Quantum Computing: Great Expectations

Quantum Computing for Nuclear Physics Workshop

Dave Bacon
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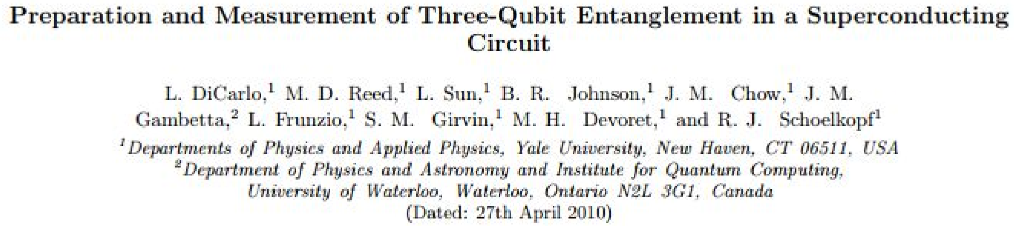
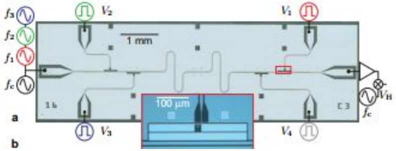
In a Galaxy Seven Years Ago...

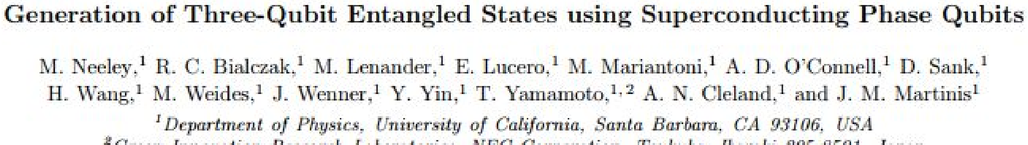


Preparation and Measurement of Three-Qubit Entanglement in a Superconducting Circuit

L. DiCarlo,[1] M. D. Reed,[1] L. Sun,[1] B. R. Johnson,[1] J. M. Chow,[1] J. M. Gambetta,[2] L. Frunzio,[1] S. M. Girvin,[1] M. H. Devoret,[1] and R. J. Schoelkopf[1]
[1]Departments of Physics and Applied Physics, Yale University, New Haven, CT 06511, USA
[2]Department of Physics and Astronomy and Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
(Dated: 27th April 2010)



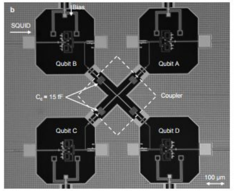
0.88 fidelity



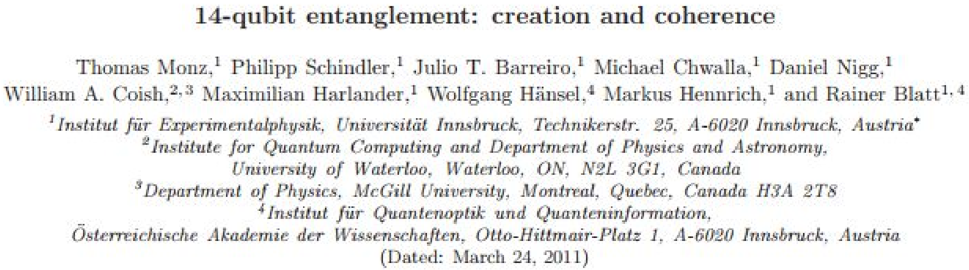
Generation of Three-Qubit Entangled States using Superconducting Phase Qubits

M. Neeley,[1] R. C. Bialczak,[1] M. Lenander,[1] E. Lucero,[1] M. Mariantoni,[1] A. D. O'Connell,[1] D. Sank,[1] H. Wang,[1] M. Weides,[1] J. Wenner,[1] Y. Yin,[1] T. Yamamoto,[1,2] A. N. Cleland,[1] and J. M. Martinis[1]
[1]Department of Physics, University of California, Santa Barbara, CA 93106, USA
[2]Green Innovation Research Laboratories, NEC Corporation, Tsukuba, Ibaraki 305-8501, Japan

(2010)

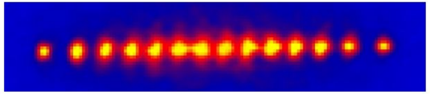


0.78 fidelity



14-qubit entanglement: creation and coherence

Thomas Monz,[1] Philipp Schindler,[1] Julio T. Barreiro,[1] Michael Chwalla,[1] Daniel Nigg,[1] William A. Coish,[2,3] Maximilian Harlander,[1] Wolfgang Hänsel,[4] Markus Hennrich,[1] and Rainer Blatt[1,4]
*[1]Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria**
[2]Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, N2L 3G1, Canada
[3]Department of Physics, McGill University, Montreal, Quebec, Canada H3A 2T8
[4]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, A-6020 Innsbruck, Austria
(Dated: March 24, 2011)



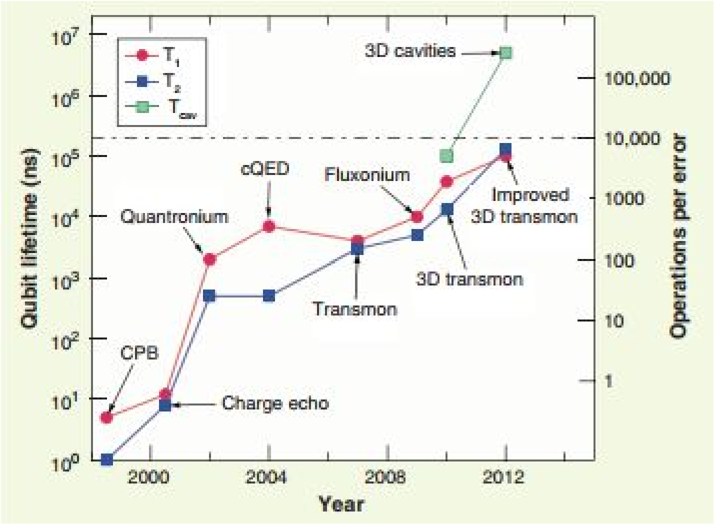
fidelities:
14 qubits: 0.50
3 qubits: 0.97

What Has Changed?

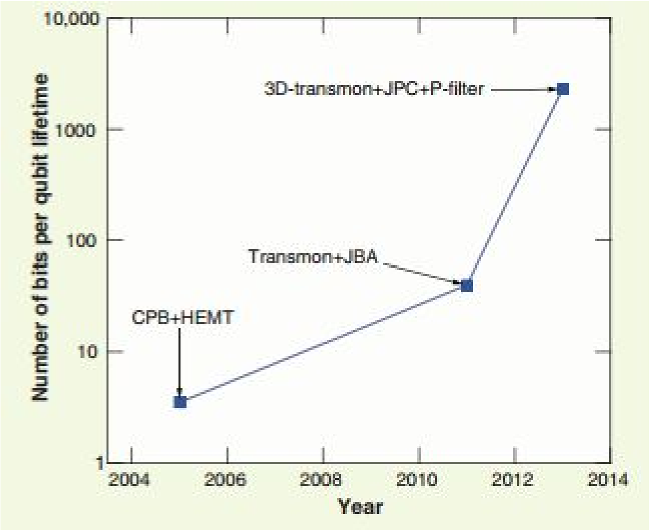
All the authors moved to industry? ;)

What Has Changed? (superconducting qubits)

Progress on all fronts



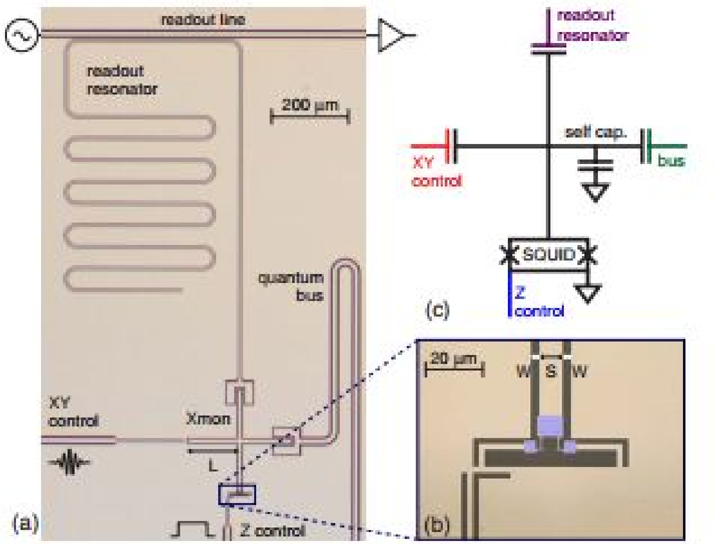
decoherence



measurement

Devoret and Schoelkopf, Science 399, p1169 (2013)

This Talk: XMon Transmon Qubits



Barends, Kelly *et al* PRL 111, p080502 (2013)

Frequency tunable superconducting qubit (based on planar transmon)

John Martinis
and team (Santa Barbar)

What Changed?

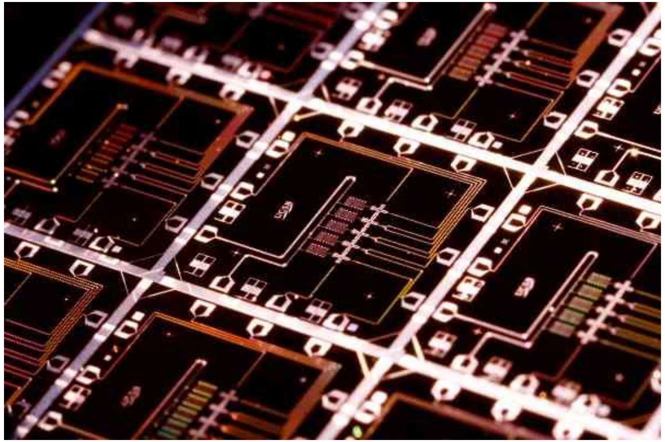


Photo credit: Erik Lucero

“Superconducting quantum circuits at the surface code threshold for fault tolerance” Barends, Kelly *et al* Nature 2014

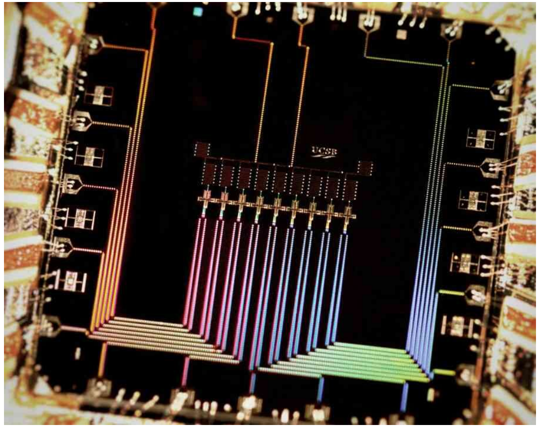


Photo credit: Julian Kelly

“State preservation by repetitive error detection in a superconducting quantum circuit” Kelly, Barends, Fowler *et al* Nature 2015

More Qubits. “Yes But”

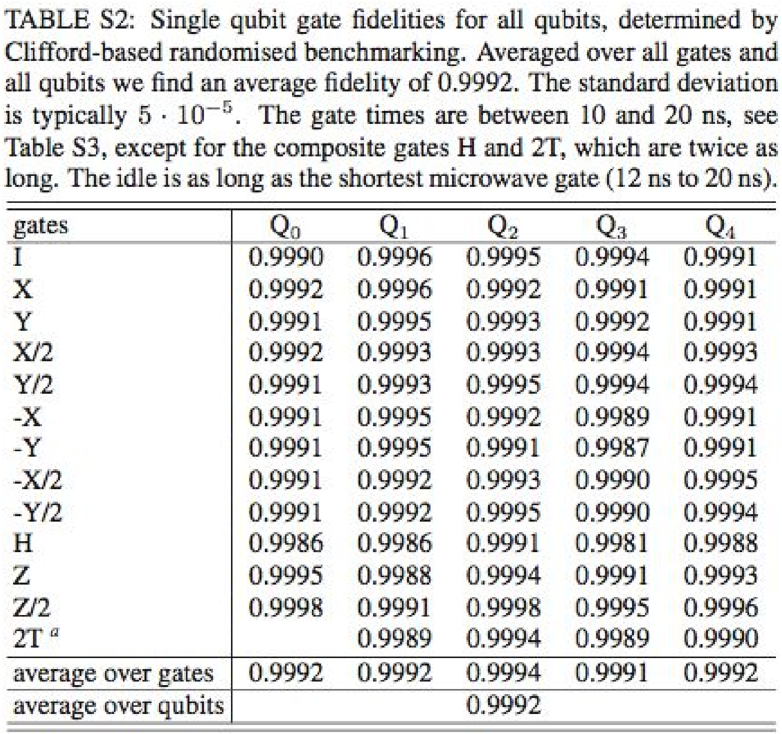


TABLE S2: Single qubit gate fidelities for all qubits, determined by Clifford-based randomised benchmarking. Averaged over all gates and all qubits we find an average fidelity of 0.9992. The standard deviation is typically $5 \cdot 10^{-5}$. The gate times are between 10 and 20 ns, see Table S3, except for the composite gates H and 2T, which are twice as long. The idle is as long as the shortest microwave gate (12 ns to 20 ns).

gates	Q_0	Q_1	Q_2	Q_3	Q_4
I	0.9990	0.9996	0.9995	0.9994	0.9991
X	0.9992	0.9996	0.9992	0.9991	0.9991
Y	0.9991	0.9995	0.9993	0.9992	0.9991
X/2	0.9992	0.9993	0.9993	0.9994	0.9993
Y/2	0.9991	0.9993	0.9995	0.9994	0.9994
-X	0.9991	0.9995	0.9992	0.9989	0.9991
-Y	0.9991	0.9995	0.9991	0.9987	0.9991
-X/2	0.9991	0.9992	0.9993	0.9990	0.9995
-Y/2	0.9991	0.9992	0.9995	0.9990	0.9994
H	0.9986	0.9986	0.9991	0.9981	0.9988
Z	0.9995	0.9988	0.9994	0.9991	0.9993
Z/2	0.9998	0.9991	0.9998	0.9995	0.9996
2T [a]		0.9989	0.9994	0.9989	0.9990
average over gates	0.9992	0.9992	0.9994	0.9991	0.9992
average over qubits			0.9992		

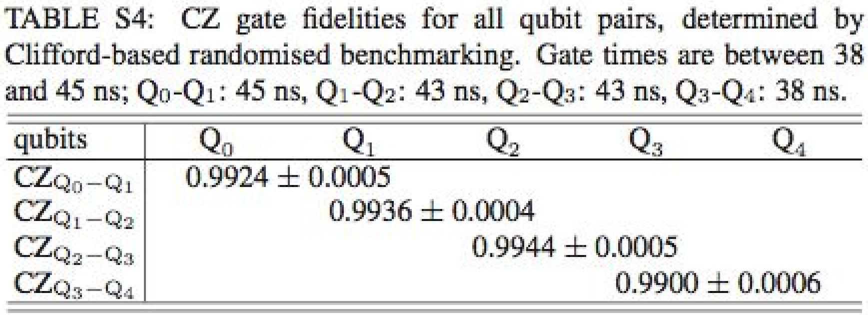


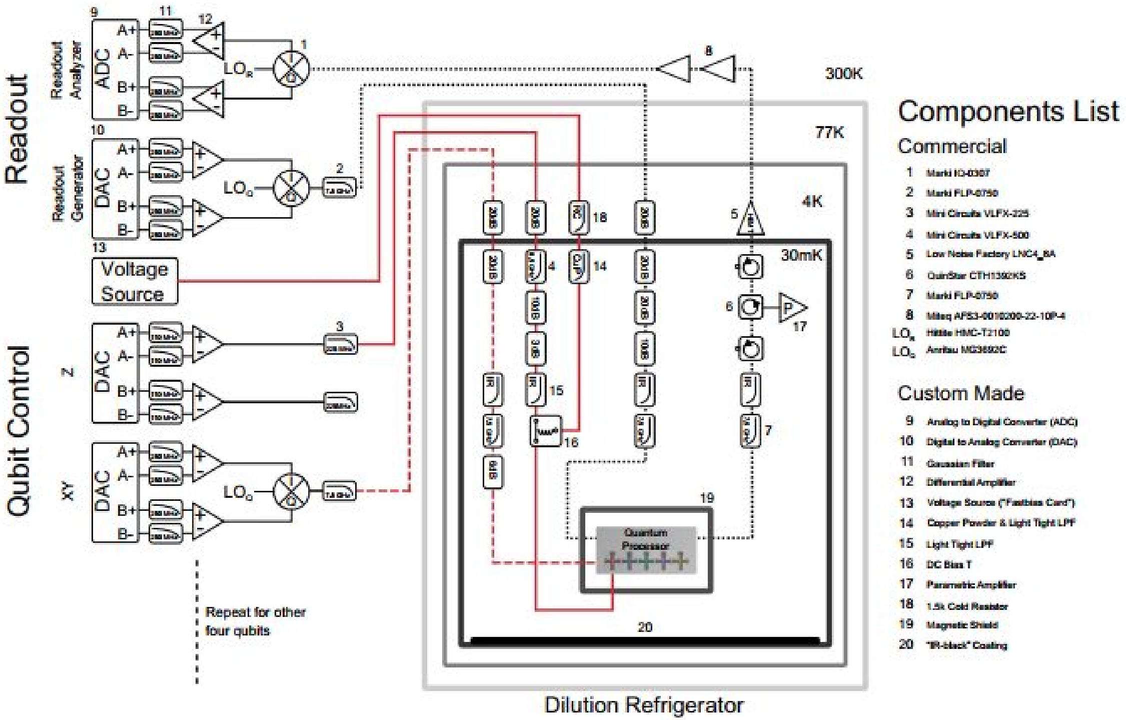
TABLE S4: CZ gate fidelities for all qubit pairs, determined by Clifford-based randomised benchmarking. Gate times are between 38 and 45 ns; Q_0-Q_1: 45 ns, Q_1-Q_2: 43 ns, Q_2-Q_3: 43 ns, Q_3-Q_4: 38 ns.

qubits	Q_0	Q_1	Q_2	Q_3	Q_4
$CZ_{Q_0-Q_1}$	0.9924 ± 0.0005				
$CZ_{Q_1-Q_2}$		0.9936 ± 0.0004			
$CZ_{Q_2-Q_3}$			0.9944 ± 0.0005		
$CZ_{Q_3-Q_4}$				0.9900 ± 0.0006	

Single qubit fidelities: 0.9992
Two qubit fidelities: 0.992
Measurement fidelity: 0.99
T_1: 20-40μs
1 qubit gates: 10-20ns
2 qubit gates: 38-45ns

More Qubits. “Yes But”

Industry groups have been allowed to focus on complete system design, and increasing the speed of their development lifecycle



Components List

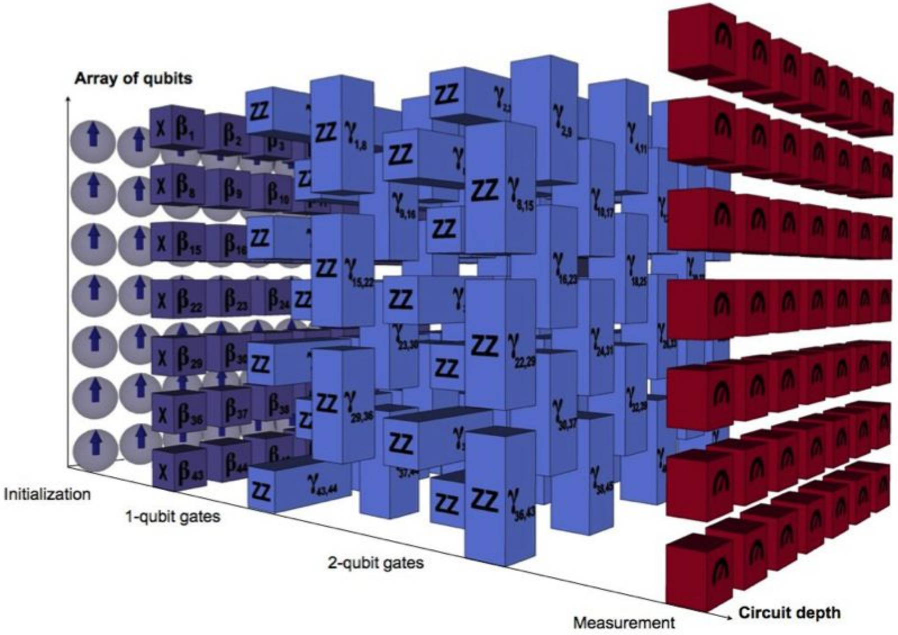
Commercial

1	Marki IQ-0307
2	Marki FLP-0750
3	Mini Circuits VLFX-225
4	Mini Circuits VLFX-500
5	Low Noise Factory LNC4_8A
6	QuinStar CTH1392KS
7	Marki FLP-0750
8	Miteq AFS3-00100200-22-10P-4
LO_R	Hittite HMC-T2100
LO_Q	Anritsu MG3692C

Custom Made

9	Analog to Digital Converter (ADC)
10	Digital to Analog Converter (DAC)
11	Gaussian Filter
12	Differential Amplifier
13	Voltage Source ("Fastbias Card")
14	Copper Powder & Light Tight LPF
15	Light Tight LPF
16	DC Bias T
17	Parametric Amplifier
18	1.5k Cold Resistor
19	Magnetic Shield
20	"IR-black" Coating

Low Gate Count Circuits



T_1: 20-40μs
1 qubit gates: 10-20ns
2 qubit gates: 38-45ns

Depth 500 before decoherence
(need to refocus for T_2)

Limit: gate and measurement fidelity.

(all from Barends, Kelly *et al* Nature 2014)

What can we do?

A Naive calculation:

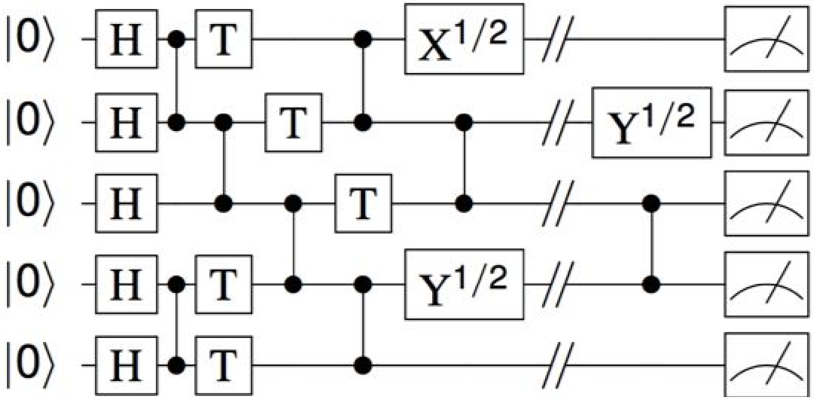
$$2 * 2^{49} * (4 \text{ bytes}) = 4.5 \text{ petabytes}$$

TOP500 #1 supercomputer Sunway TaihuLight has 1.3 petabytes memory.

At around 49 qubits, direct (naive) simulation becomes something that challenges today’s best supercomputers.

Experiment to demonstrate quantum computational supremacy

1. Formulate a random circuit U (from universal gate set)

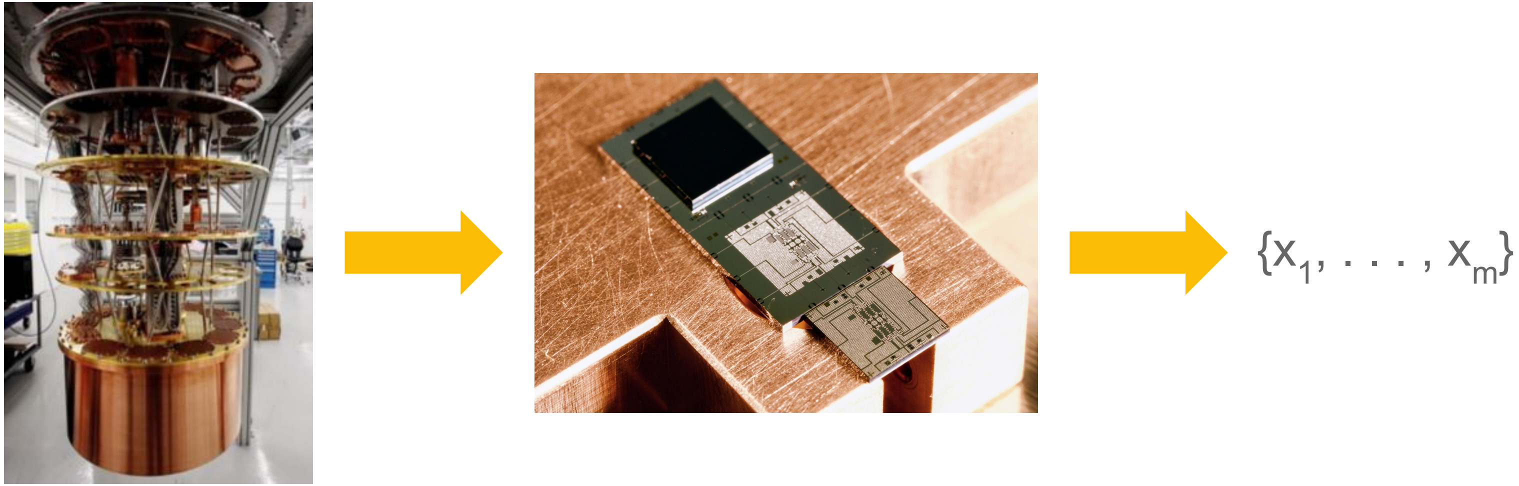


$$|0\rangle^{\otimes n} \mapsto H^{\otimes n}\,|0\rangle^{\otimes n} = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes n} \mapsto U\left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes n} = \sum_{i=1}^{2^n} c_i\,|x_i\rangle$$

$$p_U(x_i) = |c_i|^2$$

Experiment to demonstrate quantum computational supremacy

2. Program quantum processor to run U and take large sample $S = \{x_1, \ldots, x_m\}$ of bit-strings x in the computational basis



Experiment to demonstrate quantum computational supremacy

3. Compute quantities log $p_U(x_j)$ with supercomputer.

Cori II at US Lawrence Berkeley National Laboratory used to simulate 45 qubit circuit
Steiger and Hähner (2017)

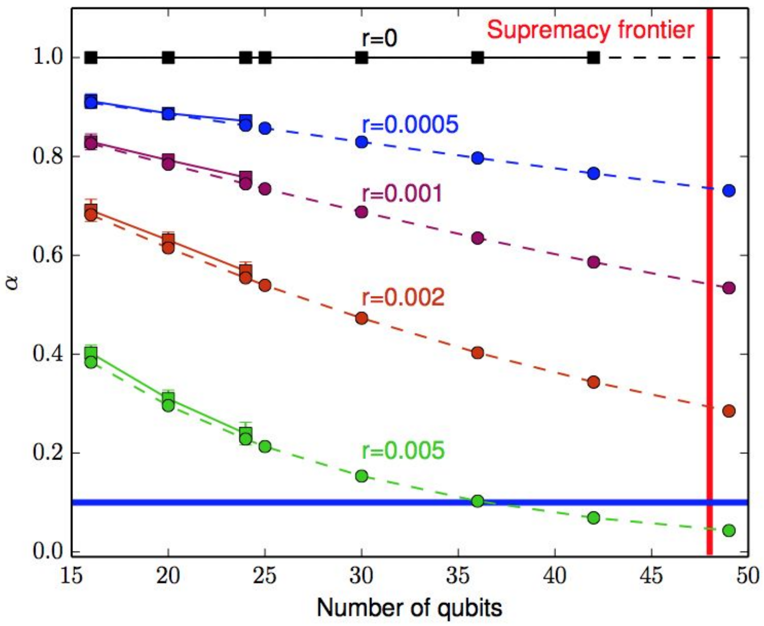
Experiment to demonstrate quantum computational supremacy

4. Measure quality α of a sampler S as the average difference between its cross entropy and the cross entropy of a uniform classical sampler.

$$H\left(p_S(x_i), p_U(x_i)\right) = -\sum_{i=1}^{m} p_S(x_i) \log\left(p_U(x_i)\right)$$

α=1 <=> $p_S(x_i) = p_U(x_i)$

α=0 <=> $p_S(x_i)$ and $p_U(x_i)$ uncorrelated



$$\alpha \approx exp(-r_{\text{init}}n - r_1 g_1 - r_2 g_2 - r_{\text{measure}}n)$$

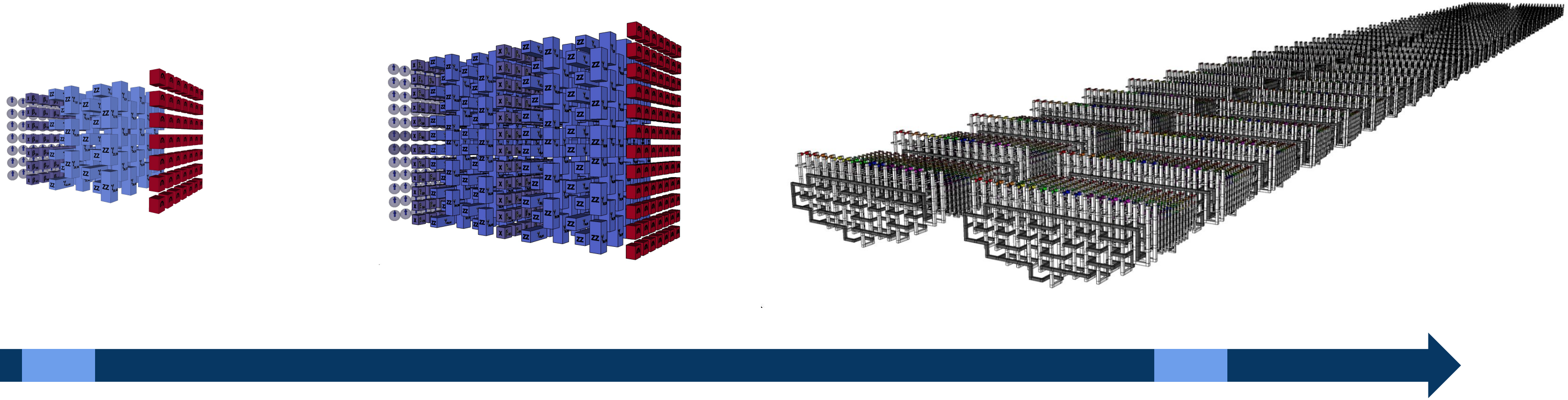
Important

- “Computational Supremacy” dependent on
  - **number** of qubits
  - **depth** of circuit
  - ability to get to “**random** enough” circuits
  - **errors** (gate, measurement)
- Time-space trade-off
  - One can get around naive memory calculation, but at the cost of more time (Aaronson and Chen 2016).
    - Halving memory multiplies run time by depth
- A plea to the quantum computer simulation community
  - Report your speeds, as well as your memory consumption
  - Describe your benchmark in detail so others can reproduce it

Even More Important

“Computational Supremacy” is the starting point

What can we do?



49 qubits x 40 depth

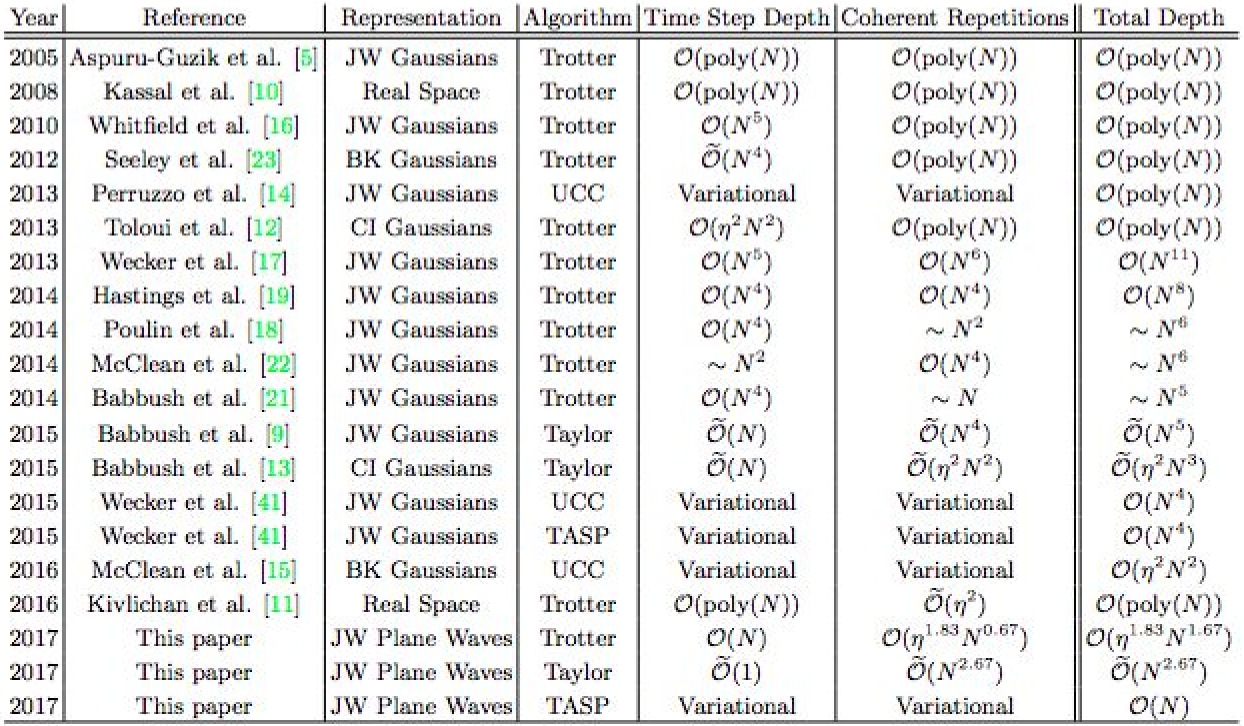
quantum
computational
supremacy

What goes here?

~10^6 qubits

error corrected
quantum
computer

Chemistry Simulation?

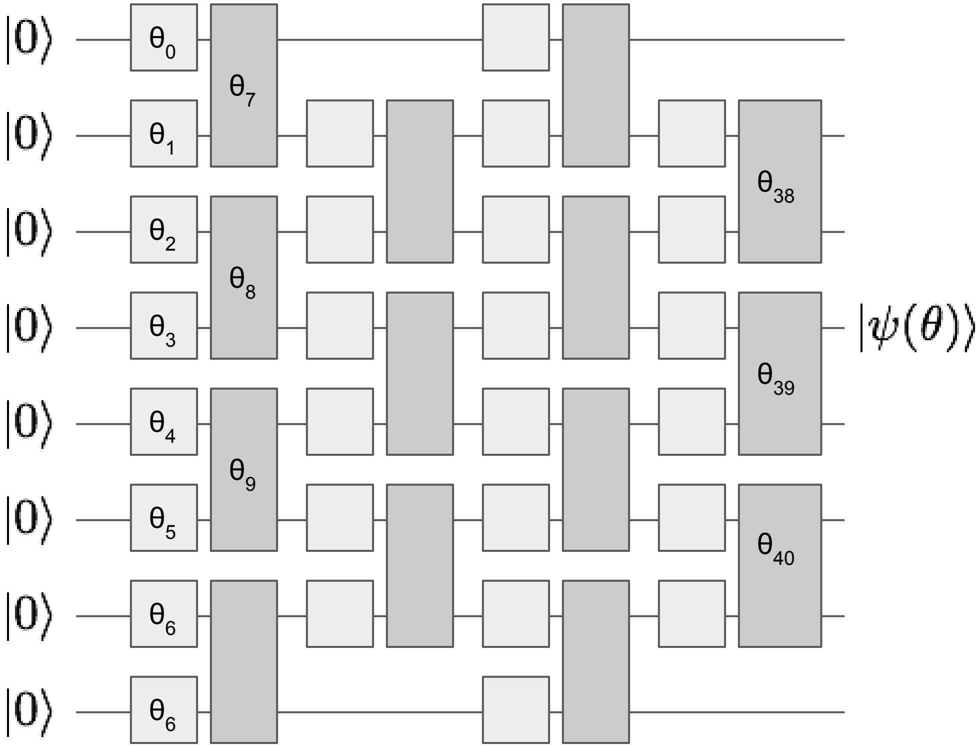


Year	Reference	Representation	Algorithm	Time Step Depth	Coherent Repetitions	Total Depth
2005	Aspuru-Guzik et al. [5]	JW Gaussians	Trotter	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2008	Kassal et al. [10]	Real Space	Trotter	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2010	Whitfield et al. [16]	JW Gaussians	Trotter	$\mathcal{O}(N^5)$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2012	Seeley et al. [23]	BK Gaussians	Trotter	$\widetilde{\mathcal{O}}(N^4)$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2013	Perruzzo et al. [14]	JW Gaussians	UCC	Variational	Variational	$\mathcal{O}(\text{poly}(N))$
2013	Toloui et al. [12]	CI Gaussians	Trotter	$\mathcal{O}(\eta^2 N^2)$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2013	Wecker et al. [17]	JW Gaussians	Trotter	$\mathcal{O}(N^5)$	$\mathcal{O}(N^6)$	$\mathcal{O}(N^{11})$
2014	Hastings et al. [19]	JW Gaussians	Trotter	$\mathcal{O}(N^4)$	$\mathcal{O}(N^4)$	$\mathcal{O}(N^8)$
2014	Poulin et al. [18]	JW Gaussians	Trotter	$\mathcal{O}(N^4)$	$\sim N^2$	$\sim N^6$
2014	McClean et al. [22]	JW Gaussians	Trotter	$\sim N^2$	$\mathcal{O}(N^4)$	$\sim N^6$
2014	Babbush et al. [21]	JW Gaussians	Trotter	$\mathcal{O}(N^4)$	$\sim N$	$\sim N^5$
2015	Babbush et al. [9]	JW Gaussians	Taylor	$\widetilde{\mathcal{O}}(N)$	$\widetilde{\mathcal{O}}(N^4)$	$\widetilde{\mathcal{O}}(N^5)$
2015	Babbush et al. [13]	CI Gaussians	Taylor	$\widetilde{\mathcal{O}}(N)$	$\widetilde{\mathcal{O}}(\eta^2 N^2)$	$\widetilde{\mathcal{O}}(\eta^2 N^3)$
2015	Wecker et al. [41]	JW Gaussians	UCC	Variational	Variational	$\mathcal{O}(N^4)$
2015	Wecker et al. [41]	JW Gaussians	TASP	Variational	Variational	$\mathcal{O}(N^4)$
2016	McClean et al. [15]	BK Gaussians	UCC	Variational	Variational	$\mathcal{O}(\eta^2 N^2)$
2016	Kivlichan et al. [11]	Real Space	Trotter	$\mathcal{O}(\text{poly}(N))$	$\widetilde{\mathcal{O}}(\eta^2)$	$\mathcal{O}(\text{poly}(N))$
2017	This paper	JW Plane Waves	Trotter	$\mathcal{O}(N)$	$\mathcal{O}(\eta^{1.83} N^{0.67})$	$\mathcal{O}(\eta^{1.83} N^{1.67})$
2017	This paper	JW Plane Waves	Taylor	$\widetilde{\mathcal{O}}(1)$	$\widetilde{\mathcal{O}}(N^{2.67})$	$\widetilde{\mathcal{O}}(N^{2.67})$
2017	This paper	JW Plane Waves	TASP	Variational	Variational	$\mathcal{O}(N)$

The Coming Age of Heuristic Quantum Algorithms?

“What is the chance that the only problems for which quantum computing provides an advantage are those for which we can prove, mathematically, that it has an advantage?” - Eleanor Rieffel (NASA) 2017

Variational Eigensolvers



Problem: Find ground state of many-body Hamiltonian

$$E_0 = \min_{\psi} \langle \psi | H | \psi \rangle$$

Use low depth quantum circuit as an ansatz

$$E(\theta) = \langle \psi(\theta) | H | \psi(\theta) \rangle$$

Wrap calculations of expectation values into blackbox non-linear optimizers

Variational Ansatz

Lots of choices for variational ansatz:

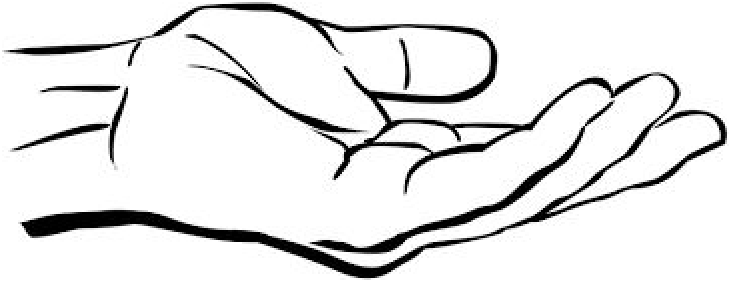
- trotterized adiabatic evolution
- unitary coupled cluster
- ...

Note:

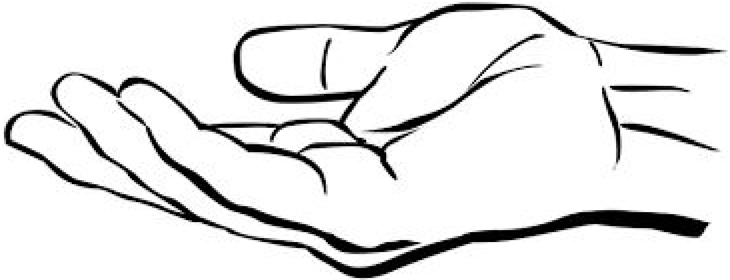
- Can incorporate known symmetries into ansatz
- Can tailor ansatz to be resistant to dominate noise

But Will It Work?

Sampling from low depth quantum circuits often classically intractable

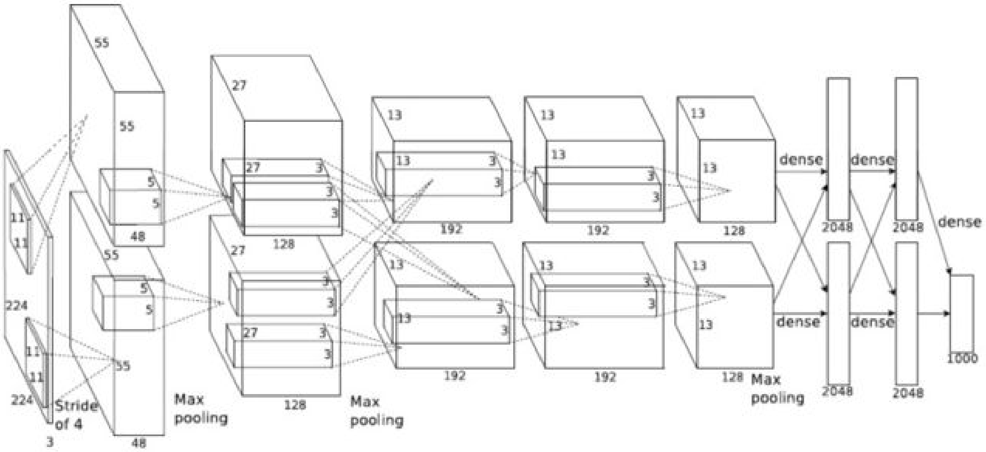


General limit versions of problems often quantumly intractable



Sometimes we only care about beyond classically solvable scale problems.

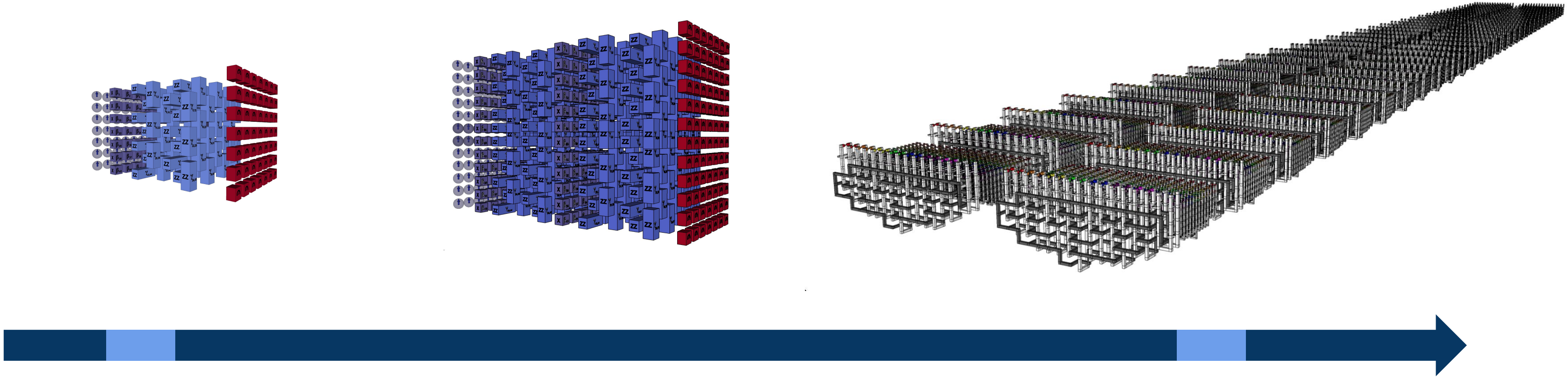
A Deep Learning Lesson?



Training of deep neural networks had little (no?) theory that say it will work.

Yet multiple heuristic insights algorithms were developed that lead to best in class machine learning models.

Platforms



49 qubits x 40 depth

~10^6 qubits

platforms for testing near term quantum algorithms

Platforms

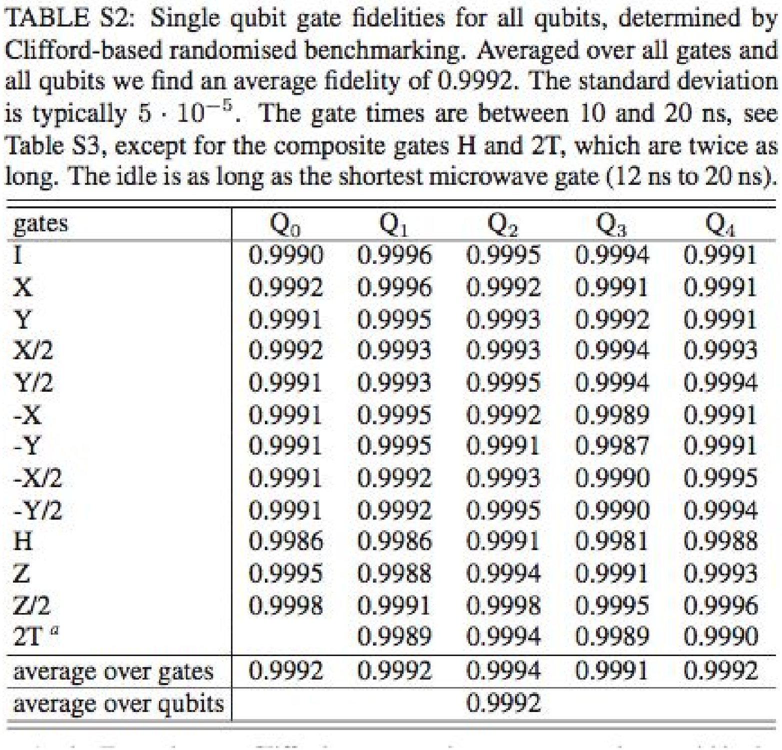


TABLE S2: Single qubit gate fidelities for all qubits, determined by Clifford-based randomised benchmarking. Averaged over all gates and all qubits we find an average fidelity of 0.9992. The standard deviation is typically $5 \cdot 10^{-5}$. The gate times are between 10 and 20 ns, see Table S3, except for the composite gates H and 2T, which are twice as long. The idle is as long as the shortest microwave gate (12 ns to 20 ns).

gates	Q_0	Q_1	Q_2	Q_3	Q_4
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Y	0.9991	0.9995	0.9993	0.9992	0.9991
X/2	0.9992	0.9993	0.9993	0.9994	0.9993
Y/2	0.9991	0.9993	0.9995	0.9994	0.9994
-X	0.9991	0.9995	0.9992	0.9989	0.9991
-Y	0.9991	0.9995	0.9991	0.9987	0.9991
-X/2	0.9991	0.9992	0.9993	0.9990	0.9995
-Y/2	0.9991	0.9992	0.9995	0.9990	0.9994
H	0.9986	0.9986	0.9991	0.9981	0.9988
Z	0.9995	0.9988	0.9994	0.9991	0.9993
Z/2	0.9998	0.9991	0.9998	0.9995	0.9996
2T [a]		0.9989	0.9994	0.9989	0.9990
average over gates	0.9992	0.9992	0.9994	0.9991	0.9992
average over qubits			0.9992		

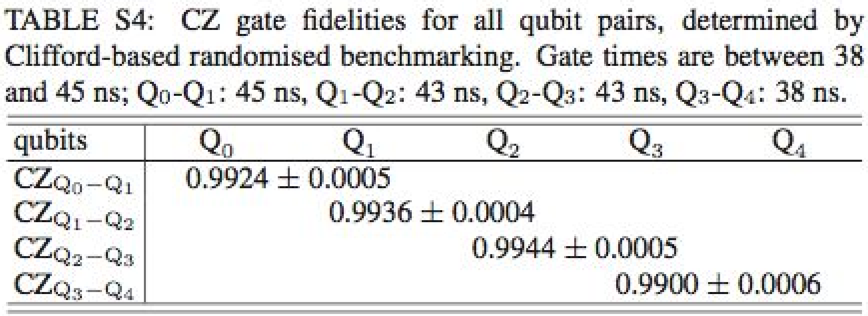

TABLE S4: CZ gate fidelities for all qubit pairs, determined by Clifford-based randomised benchmarking. Gate times are between 38 and 45 ns; Q_0-Q_1: 45 ns, Q_1-Q_2: 43 ns, Q_2-Q_3: 43 ns, Q_3-Q_4: 38 ns.

qubits	Q_0	Q_1	Q_2	Q_3	Q_4
$CZ_{Q_0-Q_1}$	0.9924 ± 0.0005				
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Single qubit fidelities: 0.9992
Two qubit fidelities: 0.992
Measurement fidelity: 0.99
T_1: 20-40μs
1 qubit gates: 10-20ns
2 qubit gates: 38-45ns

Platforms

Near term quantum computers will require more than just an abstract quantum circuit model. Be prepared to worry about:

- Connectivity / geometry of chip
- Gate error rates, decoherence times, measurement error rate
- Cross-talk, calibrations
- Error models
- Native gate set
- Gate set constraints
- Experiment cycle time
- Interface to and from classical bits
- Available classical compute

“Google is interested in having external research run experiments on their quantum computers, as they have done in the past.”

Interested?

Contact me: dabacon@google.com

Seattle Quantum Beer

Monthly-ish Google, Microsoft, Alibaba, UW folks meetup

Randomly rotates around area, default location is Postdoc Brewery in Redmond

dabacon@gmail.com

https://groups.google.com/forum/#!forum/quantum-beer-sea