quantum engineered systems

- Quantum computation
  - Gate-based implementation of quantum algorithms (Shor, Grover)
  - Quantum simulation of complex systems (e.g. molecular chemistry)
  - Adiabatic evolution for minimization problems (e.g. traveling salesman)

- Quantum communication
  - Quantum key distribution
  - Quantum repeaters

- Quantum sensing
  - Detection of weak fields
  - Detection of small displacements
  - Long baseline interference

- Ions, Rydberg atoms, BECs
- Atomic defects (NV, P in Si)
- Semiconductor quantum dots
- Superconducting circuits
Superconducting circuits in the traditional semiconductor technology roadmap

- Materials
- Device design
- Circuit design
- Interconnects
- Board level integration
- Systems integration
- Packaging

- Current focus of most research
- Tightly interconnected for engineered quantum devices/circuits
Superconducting qubits

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

Microwave frequency circuits: \( \omega / 2\pi \sim 5 - 10 \text{ GHz} \)

• Operate at 25 mK: \( k_B T \ll \hbar \omega \Rightarrow \text{quantum ground state} \)

• Need anharmonicity to enable quantum control
Superconducting qubits

- Qubit levels $|g\rangle$ and $|e\rangle$
- Qubit frequency $\omega_{ge} \sim 4 - 6$ GHz
- Anharmonicity at single photon level: $\omega_{ef} \approx 0.95 \omega_{ge}$
- Can tune $\omega_{ge}$ & $\omega_{ef}$ by changing flux through qubit
- Qubit $T_1$ is determined by loss mechanisms in capacitor
Measurement:
- Dispersive resonator readout
- Measure change in phase of few-photon excitation in readout resonator
- Projective & accurate

Z rotations:
- Flux tuning varies $L$
- Changes $\omega_{ge}$

X and Y rotations:
- Microwaves at $\omega_{ge}$

Transmon qubit (UCSB variant)

Z control
Josephson junctions in flux loop
Coupling to other qubits
direct capacitive coupling between qubits

readout waveguide

readout resonators (one per qubit)

two control lines per qubit
High fidelity quantum gates

- Complete set of single qubit gates needed to execute an arbitrary quantum algorithm
- All single qubit gates operate with fidelity > 99.9% (randomized benchmarking)
- Controlled Z gate (equivalent to CNOT):
  - 40 ns execution time
  - 99.5% fidelity
- State preparation and measurement fidelity ~ 90%

How do we measure these low error rates?

<table>
<thead>
<tr>
<th>Gate</th>
<th>Fidelity (±0.03)</th>
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<tbody>
<tr>
<td>X</td>
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<td>S (Z/2)</td>
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<td>T (e^{i\pi/4})</td>
<td>No RB method – not a Clifford</td>
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Controlled Z (CZ) gate:
\[ |e_A e_B\rangle \Rightarrow -|e_A e_B\rangle \]
Other states left unchanged

Avoided crossing \(|e_A e_B\rangle - |f_A g_B\rangle\):

\[
U = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & -1
\end{pmatrix}
\]

Direct capacitive coupling
Benchmarking

- Imperfect state preparation
- Imperfect state measurement
- Individual gate errors small compared to SPAM

Randomized benchmarking
High fidelity quantum gates

- Complete set of single qubit gates needed to execute an arbitrary quantum algorithm
- All single qubit gates operate with fidelity > 99.9% (randomized benchmarking)
- Controlled Z gate (equivalent to CNOT):
  - 40 ns execution time
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- State preparation and measurement fidelity ~ 90%
- Measurement now 98% in 150 ns
- Dominant errors due to $T_1$ decay

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Progress in qubit $T_1$

(UC Santa Barbara results)

Improvements:
- Fewer imperfections
- Reduced electric fields
- Better circuit design
Aluminum resonators on sapphire

- MBE grown Al on annealed sapphire gives best performance
- Intrinsic $Q$ around $2 \times 10^6$ at low power
- Film quality & substrate properties critical
Superconducting qubits on sapphire

- $T_1 (Q)$ vary strongly with frequency (repeatable)
- $T_1 (Q)$ consistent with two-level states

![Graph showing $T_1$ and Q vs. qubit frequency for different resonator configurations.](image)

*Resonators have Q’s 3-5 times higher*
Defects: Two-level states at GHz frequencies

- GHz-frequency two-level states become active at low temperatures
- Circuits primarily sensitive to electrically active TLS
- Reduce qubit $T_1$ and resonator $Q$
- Participation strongest for aligned dipoles in strong electric fields

What are these TLS?  
Where do they come from?  
How do we minimize/eliminate them?
Limiting effects due to materials

Two-level states
- Most important contributor to qubit $T_1$
- Resonators (single step fabrication) have 3-5 times fewer TLS
- Origin unknown
- Become active at low temperatures
- Vary with substrate and substrate preparation

Flux noise
- Important limiting effect on qubit $T_\phi$
- No apparent effect on resonators
- Origin unknown
- Investigated since 1980s in SQUIDs
- Surface density of correlated magnetic dipoles ($\sim 10^{13}$/cm$^2$)?
Programming a 5 qubit GHZ state $|ggggg\rangle + |eeeee\rangle$
Superconducting implementation of Shor’s algorithm

- Quantum processor with 4 qubits and 5 microwave resonators
- von Neumann architecture to factor 15 using Shor’s algorithm
- Achieves correct answer 48% of attempts (best possible 50%)

Building perfection from imperfection: The surface code

Square array of physical qubits
Only nearest-neighbor coupling

Data qubit:
Stores computational state $|\psi\rangle$

Measure-X qubit:
Stabilizes data qubits $\hat{X}\hat{X}\hat{X}\hat{X}$

Measure-Z qubit:
Stabilizes data qubits $\hat{Z}\hat{Z}\hat{Z}\hat{Z}$

Surface code $\hat{X}$ stabilizer cycle:
- Qubit state reset
- Hadamard gate
- Multiple two-qubit CNOTs
- Projective measurement

Result: $\hat{X}\hat{X}\hat{X}\hat{X}$ eigenstate

Need overall fidelity > 99.5%
Quantum algorithms

- Quantum entanglement enables new problem-solving algorithms
  - Deutsch-Jozsa: Given a black-box function \( f : \{0,1\}^n \rightarrow \{0,1\} \), where \( \{0,1\}^n \) is an \( n \)-element binary vector, determine whether \( f \) is constant or balanced.
    
    Classical algorithm needs \( 2^{n-1} + 1 \) function evaluations (worst case).
    
    Deutsch-Jozsa gets answer with one evaluation (non-probabilistic).

- Grover: Given a black-box function \( g : \{0,1\}^n \rightarrow \{0,1\} \), where \( \{0,1\}^n \) has \( 2^n \) possible values, find \( x \) such that \( g(x) = 1 \).

    Classical algorithm needs \( 2^{n/2} \) function evaluations. Grover gets high-probability answer with \( \sqrt{2^n} \) evaluations (quadratic speed-up).

    Makes brute-force attack on small (128-bit) RSA encryption feasible.

- Shor: Find the prime factors of the integer \( N \).

  Classical sieve algorithm: \( \mathcal{O}(\exp(1.9(\log N)^{1/3}(\log \log N)^{2/3})) \) steps.

  Quantum Shor algorithm: \( \mathcal{O}(((\log N)^2(\log \log N)(\log \log \log N))) \) steps

  Answer is probabilistic; assumes unlimited resources.
Building perfection from imperfection: The surface code

- Assume error rate 1/10\(^{th}\) threshold (99.95% fidelity)

Logical memory qubit from array of physical qubits

- \(\times 1,000\) smaller error rate: \(~600\) physical qubits
- \(\times 1,000,000\) smaller error rate: \(~2,000\) physical qubits
- \(\times 1,000,000,000\) smaller error rate: \(~4,500\) physical qubits

Circuit to demonstrate topological CNOT:

- With \(\times 1,000\) smaller error rate: \(~1,800\) physical qubits

Prime factoring with Shor’s algorithm:

- Factor a 15 bit number \((10^5)\): \(~40,000,000\) qubits
- Factor a 2000 bit number \((10^{600})\): \(~1,000,000,000\) qubits
What does this code do? It “purifies” a special state:

\[ |A\rangle = |g\rangle + e^{i\pi/4} |e\rangle \]

Needed for \( T \) gate

99% of a factoring computer is used to purify \( |A\rangle \) states
“Gate-based” quantum computation: Challenges

- Scale-up challenge: 1D to 2D qubit circuits
- Demonstrate full quantum error correction
  Fix $X, Y, Z$ errors caused by environment
- Demonstrate logical qubit
  Logical qubit state lifetime longer than physical qubit lifetime
- Demonstrate “large” logical qubit entanglement
- Demonstrate protected logical operations
  Logical qubit manipulations with error protection
- Scale-up challenge: 2D to 3D wiring interconnects
- Quantum simulations: Useful & interesting problems
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