The Prospects for Quantum Computing with Superconducting Circuits

Disclosure: I am also a co-founder and equity holder at Quantum Circuits, Inc. www.quantumcircuits.com

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A Personal Perspective on Future of QC

At a tipping point: onset of scaling era for quantum computing!

We will build (in next few years) interesting quantum devices:
= complexity that CANNOT EVER be classically simulated
(> 50 qubits or equivalent)

Research becoming more technical, but also more modular/parallelized

A merger is needed:
quantum device physics
systems engineering
information thy./algorithms

“quantum computer science”

Still lots of innovation in physics, engineering, and theory ahead!
Outline

• A brief introduction to quantum computing

• Primer on superconducting quantum circuits

• Quantum error correction and hardware-efficiency: demonstrating “break-even” for QEC

• The modular architecture teleported gates: the first C-NOT between logical qubits
Quantum Computing is a New Paradigm

- Quantum computing: a completely new way to store and process information.

- **Superposition**: each quantum bit can be **BOTH** a zero and a one.

- **Entanglement**: the quantum computer can explore **ALL** possible outcomes.

- **Massive parallelism**: can enable computations that are impossible on **ANY** conventional computer.
Classical vs. Quantum Bits

Information as state of a two-level quantum system

Classical bit

Quantum bits (or “qubits”)

Classical bit states

| g ⟩ = | 0 ⟩
| e ⟩ = | 1 ⟩

0 OR 1 only!

Quantum states

| g ⟩ = | 0 ⟩
| e ⟩ = | 1 ⟩
| up ⟩ = | 0 ⟩
| down ⟩ = | 1 ⟩

0 AND 1 at same time!

Superposition:

| Ψ ⟩ = α | 0 ⟩ + β | 1 ⟩
What’s so special about the quantum world?

Part 1: Superposition

“the twin-slit experiment”

source of particles

Classical objects go *either* one way or the other.

Quantum objects (electrons, photons) go *both* ways.
What’s so special about the quantum world?

Part 2: Entanglement, or when more is (exponentially) different!

Start with N non-interacting qubits

\[ |\Psi_{tot}\rangle = (\alpha_1 |0\rangle + \beta_1 |1\rangle) \otimes (\alpha_2 |0\rangle + \beta_2 |1\rangle) \otimes \ldots (\alpha_N |0\rangle + \beta_N |1\rangle) \]

“Product” state (non-interacting) of N qubits: \( \sim N \) bits of info
What’s so special about the quantum world?

Part 2: Entanglement, or when more is (exponentially) different!

Most general state of $N (=5)$ interacting qubits:

$$|\Psi_{tot}\rangle = c_1|00001\rangle + c_2|00010\rangle + \ldots + c_{64}|11111\rangle$$

Now we need $2^N (=64)$ separate complex amplitudes for the state. Entangled state of $N$ qubits: $\sim 2^N(2^N-1)$ bits of info!

And simulating a 200-qubit machine requires $\sim 10^{60}$ classical bits!
What’s the catch?
Part 3: Decoherence and Errors
Want qubits to interact strongly with each other, but nothing else!

Correcting even rare errors will use most of the resources!
Some Potential Applications for QC

Quantum materials

Quantum chemistry

Machine learning

Cryptography
A universal gate set

- Perform *any* operation using just a few gates, e.g:
  - $|0\rangle_1 \rightarrow H$ Hadamard
  - $|0\rangle_1 \rightarrow S$ Phase gate
  - $|0\rangle_1 \rightarrow T$ T gate
  - $|0\rangle_1 \rightarrow \text{CNOT}$ operation

Generating entanglement

Routine engineering and calibration tests:

Carry out spooky operations that Einstein said were impossible!

- $|\psi\rangle = (|00\rangle + |10\rangle) / \sqrt{2}$
- $|\psi\rangle = (|00\rangle + |11\rangle) / \sqrt{2}$
- $|\psi\rangle = (|00\rangle + |10\rangle) / \sqrt{2}$
- $|\psi\rangle = (|00\rangle + |11\rangle) / \sqrt{2}$
Where is Quantum Computing Today?

- Have science to establish that a solid-state quantum computer is possible!
- Next goal is to make QC robust and scalable via error-correction.

from M. Devoret and RS, Science (2013)
How to build a quantum computer?
Several Possible Qubit Technologies

Trapped Ions

N-V Centers in Diamond

Majorana Fermions, Topological QC

Quantum Dots

Superconducting Circuits
Transmon Qubit

Josephson tunnel junction

Simple fabrication:
1 layer, shadow evaporated Al

Many adopters:
UCSB/Google, IBM, Berkeley, Princeton, Delft, Zurich, Chicago…

Koch et al., 2007.
Expt: Houck et al., 2008.

T = 10 mK

AlOx tunnel barrier

200 nm
Superconducting Qubits: the Transmon

Non-linear electromagnetic oscillator

$\omega_{01} \neq \omega_{12}$

$\omega_{01} \sim 5 - 10 \text{ GHz}$

$\hbar \omega/k_B \sim 0.25 \text{ K}$

Bit energy: $\sim 10 \mu\text{eV}$ or $10^{-24} \text{ J}$

“Voltage level”: $1 \mu\text{V}$ (RMS)

Logical “0”: ground state

Logical “1”: one $\mu$-wave “photon”

Excite & control with GHz signal on wires: gate time $\sim 10 \text{ ns}$

Long coherence = high quality factors

Superconductivity should prevent losses (gapped!)
How Qubits Work

Superposition state:

$$|\Psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + \sin\left(\frac{\theta}{2}\right)e^{i\varphi}|1\rangle$$

Single qubit gates = rotation using analog microwave pulses:

$$V(t) = A(t)\cos(\omega_{01}t + \varphi)$$

RF amplitude and phase determines the “rotation” angle
Qubit Control & Msmt. w/ "Software Radio"

Oscillator \( (\omega_{01}) \)

FPGA

ADC

DAC

Qubit \( (\omega_{01}) \)

HEMT

\(~ 100 \text{ dB total gain}\)

\(~ 100 \text{ dB attenuation}\)

\(300 \text{ K}\)

\(10 \text{ mK}\)
Advantages of Circuit QED

- quantum “bus” via microwave lines
- 1st solid-state quantum processor
  e.g. DiCarlo,…, RJS Nature 460, 240 (2009).

- Superconductivity suppresses dissipation
  - Josephson junctions and cavities are really, really good!
- All electronic control, leverage Moore’s law
- Strong interactions between qubits, connect by microwaves
- Only solid-state system to demonstrate all DiVincenzo reqs.?
Remarkable Progress in Coherence

Progress = 10x every 3 years!
and Remarkable Progress in Measurement

Single quantum jumps of a transmon qubit!

Readout with fidelity > 99.5% in ~ 300 nsec

Many groups now use paramps:
  Berkeley, Delft, JILA, ENS/Paris, IBM, Saclay, UCSB/Google, …

*First jumps: R. Vijay, …, Siddiqi, 2011 (Berkeley)
Some Interesting Questions

• What is the best architecture for a quantum computer?
  - now becoming a practical question!

• What is the best way to do quantum error correction (QEC)?

• How much overhead will this entail?

• What is the first useful computation/simulation that we can do?
  - and how much QEC is necessary for that?

• How do we simplify and master the complexity?

• How do we engage the necessary systems engineers?
Quantum error correction and demonstrating breakeven

Classical Error Correction

Repetition code: redundantly encode, majority voting

<table>
<thead>
<tr>
<th>Sent</th>
<th>0 → 000</th>
<th>1 → 111</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-p</td>
<td>1-p</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>p</td>
</tr>
</tbody>
</table>

Reduces classical error rate to $3p^2 - 2p^3$

Can we do this for quantum computing? Some reasons to think no:

- “No cloning” theorem
- Errors are continuous (or are they?)
- Measurements change the state
How Do You Correct *Quantum* Errors?

Replace physical qubit with a logical register of three qubits (e.g. Shor, Gottesman, …)

\[ \alpha \left| 0 \right> + \beta \left| 1 \right> \rightarrow \alpha \left| 000 \right> + \beta \left| 111 \right> \]

“a GHZ entangled state”

Now measure the quantum version of their parity:

\[ \left< Z_1 Z_2 \right> = +1 \text{ or } -1 \]

and tell me *only* the correlations!!

<table>
<thead>
<tr>
<th>Flipped qubit</th>
<th>State</th>
<th>$Z_1Z_2$</th>
<th>$Z_2Z_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>$\left</td>
<td>000 \right&gt; + \left</td>
<td>111 \right&gt;$</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>$\left</td>
<td>100 \right&gt; + \left</td>
<td>011 \right&gt;$</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>$\left</td>
<td>010 \right&gt; + \left</td>
<td>101 \right&gt;$</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>$\left</td>
<td>001 \right&gt; + \left</td>
<td>110 \right&gt;$</td>
</tr>
</tbody>
</table>

Each error has a **different** observable! - The basis for the *bit flip code*
A Few Challenges for Error Correction

- **complexity:** conventional schemes require large circuits
  - lots of engineering before you know what works

- **overhead:** errors get worse before they get better
  - more qubits = more failure modes

- **performance:** must keep rates and types of errors low
  - including systematic or correlated errors

- **debugging:** how do you optimize something you can’t “see”?  
  - tomography and calibration scales as $2^N$

  a possible solution: **hardware-efficiency**

  = achieving the same function using fewer parts
The Yale Strategy

- We aren’t scaling up to eventually error-correct...
- We are error-correcting first, so that we can scale robustly!

A logical qubit is:
A register or system where a quantum bit is redundantly encoded, with a symmetry you can use to detect and correct errors

- Fault-tolerance isn’t a state of being or enlightenment, it is a feature you must incorporate as you go.
- The performance of QEC systems and their fault-tolerance can be quantitatively tested starting TODAY.
Choosing a QEC Scheme?

### Standard (Steane) Code

- 13 qubits
- 50 gates
- 20 channels
- 6 readouts

### Surface Code

- ~ 20 - 50 qubits?
- > 200 gates
- 100 channels
- ~ 50 readouts

### “Cat Code”?

- 1 qubit & 1 cavity
- 1 gate
- 3 channels
- 1 readout

**Resource count for first-level QEC memory**

<table>
<thead>
<tr>
<th>Stabilizer QEC</th>
<th>Surface Code</th>
<th>Cat Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 qubits</td>
<td>~ 20 - 50 qubits?</td>
<td>1 qubit &amp; 1 cavity</td>
</tr>
<tr>
<td>50 gates</td>
<td>&gt; 200 gates</td>
<td>1 gate</td>
</tr>
<tr>
<td>20 channels</td>
<td>100 channels</td>
<td>3 channels</td>
</tr>
<tr>
<td>6 readouts</td>
<td>~ 50 readouts</td>
<td>1 readout</td>
</tr>
</tbody>
</table>

**“Hardware efficiency”:** do the same function with fewer parts!
Cavity + Transmon Platform

- **cavity**: a qu-"dit" or register for logical qubits
  - only **single error process**: photon loss

- **transmon**: the nonlinear ancilla & coupler for operations
  - RF pulses turn couplings on and off

Coaxial post cavities
High Q “qudit”
$T_1 > 0.001$ sec

Fixed frequency transmons
non-linear “ancilla”
$T_1 \sim 50$ μsec

On-chip readouts & Purcell filters

C. Axline Appl. Phys. Lett. 109, 042601 (2016)
Coding Information in Oscillators?

Continuous variables:

1) “GKP” codes
   e.g. (Gottesman, Kitaev, and Preskill, 2001)

2) “cat” codes
   (Mirrahimi, Leghtas, MD, RS, 2013)

3) “binomial” codes
   (M. Michael, …, Jiang, Girvin, 2016)

And these can all be built and tested today!
Redundant Encoding in Cat States

Hardware-Efficient Code:
Corrects for single photon loss

$|0_L\rangle = |C^+_\alpha\rangle = \mathcal{N}(|\alpha\rangle + |-\alpha\rangle)$

$|1_L\rangle = |C^+_i\alpha\rangle = \mathcal{N}(|i\alpha\rangle + |-i\alpha\rangle)$

$c_g |g\rangle + c_e |e\rangle \Rightarrow c_g |0_L\rangle + c_e |1_L\rangle$

*Store a **qubit** as a **superposition** of two cats of same **parity***

*Leghtas, Mirrahimi, et al., PRL 111, 120501, (2013)
Implementing a Full QEC System: Debugger View

This is all data!

Implementing a Full QEC System: Debugger View

(a) Encode
(b) Track Error Syndrome

Implementing a Full QEC System: Debugger View

Extending the Lifetime of a Qubit

lifetime gain of QEC > 2x

\[ |\psi\rangle = \alpha |0_L\rangle + \beta |1_L\rangle \]

Main limitation: measurement is not performed fault-tolerantly!

Next step: hardware-efficient incorporation of FT

\( \tau \approx 320\mu s \)

\( \tau \approx 130\mu s \)
The modular architecture and demonstrating a teleported gate
Modular Architecture* for QC

**Key Advantages**
- Hierarchical complexity
- Testable parts
- Any-to-any connectivity
- Reconfigurable and general purpose
- Improves isolation and crosstalk

Module = small quantum system, equivalent of ~ 10-100 qubits
contains 1st level logical qubits

Router = directs quantum signals to pairs of modules

Detectors = measurements or other remote entanglement

*e.g. Kimble, “The Quantum Internet”, 2008.
or Duan, Blinov, Moehring, and Monroe, 2004.*
Logic Between Modules: Teleported Gates*

Requirements:
- Inter-module entangled pair
- Local operations
- Measurements on comm. qubits
- Real-time feedback and conditional logic

Only LOCC after Bell generation!

*Gottesman & Chuang, 1999
Eisert et al., 2000
Implementing a Teleported C-NOT

Mem. 1  Comm. 1  Bus  Comm. 2  Mem. 2

State prep.  CNOT teleportation

- Two “Y-mon” qubits
- Two millisecond cavities for logical memories
- Connecting bus and two readouts
- Two JPC paramps
- One 4U crate FPGA system with custom software

Teleported C-NOT: Kitten Logical Encoding

Error-correctable logical states in cavity

\[ |0\rangle_L \equiv |2\rangle \quad |1\rangle_L \equiv \frac{1}{\sqrt{2}} (|0\rangle + |4\rangle) \]

Both states are even parity, average photon number = 2

Michael et al. “New Class of Quantum Error-Correcting Codes for a Bosonic Mode” PRX 6, 031006 (2016)
Teleported C-NOT: Kitten Logical Encoding

**Truth table** for error-correctable logical states in cavity

**Input states:**

<table>
<thead>
<tr>
<th>Logical 1 (control)</th>
<th>Logical 2 (target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
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**Output states:**

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**Teleported C-NOT: Kitten Logical Encoding**

*Truth table* for error-correctable logical states in cavity

| Input states: | \(|0_L 0_L\rangle\) | \(|0_L 1_L\rangle\) | \(|1_L 0_L\rangle\) | \(|1_L 1_L\rangle\) |
|---------------|---------------------|---------------------|---------------------|---------------------|
| Logical 1     | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| (control)     | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |
| Logical 2     | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| (target)      | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) |

| Output states: | \(|0_L 0_L\rangle\) | \(|0_L 1_L\rangle\) | \(|1_L 1_L\rangle\) | \(|1_L 0_L\rangle\) |
|---------------|---------------------|---------------------|---------------------|---------------------|
| Logical 1     | ![Image](image17.png) | ![Image](image18.png) | ![Image](image19.png) | ![Image](image20.png) |
| (control)     | ![Image](image21.png) | ![Image](image22.png) | ![Image](image23.png) | ![Image](image24.png) |
| Logical 2     | ![Image](image25.png) | ![Image](image26.png) | ![Image](image27.png) | ![Image](image28.png) |
| (target)      | ![Image](image29.png) | ![Image](image30.png) | ![Image](image31.png) | ![Image](image32.png) |

![Colorbar](image33.png)

*Parity*
Where is Quantum Computing Today?

- Have science to establish that a solid-state quantum computer is possible!
- Next goal is to make QC robust and scalable via error-correction.

from M. Devoret and RS, Science (2013)
Working with Logical Qubits

Necessary steps along the way

1) Create the code (build good encode-decode unitaries)
2) Measure error syndrome (build complex parity measurements)
3) Track and correct the errors (demonstrate lifetime extension)
4) Logical 1-qubit operations (manipulate precisely in high-d space)
5) Entangle two logicals (create logical C-NOT)
6) Operate gates, while correcting (compute with logical qubits)

Rabi oscillations while cat pumping: Touzard et al. arXiv/1705.02401
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Taekwan Yoon
Brian Lester
Chan U Lei
Parker Henry
Summary

• Superconducting quantum circuits are a promising path to universal quantum computation.

• Basic science is established, current research focuses on making computations robust and scalable thru QEC.

• The pace of progress is accelerating.

• Plenty of systems engineering challenges to tackle, but plenty of need for basic science and innovation - let’s find even better ways to move forward!

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