

# Quantum Computation

DOE ATPESC workshop  
31-July-17  
IBM-Q Group  
Christopher Lirakis



# EMAIL

- DOE ATPESC workshop: <https://extremecomputingtraining.anl.gov>
- Chris Lirakis will present a talk entitled “Quantum Computing” on July 31st, from 1:30 pm - 2:15 pm

2) Chris will then have 1 hr more time, and we encourage some demonstrations, or hands on if that is possible. That will be from 2:15 pm - 3:15 pm. Of course, if you would rather present longer in the first lecture, and then have a shorter demo / hands on, that's fine. Your total time is from 1:30 to 3:15. This is the first time to cover Quantum in the ATPESC series, which the DOE has been running since 2013 (this will be our 5th year!). We are very excited to let the students see what the future might hold.



# Topics

- High Level Overview – The QC promise
- Popular Modalities – Encoding of information
- IBM implementation
- Applications
- IBM Quantum Experience
- Hands on Demo

This talk will focus primarily on universal gate based quantum computation.



# High Level Overview

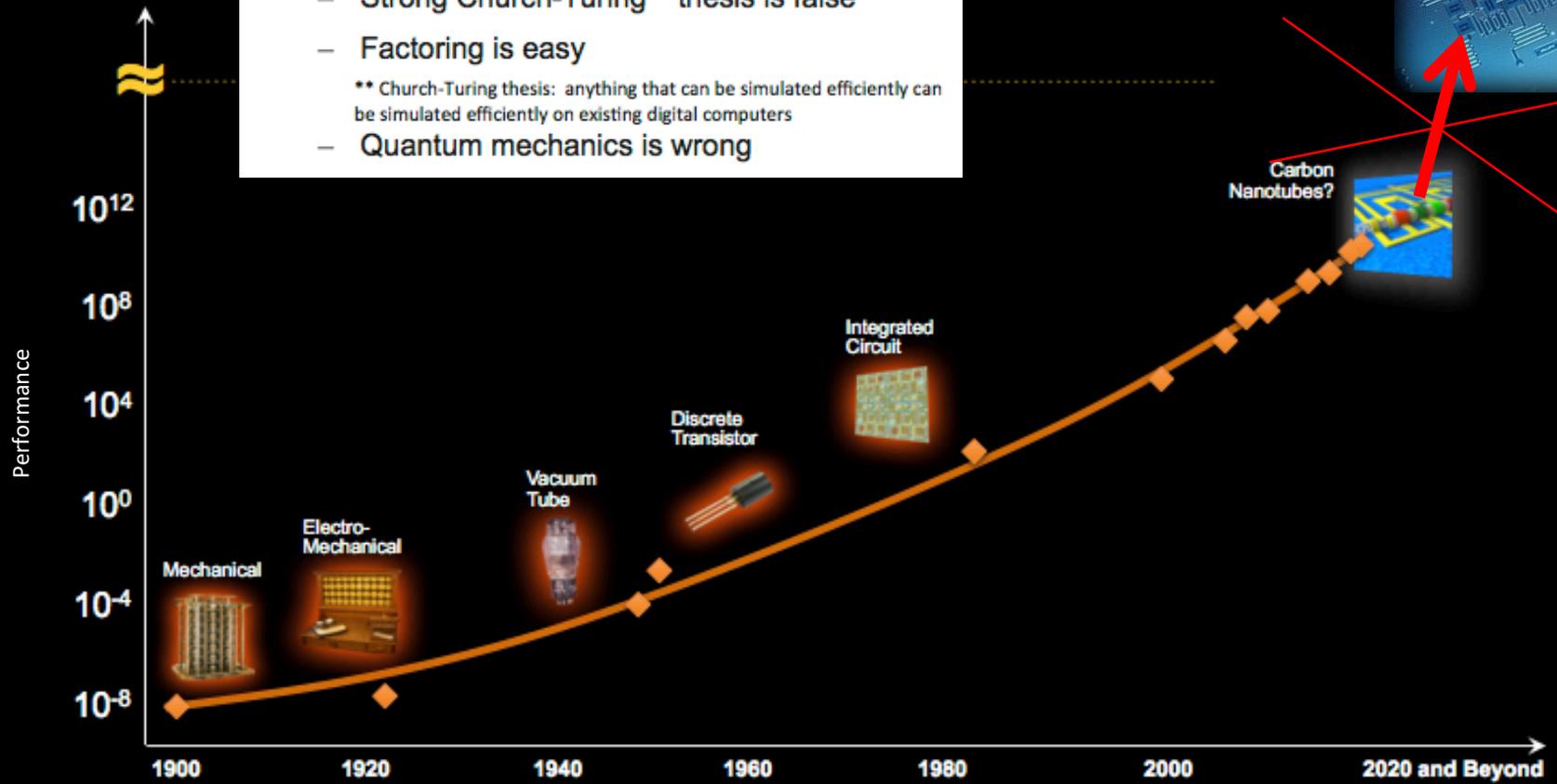
The promise of quantum computing

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**One of the following must be true\*:**

- Strong Church-Turing\*\* thesis is false
- Factoring is easy
- Quantum mechanics is wrong

\*\* Church-Turing thesis: anything that can be simulated efficiently can be simulated efficiently on existing digital computers



# Dirac & Feynman on quantum

- *“ The underlying physical laws necessary for the mathematical theory of a large part of physics [ ... ] are completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble. It therefore becomes desirable that approximate practical methods [...] should be developed... ”*

Dirac 1929

- *“I’m not happy with all the analysis that go with just classical theory, because nature isn’t classical, dammit. And if you want to make a simulation of nature, you’d better make it quantum mechanical, and, by golly, it’s a wonderful problem because it doesn’t look so easy”*

Feynman 1982



# Conventional Computing



Solving computational problems requires physical *resources* (time, memory, and space).



“easy” problems  
(polynomial  $\Rightarrow$  **efficient**)

- multiplying numbers
- word processing

“hard” problems  
(exponential  $\Rightarrow$  **intractable**)

- Algebraic and Number Theoretic Algorithms (factoring, hidden subgroup)
- Combinatorial optimization (traveling salesman)
- Machine learning
- simulating quantum mechanics

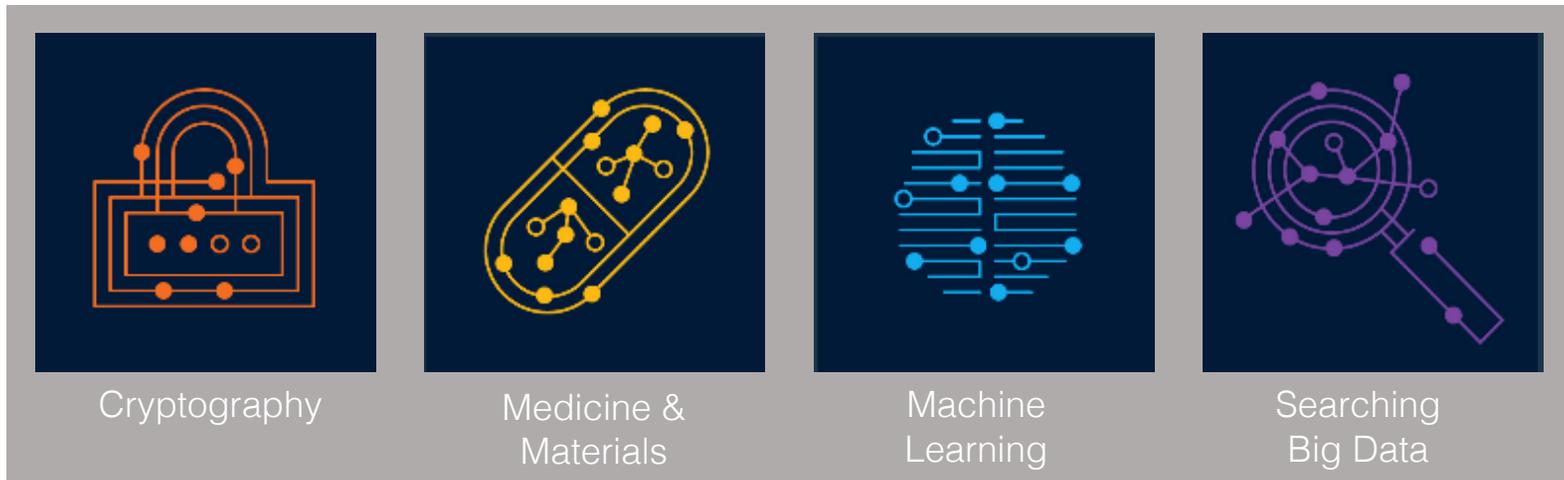


There are problems that are believed to be hard (never) for classical computers to solve

# Why quantum computing matters



With Moore's Law running out of steam, quantum computing will be among the technologies that will usher in a new era of innovation across industries.



Quantum computers could solve certain important problems that are considered intractable on classical computers! But they are unlikely to replace classical computers



# Two principles of quantum information science

Conventionally, information carriers are what a physicist would call *classical* systems

- The states are reliably distinguishable, and can be observed without disturbing the system
- To specify the joint state of two or more systems, it is sufficient to specify the state of each one separately.

## Quantum

- Attempting to observe a state in general disturbs it, while obtaining only partial information about the state (**uncertainty principle**).
- Two systems can exist in an **entangled** state, causing them to behave in ways that cannot be explained by supposing that each particle has some state of its own.

# The Bits



## Classical

All (classical) information is reducible to bits **0** and **1**.

All processing of it can be done by simple logic gates (**AND**, **NOT**) acting on bits one and two bits.

## Quantum

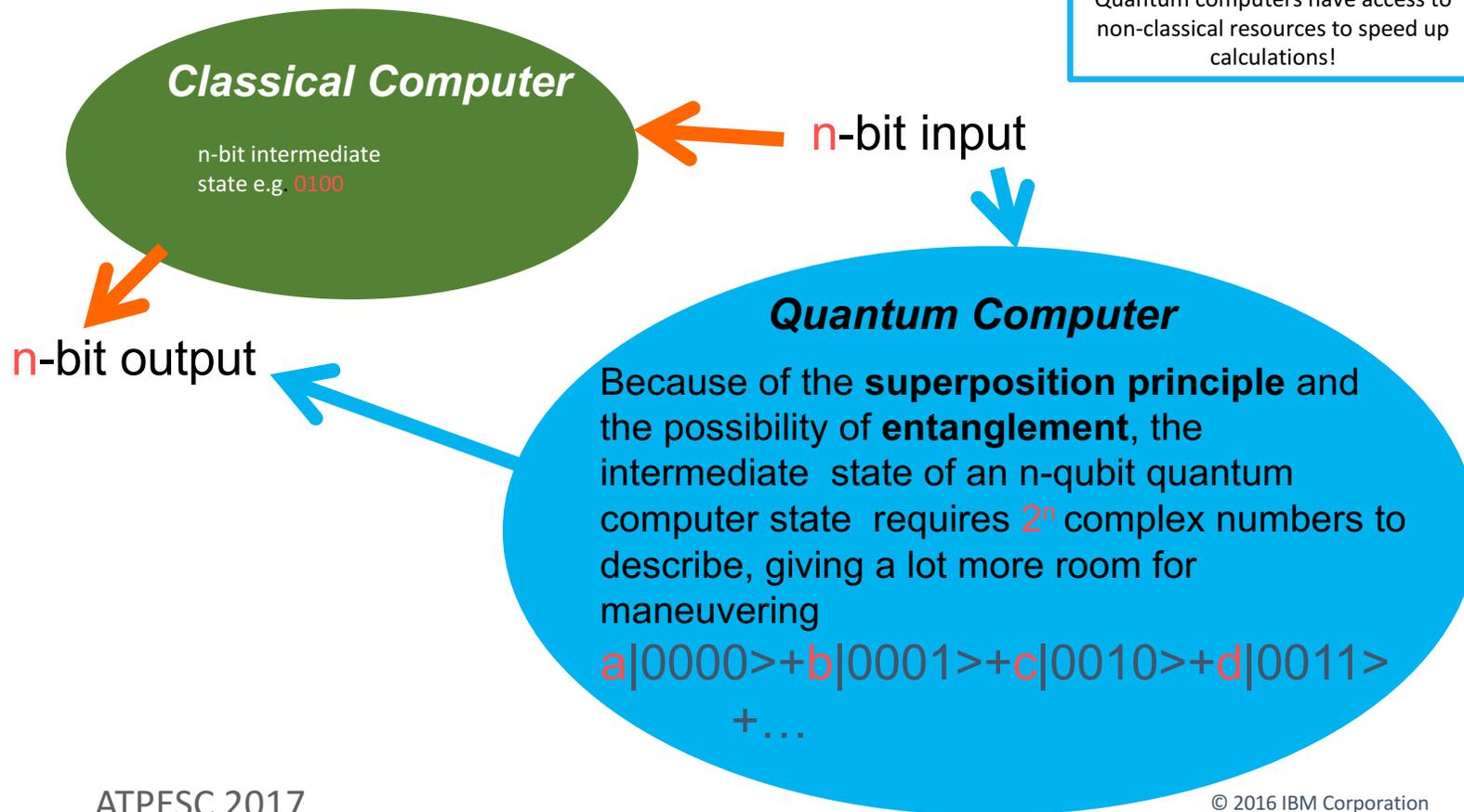
Quantum information is reducible to qubits  $\alpha|0\rangle + \beta|1\rangle$

Quantum information processing is reducible to **one** and **two-qubit** gate operations

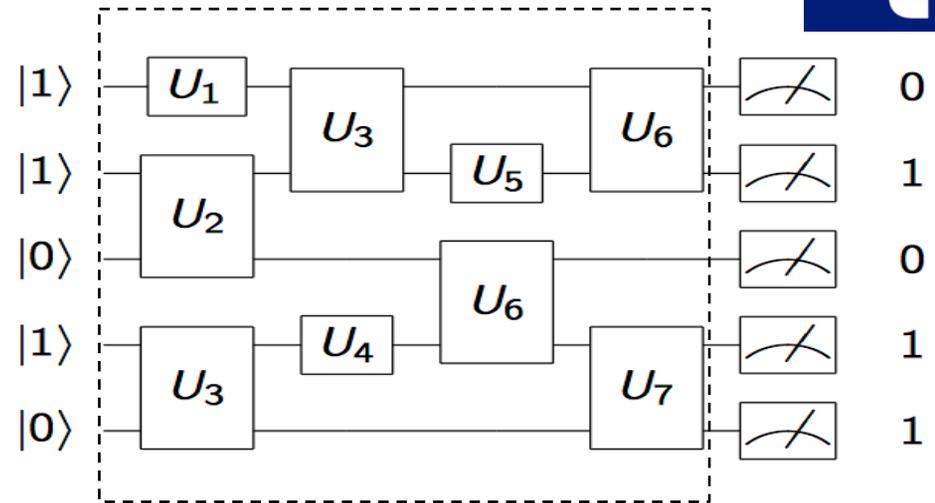
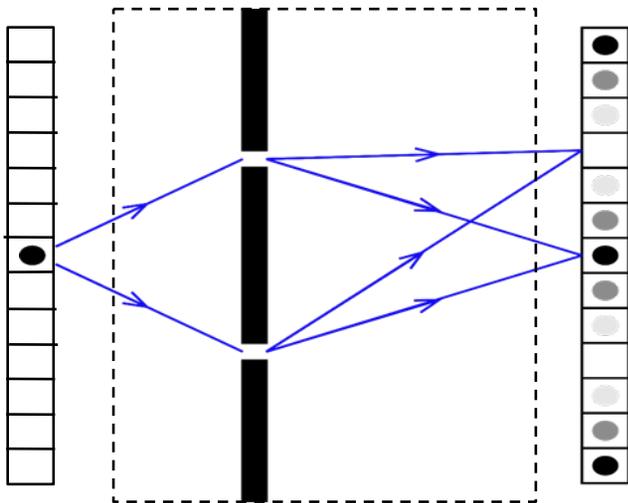
# Classical vs Quantum Computing



Quantum computers have access to non-classical resources to speed up calculations!



# Quantum Computing: Extra power from interference



- Many computational paths from the initial state to each final state
- Each path accumulates a complex phase, e.g.  $1, -1, i, e^{i\pi/4}$
- Output probability is concentrated at the final states where (almost) all paths arrive with (approximately) the same phase.

# Quantum Computing

Solving computational problems requires physical *resources* (time, memory, and space).



1+1=2

“easy” problems  
(polynomial  $\Rightarrow$  efficient)

- multiplying numbers
- word processing

“hard” problems  
(exponential  $\Rightarrow$  intractable)

- factoring (secure communication)
- optimization (traveling salesman)
- simulating quantum mechanics



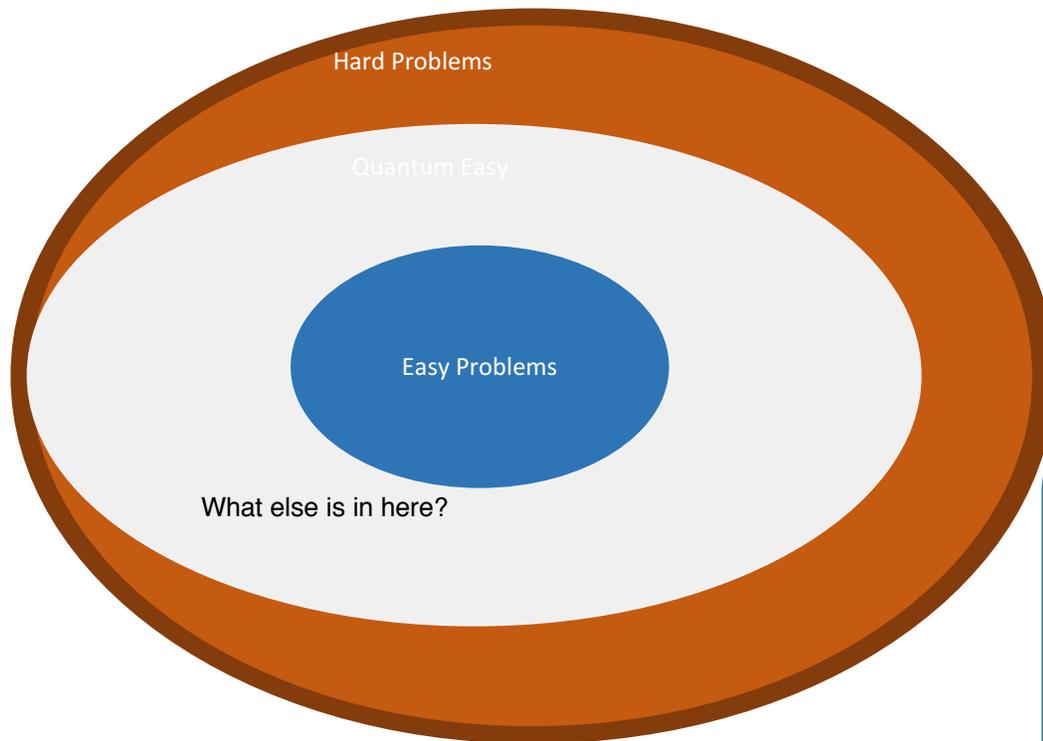
Quantum computers could solve certain important problems that are considered intractable on classical computers!

But they are unlikely to replace classical computers

# Quantum computing

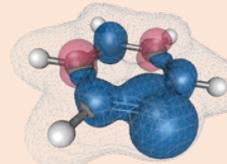
“easy” problems (polynomial  $\Rightarrow$  **efficient**)

“hard” problems (exponential  $\Rightarrow$  **intractable**)  
Hardest (NP-Complete)



Move After 7

Molecular Dynamics, Drug Design & Materials



This **laptop** could simulate a **25** electron system, **Titan** a **43** electron system but **no standard computer** ever built could simulate a **50** electron system exactly.

Species	Name	Bond type	Bond Length (Å)		
			Experimental	Calculated	Difference
CaF	Calcium monofluoride	rFCa	1.967	4.079	2.112
Na <sub>2</sub>	Sodium diatomic	rNaNa	3.079	2.379	-0.700

$$\Phi(x_1, \dots, x_N)$$

<http://cccbdb.nist.gov>

I. Bloch, J. Dalibard & S. Nascimbène, Nature Physics, 8, 267 (2012); R. Blatt & C. F. Roos, Nature Physics, 8, 277 (2012); A. Aspuru-Guzik and P. Walther, Nature Physics, 8, 285 (2012);

Customer BigCorp. orders various different lengths of wood and we need to check if we can fulfill the order and minimize waste

BigCorp P.O. 1234	
Length	Qty
17'	103
20'	107
8'	86
.	.
.	.
.	.



How to minimize wastage?

can I fulfil this order?



The solutions requires starting with an initial choice and trying all possibilities (Exponential)



Do not believe it is possible to drastically speed up NP-complete problems  
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“The Quantum Zoo”: <http://math.nist.gov/quantum/zoo/>

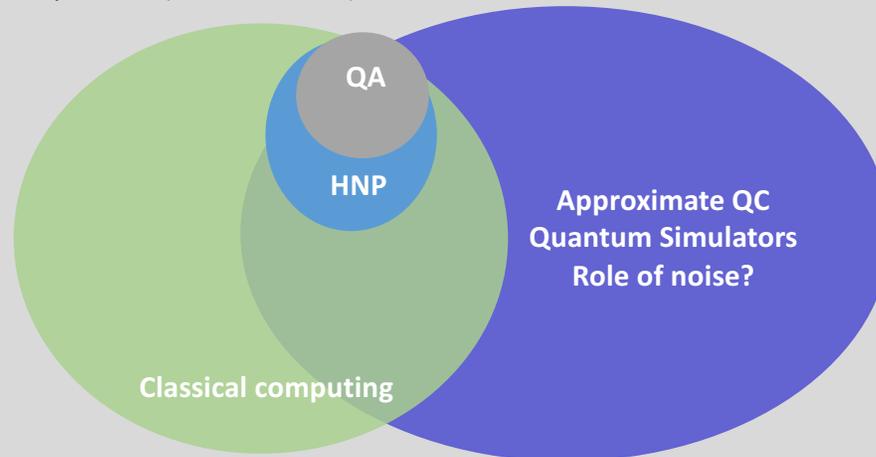
# Types of Quantum computing

Move After 7



## Fault Tolerant Quantum Computing:

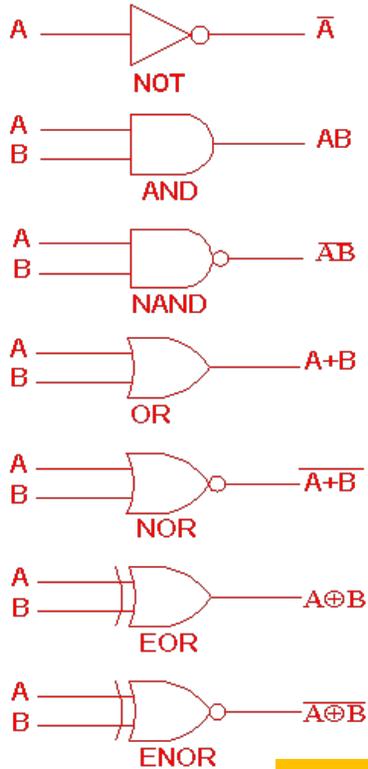
- Time evolution of quantum systems (Simulating Hamiltonian dynamics)
- Measuring complicated observables (Quantum phase estimation)
- Amplification of amplitudes (Grover search)



\*QA = Quantum Annealer

\*HNP = Classical Heuristic NP-Complete solvers

# Gates



**NOT gate**

A	$\bar{A}$
0	1
1	0

**2 Input AND gate**

A	B	AB
0	0	0
0	1	0
1	0	0
1	1	1

**2 Input NAND gate**

A	B	$\overline{AB}$
0	0	1
0	1	1
1	0	1
1	1	0

**2 Input OR gate**

A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

**2 Input NOR gate**

A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

**2 Input EXOR gate**

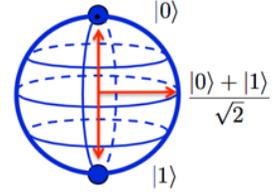
A	B	$A \oplus B$
0	0	0
0	1	1
1	0	1
1	1	0

**2 Input EXNOR gate**

A	B	$\overline{A \oplus B}$
0	0	1
0	1	0
1	0	0
1	1	1



**Classical Bit**



**Qubit**

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

2-Qubit



$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

$SWAP = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

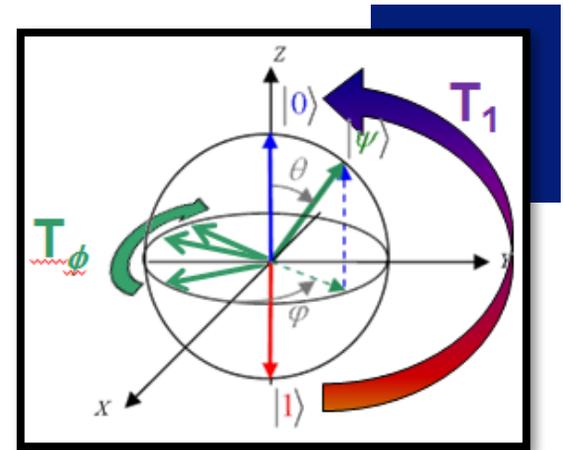
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Life is a little more complex! But we have a spanning set of gates.

# Qubits and Errors

- A qubit is a quantum two-level system
- Finite qubit coherence times
  - $T_1$ : relaxation
  - $T_\phi$ : dephasing (randomization of  $\phi$ )
    - Results from measurement (*intentional or not*)
  - $T_2$ : parallel combination of above,
- Imperfect control pulses
- Spurious inter-qubit couplings
- Imperfect qubit state measurements

→ *Errors unavoidable—Will they destroy our computation?*



$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

# Single Qubit Gates

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$R_\theta = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{bmatrix}$$

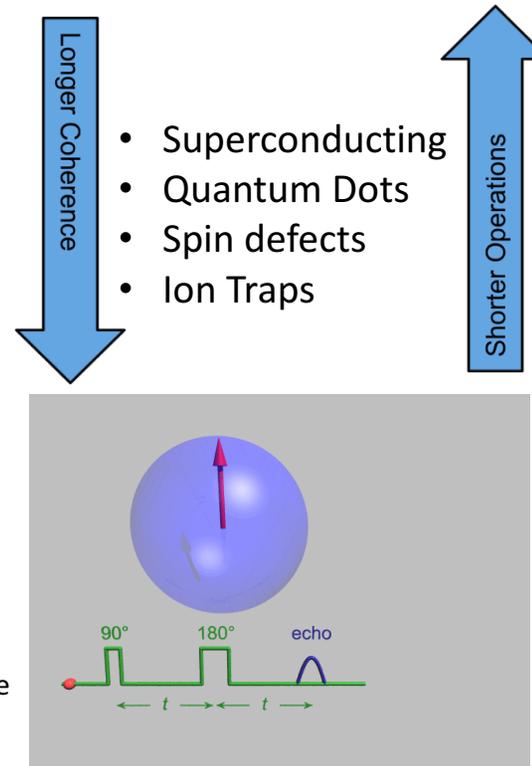
$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Decoherence

T1 – spin flip

T2 – Dephasing -

Important to have  $T_{op}/T2$  as large as possible



Pulses to manipulate single qubit on Bloch Sphere

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# Implementation

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# Experimental Implementations



*Easier to isolate, longer coherence*

*Easier to couple & construct, shorter coherence (improving)*

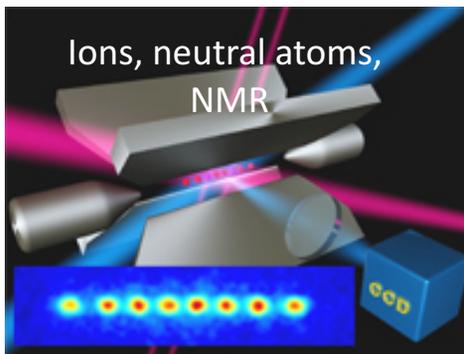


Image source: Rainer Blatt  
<http://www.quantumoptics.at/en/research.html>

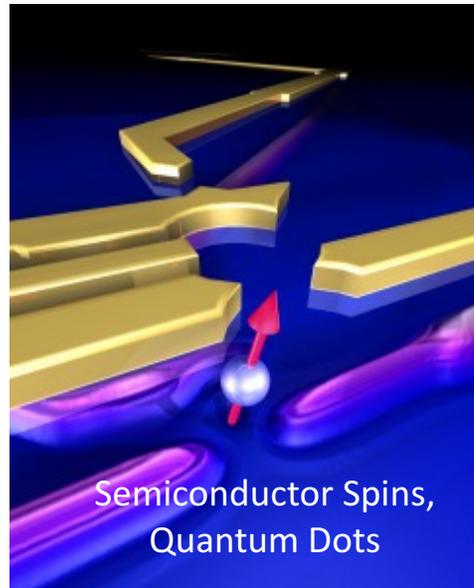
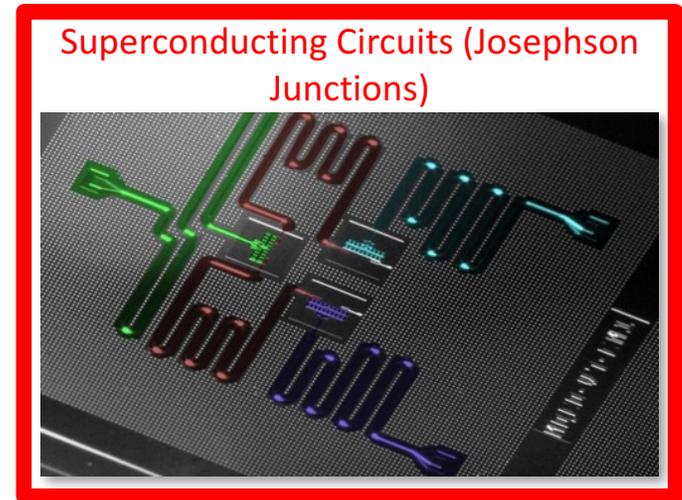


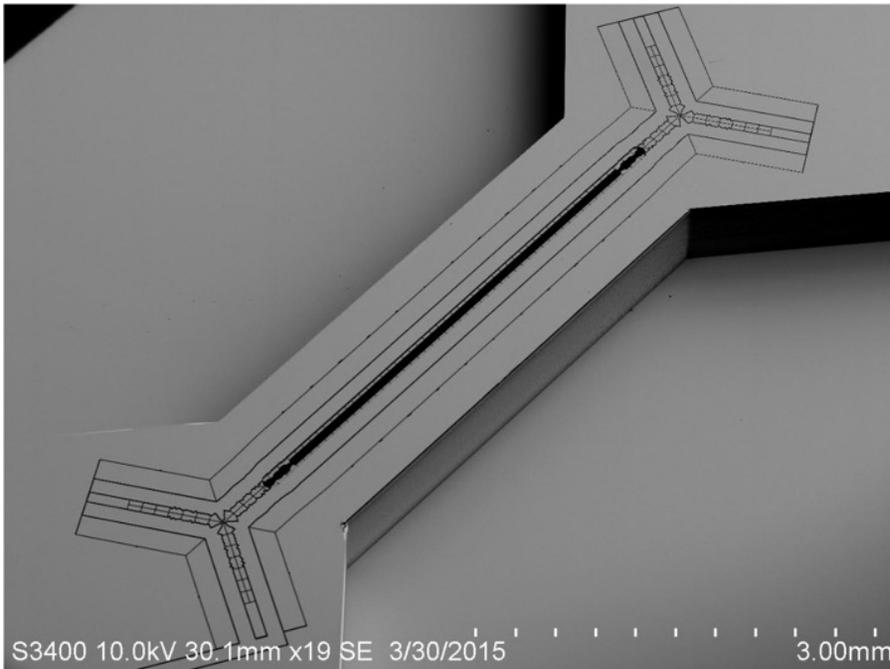
Image source: Vandersypen lab  
(Illustration by Tremani)



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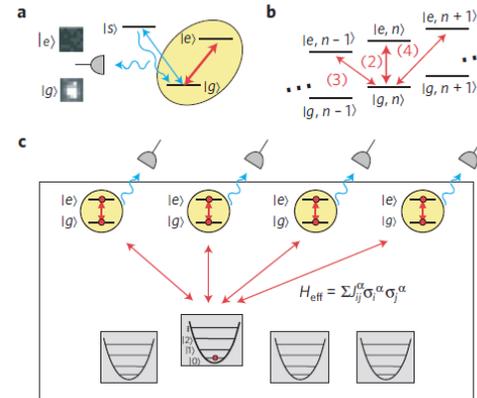
20

# Ion Traps



HOAT 2.0 – Sandia National Laboratories

And more: N. Linke et al., arXiv:1611.06946 (2016)  
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R. Blatt & C. F. Roos, Nature Physics, 8, 277 (2012)



Monz, T., et al, Science, 351(6277), 1068–1070.

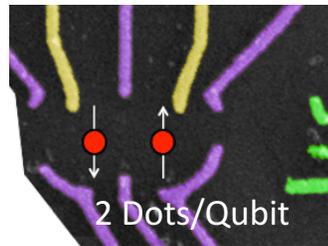
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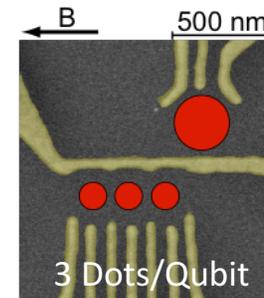
# Quantum Dots



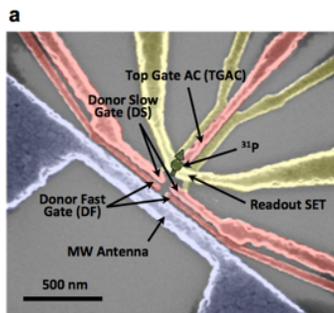
Loss and DiVincenzo, PRA 1998  
Image courtesy Lieven Vandersypen



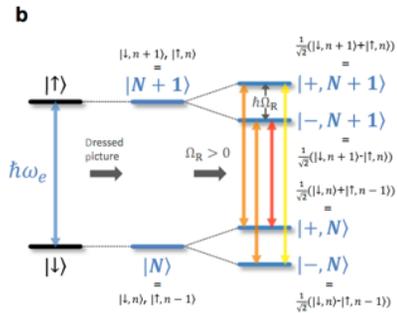
Johnson, Nature 2005  
Petta, Science 2005



Laird et. al, PRB 2010  
Image courtesy Jim Medford, Marcus Lab



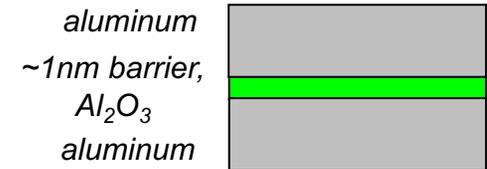
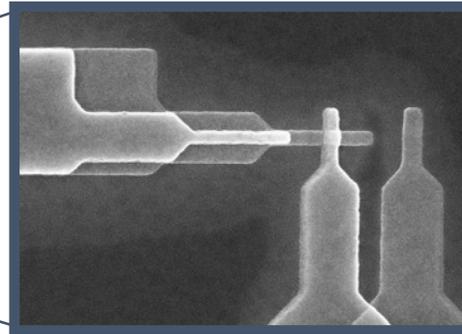
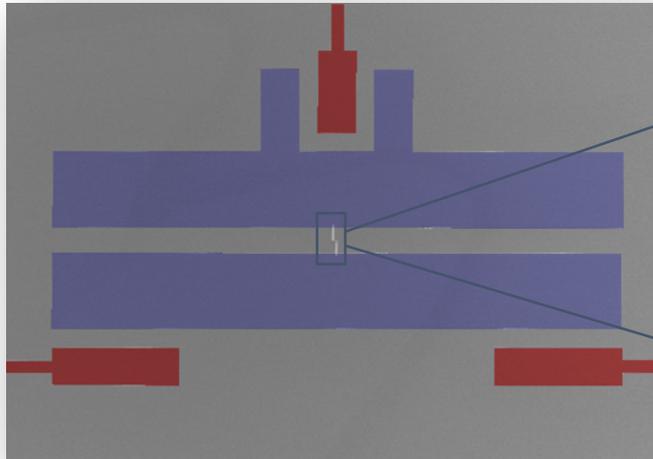
A. Laucht et al., Nature Nanotechnology 12, 61–66 (2017)



J. Nichol et al., NPJ Quant. Inf., n3:3, (2017)  
P. Cerfontaine et al., arXiv:1606.01897 (2016)

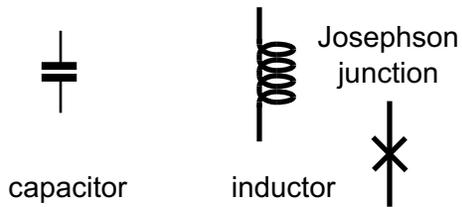
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# Single-junction transmon qubits

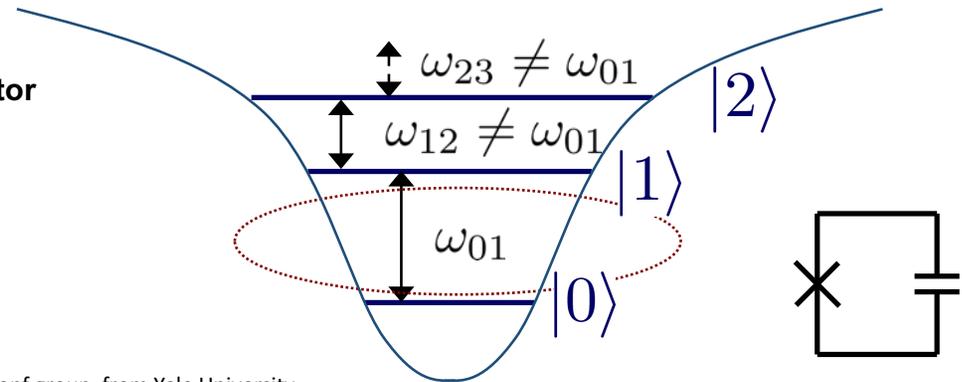
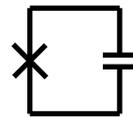


Josephson junction is a non-linear inductor

## Circuit elements

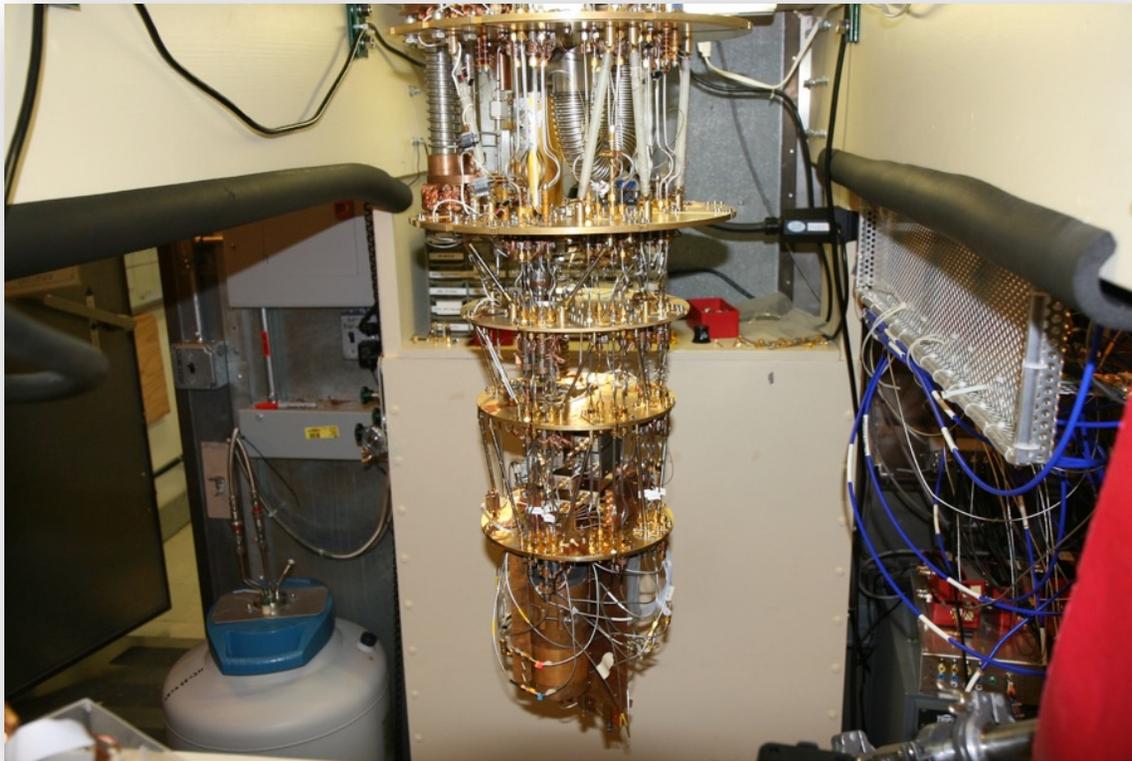


## 'anharmonic' oscillator

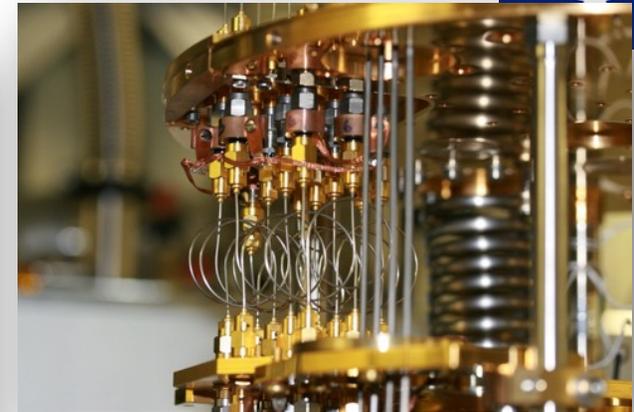


Anharmonicity:  $\omega_{12} - \omega_{01}$   
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# Inside one of the dilution refrigerators

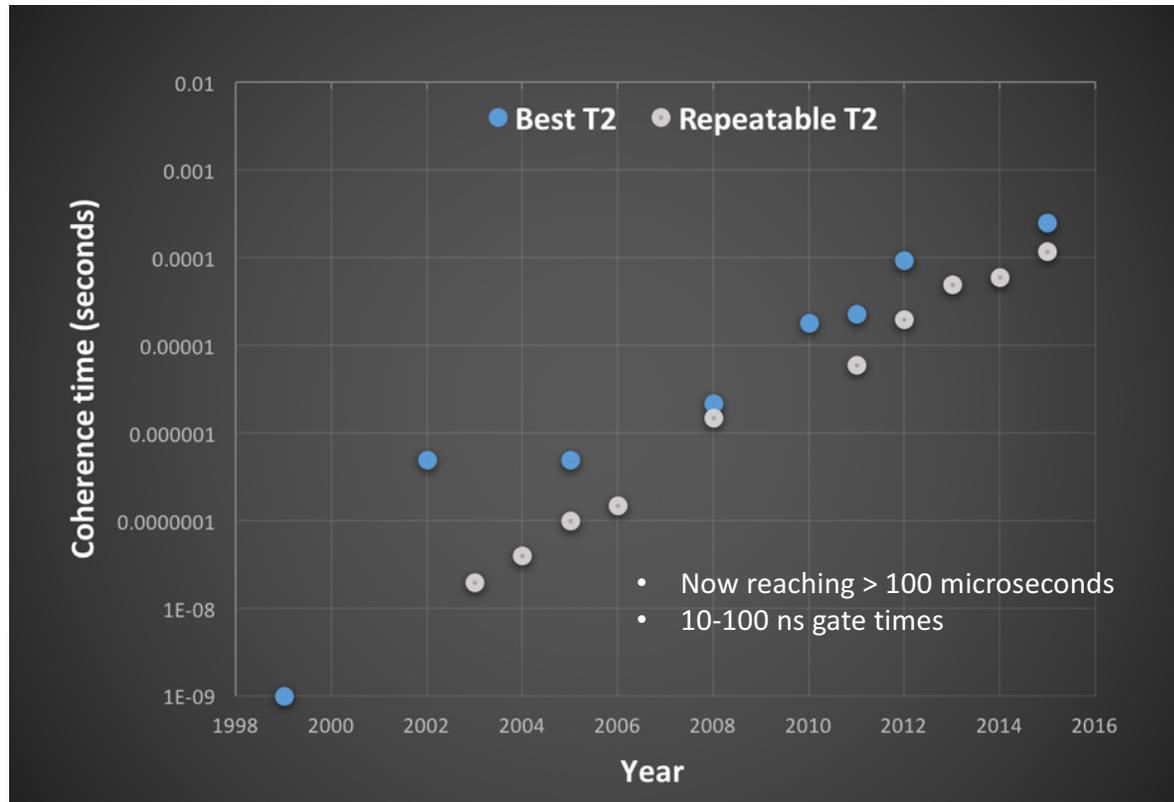


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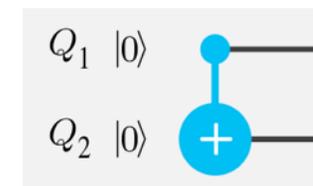
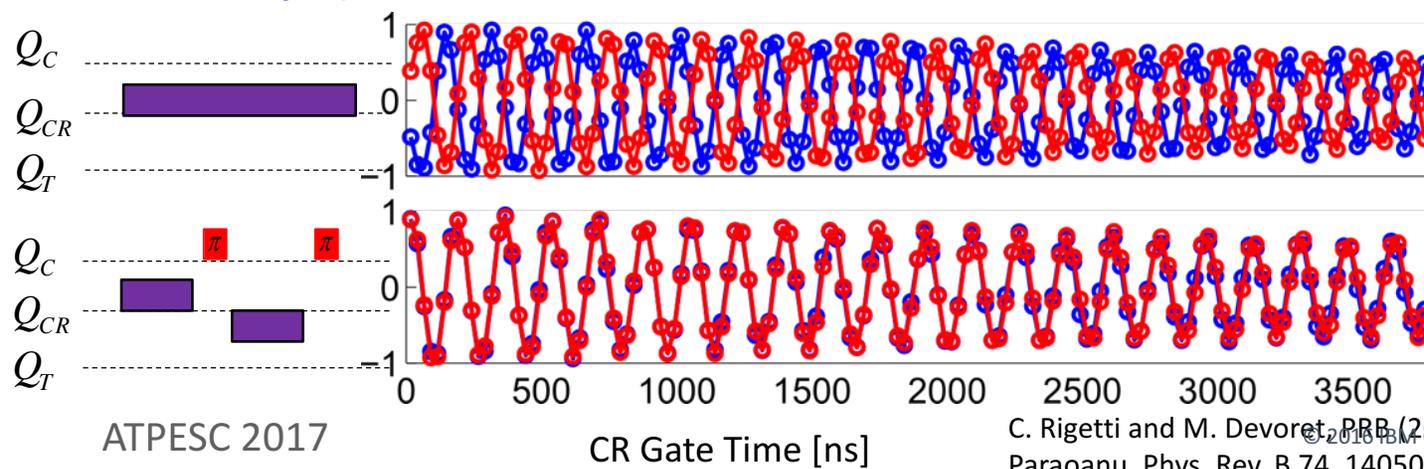
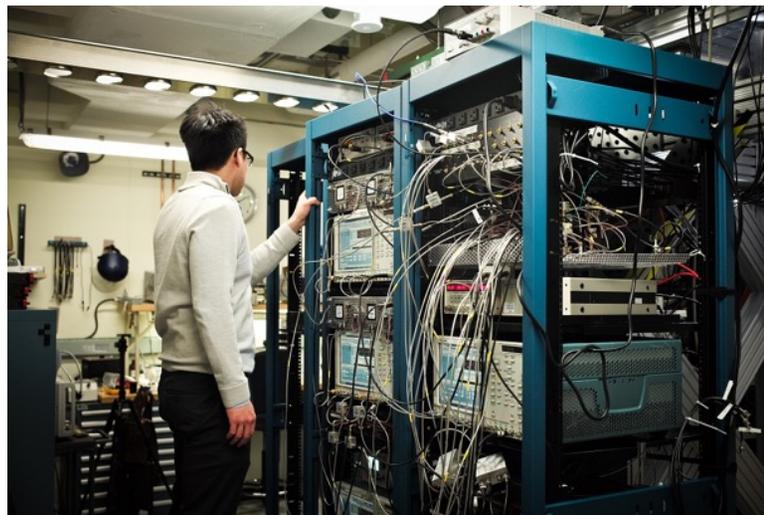
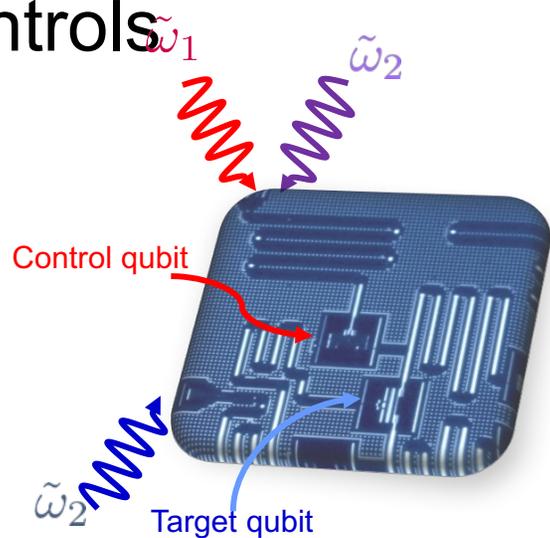
# Coherence times of superconducting qubits



- Developments to extend coherence times
  - Materials e.g. [2]
  - Design and geometries e.g. [3]
  - 3D transmon [4]
  - IR Shielding [5,6],
  - Cold normal metal cavities and cold qubits [7]
  - High Q cavities [8]
  - Titanium Nitride (collaboration with David Pappas @ NIST Boulder) [9] ...
- Remarkable progress over the past decade

[2] J. Martinis *et al.*, PRL **95** 210503 (2005)  
[3] K. Geerlings *et al.*, APL 192601 (2012)  
[4] H. Paik *et al.*, PRL **107**, 240501 (2011)  
[5] R. Barends *et al.*, APL **99**, 113507 (2011)  
[6] A. Corcoles *et al.*, APL **99**, 181906 (2011)  
[7] C. Rigetti *et al.*, PRB **86**, 100506 (2012)  
[8] M. Reagor *et al.*, arXiv:1302.4408 (2013)  
[9] J. Chang *et al.* APL 103, 012602 (2013)

# Controls



C. Rigetti and M. Devoret, *PRB*, (2010); G. S. Paraoanu, *Phys. Rev. B* 74, 140504 (2006)

# Superconducting Qubits: Community Status



Metrics not necessarily all achieved simultaneously!

- Qubit
  - Ground and excited states of anharmonic quantum oscillator
- Measurement
  - State dependent frequency shift of resonator coupled to qubit (cQED)
  - $F > 99\%$
- Initialization
  - Wait
- Single Qubit Gates
  - Microwave pulses
  - $F \sim 99.9 - 99.95\%$
- Two Qubit Gates
  - Qubit tuning, or ...
  - Microwave approach
  - $F \sim 95 - 99.5\%$
- Decoherence time
  - $T_1 \sim T_2 \sim 40-100\mu\text{s}$
- Clock speed
  - 10ns – 300ns

- [1] A. Wallraff et al., *Nature* **431**, 162-167 (2004)
  - [2] Z. Chen et al., *Phys. Rev. Lett.* **116**, 020501 (2016)
  - [3] J. Kelly et al. *Nature* 519, 66-69 (2015)
  - [4] S. Sheldon et al., *Phys. Rev. A* 93, 060302 (2016)
  - [5] R. Versluis et al., arXiv:1612.08208 (2016)
  - [6] J. Gambetta et al., *IEEE Appl. Sup.*, 27, 1700205 (2017)
  - [7] M Devoret, A. Roy, arXiv:1605.00539 (2016)
  - [8] N. Ofek et al., *Nature* 536, 441-445 (2016)
- © 2017 IBM Corporation  
...and many more



# Applications

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# Transistor Timeline

- 1874 – Point Contact Rectifier effect
- 1941 – Germanium Diodes
- 1944 – Colossus, Digital
- 1946 - Eckert-Mauchly Computer – special purpose
- 1947 – Point contact Germanium Transistor
- 1948 – Claude Shannon publishes "A Mathematical Theory of Information"
- 1954 – Silicon transistor displaces Germanium
- 1958 – Kilby introduces concept of integrated circuit. TI
- 1956 - FORTRAN
- 1959 – IBM 1401, DEC PDP-1
- 1964 – IBM 360
- 1972 – FET displaces BJT
- 2016 – End of Moore's Law

} General purpose computing

# Shor's algorithm (1994)

The problem of  
multiplication vs factoring

937 x 947 = N (easy)

887339 = p x q (harder)

## Exponential speed-up:

A task taking  $2^{100}$  seconds ( $10^{25}$  days) on a classical computer might take **100 seconds** on a quantum computer

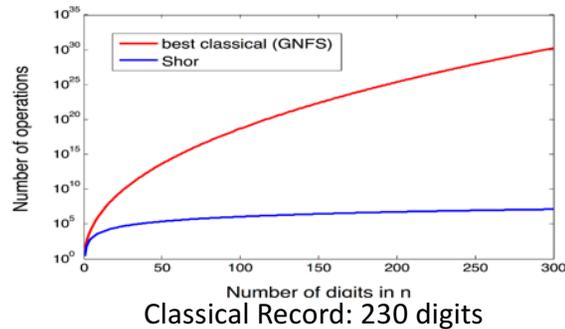
public key from google.com

Modulus (1024 bits):

de b7 26 43 a6 99 85 cd 38 a7 15 09 b9 cf 0f c9  
c3 55 8c 88 ee 8c 8d 28 27 24 4b 2a 5e a0 d8 16  
fa 61 18 4b cf 6d 60 80 d3 35 40 32 72 c0 8f 12  
d8 e5 4e 8f b9 b2 f6 d9 15 5e 5a 86 31 a3 ba 86 = p x q  
aa 6b c8 d9 71 8c cc cd 27 13 1e 9d 42 5d 38 f6  
a7 ac ef fa 62 f3 18 81 d4 24 46 7f 01 77 7c c6  
2a 89 14 99 bb 98 39 1d a8 19 fb 39 00 44 7d 1b  
94 6a 78 2d 69 ad c0 7a 2c fa d0 da 20 12 98 d3

(just short of impossible)

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best classical  
algorithm  
(number field sieve)

$\exp(C \times b^{1/3})$   
Shor's algorithm  
 $C \times b^3$



One of the following must be true\*:

- Strong Church-Turing\*\* thesis is false
- Factoring is easy
- Quantum mechanics is wrong

\*\* Church-Turing thesis: anything that can be simulated efficiently can be simulated efficiently on existing digital computers

Shor's algorithm jumpstarted the interest in quantum computing

\* Scott Aaronson, PhD thesis, UC Berkeley

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# Types of quantum computers

## **fault-tolerant quantum computer - Long term**

A universal fault-tolerant quantum computer is the holy grail of quantum information science. It would allow one to run **any** known quantum algorithms which achieve exponential speed ups over their classical counterparts.

## **Approximate quantum computer – Near term**

A quantum device which does not need fault tolerance, with the goal of demonstrating a useful application by interacting with a classical computing system, e.g. quantum chemistry, optimization

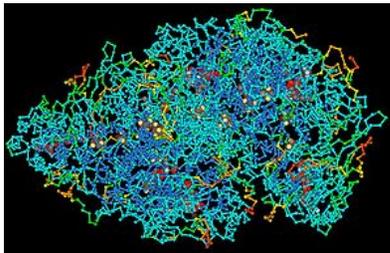
## **Quantum Supremacy – Driving force**

Quantum supremacy is an idea that before any useful quantum computer is built it may be possible to demonstrate a *special purpose* quantum device whose output cannot be simulated using existing classical computers. The notion was proposed by John Preskill in his talk “Quantum computing and the entanglement frontier” at the Caltech Solvay Conference, October 2011.

# Applications of Approximate quantum computing



## Quantum Chemistry

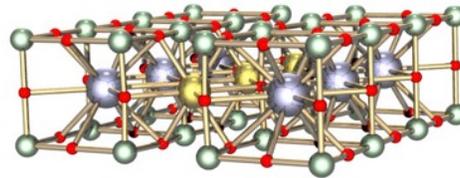


(credit: wikipedia)

### Molecule simulation

A. Peruzzo et al., *Nature Comms* **5**, 4213 (2014)

## Condensed Matter Physics

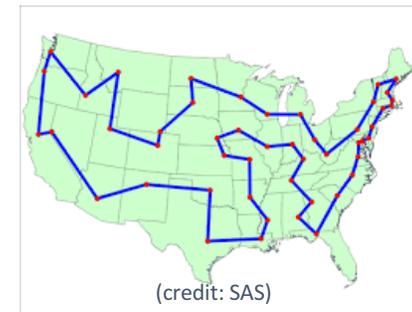


(credit: wikipedia)

### High Tc materials

J. Imriška et al., *PRB*, **94**, 035109 (2016)  
B. Bauer et al., *Phys. Rev. X* **6**, 031045 (2016)

## Quantum enhanced optimization



(credit: SAS)

### Combinatorial optimization

Farhi and Harrow, arXiv:1602.07674 (2016)  
Farhi et al., arXiv:1411.4028 (2014)



## Integration of classical HPC and quantum

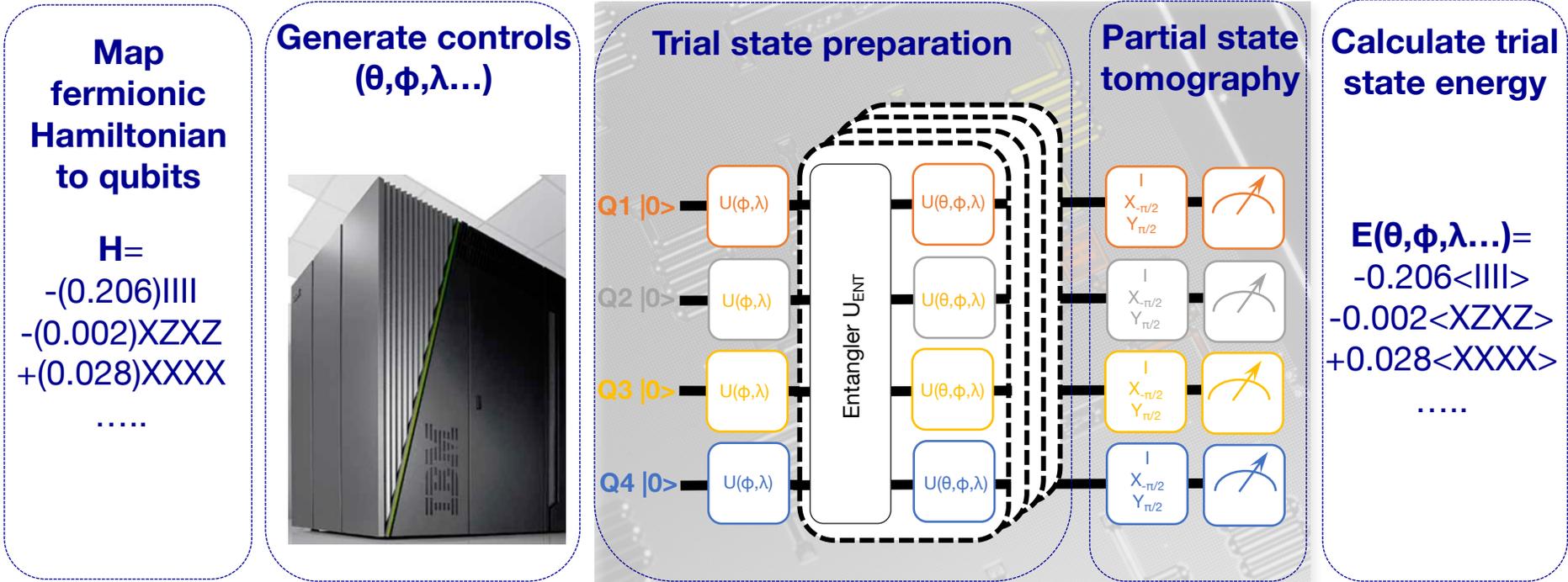
- Use the quantum computer to calculate the hard part of the problem (cost function)
- Use the classical computer to control the quantum computer

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“The Quantum Zoo”: <http://math.nist.gov/quantum/zoo/>

# The experiment: Short depth, device oriented quantum circuit



**Map fermionic Hamiltonian to qubits**

$H =$   
 $-(0.206)IIII$   
 $-(0.002)XZYZ$   
 $+(0.028)XXXX$   
 .....

**Generate controls  $(\theta, \phi, \lambda, \dots)$**

**Trial state preparation**

Q1  $|0\rangle$   $U(\phi, \lambda)$   $U(\theta, \phi, \lambda)$

Q2  $|0\rangle$   $U(\phi, \lambda)$   $U(\theta, \phi, \lambda)$

Q3  $|0\rangle$   $U(\phi, \lambda)$   $U(\theta, \phi, \lambda)$

Q4  $|0\rangle$   $U(\phi, \lambda)$   $U(\theta, \phi, \lambda)$

Entangler  $U_{ENT}$

**Partial state tomography**

$I$   $X_{-\pi/2}$   $Y_{\pi/2}$

$I$   $X_{-\pi/2}$   $Y_{\pi/2}$

$I$   $X_{-\pi/2}$   $Y_{\pi/2}$

$I$   $X_{-\pi/2}$   $Y_{\pi/2}$

**Calculate trial state energy**

$E(\theta, \phi, \lambda, \dots) =$   
 $-0.206 \langle IIII \rangle$   
 $-0.002 \langle XZYZ \rangle$   
 $+0.028 \langle XXXX \rangle$   
 .....

Optimize

# The interatomic potential of $\text{Li}_2$



	Equilibrium Separation (0.735 Å)	Dissociation Separation (4.0 Å)
Exact	-1.138	-0.9348
QC	-1.116 ± 0.00089	-0.9272 ± 0.00019

See also:

B.P.Lanyon et al Nat. Chem. 2, 106–111 (2010)

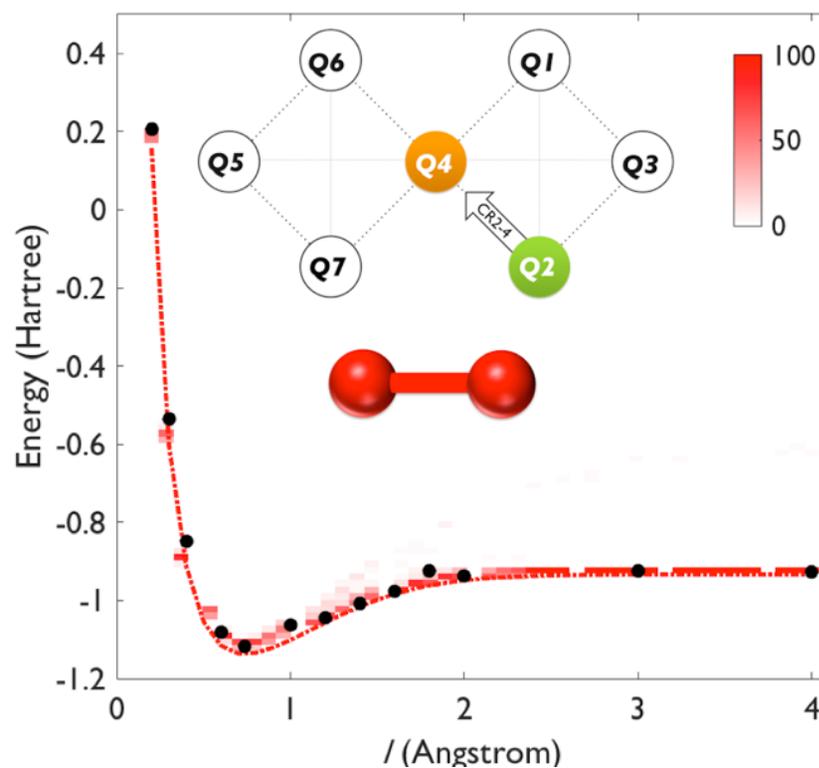
J. Du et al PRL 104, 030502 (2010)

Y. Wang et al ACS Nano, 9 (8), pp 7769–7774 (2015)

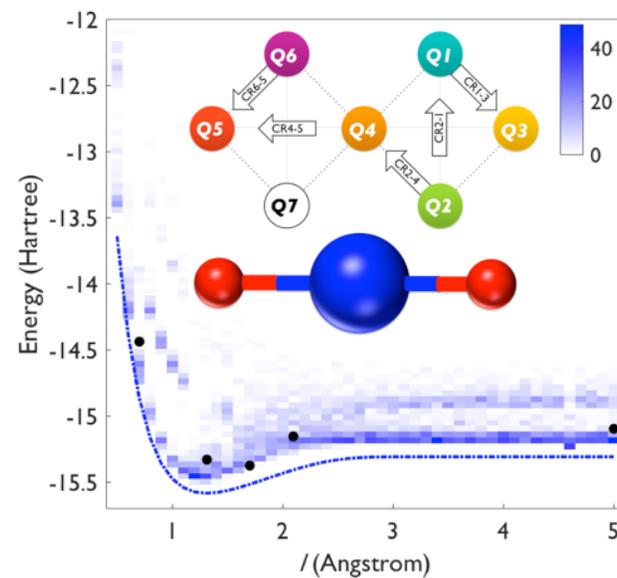
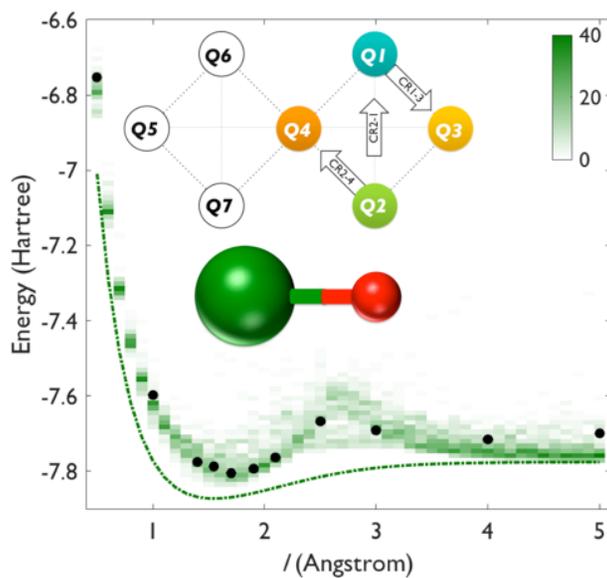
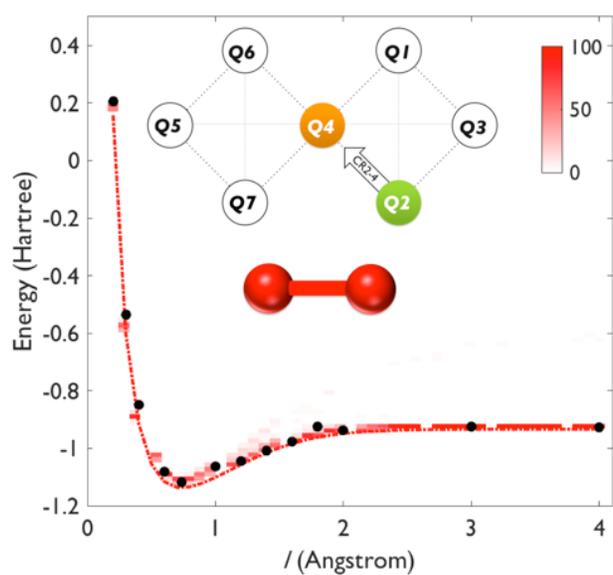
P. J. J. O'Malley et al. PRX 6, 031007 (2016)

Y. Shen et al. arXiv:1506.00443

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# Quantum chemistry



H42.00010, A. Mezzacapo  
H42.00011, A. Kandala  
B19.00001, J. Gambetta

Error mitigation:  
K. Temme et al., arXiv:1612.02058 (2016)

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# Quantum Volume - Metrics

Number of qubits (more is better)

Connectivity (more is better)

Gates set (more is better)

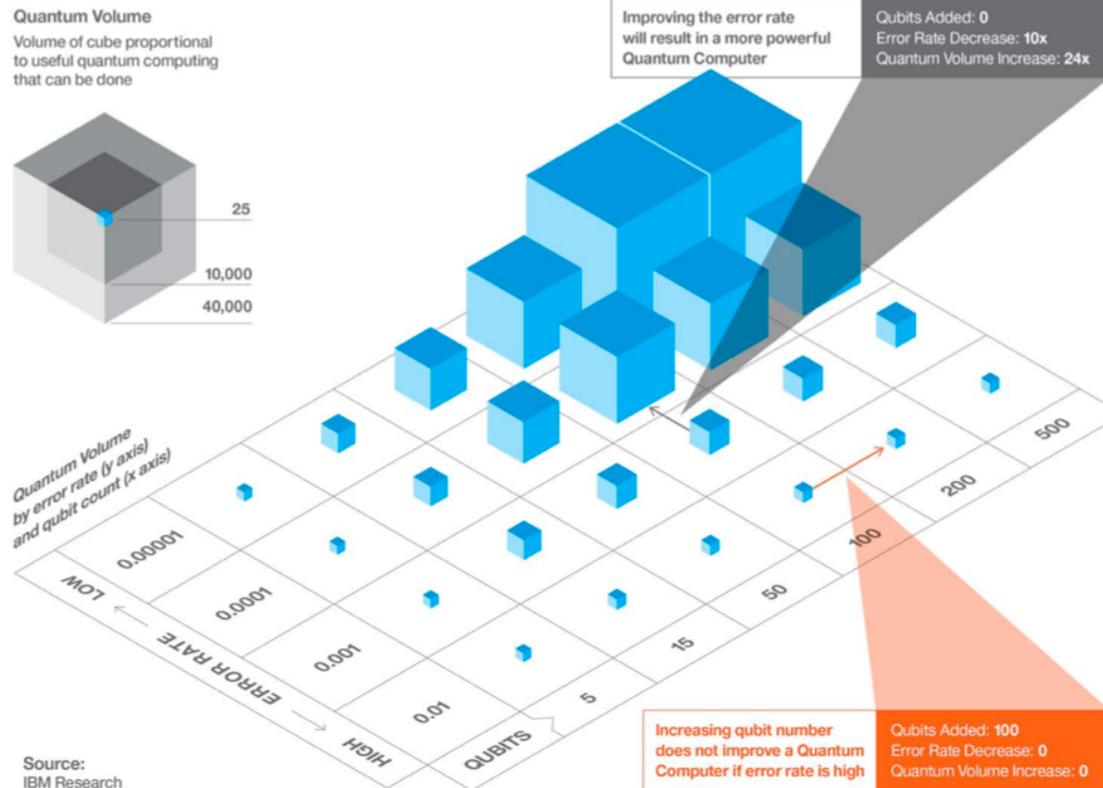
Errors (less is better)



# Quantum volume

## A Quantum Computer's power depends on more than just adding qubits

If we want to use quantum computers to solve real problems, they will need to explore a large space of quantum states. The number of qubits is important, but so is the error rate. In practical devices, the effective error rate depends on the accuracy of each operation, but also on how many operations it takes to solve a particular problem as well as how the processor performs these operations. Here we introduce a quantity called **Quantum Volume** which accounts for all of these things. Think of it as a representation of the problem space these machines can explore.





# Demonstration – IBM QX

Developing a quantum community

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# IBM Quantum Experience

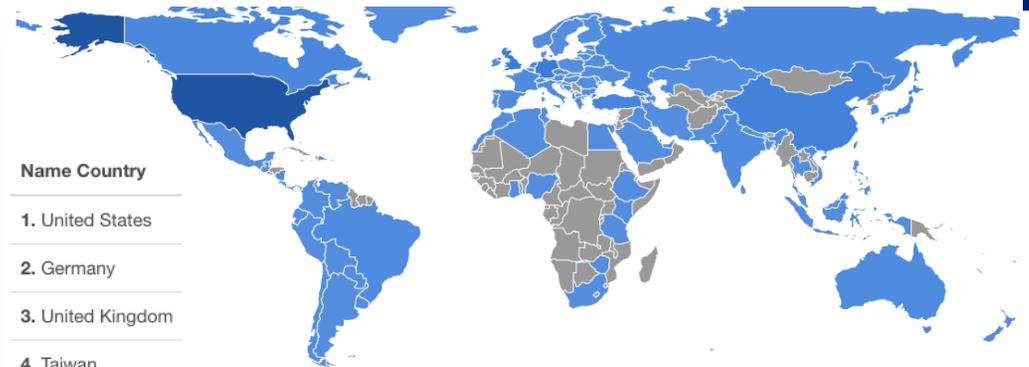
Launched May 4, 2016



 36605  
Users

 252319  
User Executions

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Name Country

1. United States
2. Germany
3. United Kingdom
4. Taiwan
5. China
6. Turkey
7. Netherlands
8. Russia
9. Japan
10. Canada

Over 121 countries have joined the Experience  
Now can log-in with  
Linkedin, Github, or Google accounts

# Quantum Community is Growing



- **Fifteen** papers submitted
- Tweets from scientist at the **South Pole**
- **10+ professors** using IBM Quantum Experience for education
- Featured at Undergrad Conference at University of Waterloo
- **MIT edX Online Course** using it (1100 students)
- Educational tool and research tool

Enrichment exercise: IBM Quantum Experience

IBM generously offers open, cloud-based, access to a real quantum-circuit-capable quantum computer, which has five superconducting "transmon" qubits. Due to constraints imposed by the topology of device interconnects, only certain two-qubit gates can be implemented in a single step; also, the cloud-based interface limits single qubit operations Pauli gates,  $S$ ,  $S^\dagger$ ,  $T$ , and  $T^\dagger$ . And gate realizations are pretty good, but imperfect: the qubits have finite (but well-characterized)  $T_1$  and  $T_2$  coherence times.

This realistic configuration is very interesting to explore, as we do in the following optional, problem.

---

IBM QE1: Five-qubit entangled state

This is a schematic diagram of IBM's five qubit chip quantum computer:

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PHYSICAL REVIEW A 94, 012314 (2016)

**Experimental test of Mermin inequalities on a five-qubit quantum computer**

Performing Quantum Computing Experiments in the Cloud

Simon J. Devitt  
Center for Emergent Matter Science, RIKEN, Wakoshi, Saitama 315-0198, Japan.

Quintuple: a Python 5-qubit quantum computer simulator to facilitate cloud quantum computing

Christine Corbett Moran<sup>a,b,\*</sup>

Quantum state reconstruction made easy: a direct method for tomography

R. P. Rundle,<sup>1</sup> Todd Tilma,<sup>2</sup> J. H. Samson,<sup>1</sup> and M. J. Everitt<sup>1,†</sup>

<sup>1</sup>Quantum Systems Engineering Research Group & Department of Physics, Loughborough University, Leicestershire LE11 3TU, United Kingdom

New J. Phys. 18 (2016) 073004 doi:10.1088/1367-2630/18/7/073004

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PAPER

Entropic uncertainty and measurement reversibility

A quantum teleportation experiment for undergraduate students

S. Fedortchenko<sup>\*</sup>  
Laboratoire Matériaux et Phénomènes Quantiques, Sorbonne Paris Cité,  
Université Paris Diderot, CNRS UMR 7160 75019 Paris, France

**Leggett-Garg test of superconducting qubit addressing the clumsiness loophole**

Emilie Huffman<sup>1,2</sup> and Ari Mizel<sup>1</sup>

<sup>1</sup>Laboratory for Physical Sciences, College Park, Maryland 20740, USA  
<sup>2</sup>Department of Physics, Duke University, Durham, North Carolina 27708, USA

The Leggett-Garg inequality holds for any macrorealistic system that is being measured noninvasively. A violation of the inequality can signal that a system does not conform to our primal intuition about the physical world. Alternatively, a violation can simply indicate that "clumsy" experimental technique led to invasive measurements. Here, we consider a recent Leggett-Garg test designed to try to rule out the mundane second possibility. We tailor this Leggett-Garg test to the IBM SQ Quantum Experience system and find compelling evidence that qubit  $Q_2$  of the system cannot be described by noninvasive macrorealism.

# IBM Quantum Experience



The screenshot shows a login modal window titled "Login" overlaid on the IBM Quantum Experience website. The modal contains the following elements:

- Header: "Login" with a close button (X).
- Form fields: "Enter your email" (highlighted in yellow) and "Password" (with a visibility toggle icon).
- Link: "Forgot your password?"
- Button: "Sign in" (orange).
- Text: "If you don't have an account you can create it in the next link: [Signup](#)"
- Section: "Or Login with..."
- Social login buttons: IBM Id, LinkedIn, Github, Google, and Twitter.

The background website shows a "Community" section with "Forum Topics (86)", a "Tags" section with various quantum-related terms, and a "Top Users" section with user avatars.

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[www.ibm.com/quantumcomputing](http://www.ibm.com/quantumcomputing)

# IBM Quantum Experience

The screenshot displays the IBM Quantum Experience Composer interface. At the top, the navigation bar includes "IBM Quantum Computing", "Quantum Experience Preview", "Account", and "Logout". Below this, a secondary navigation bar contains "Community", "User Guide", "Composer" (the active tab), "QASM Editor", and "My Scores".

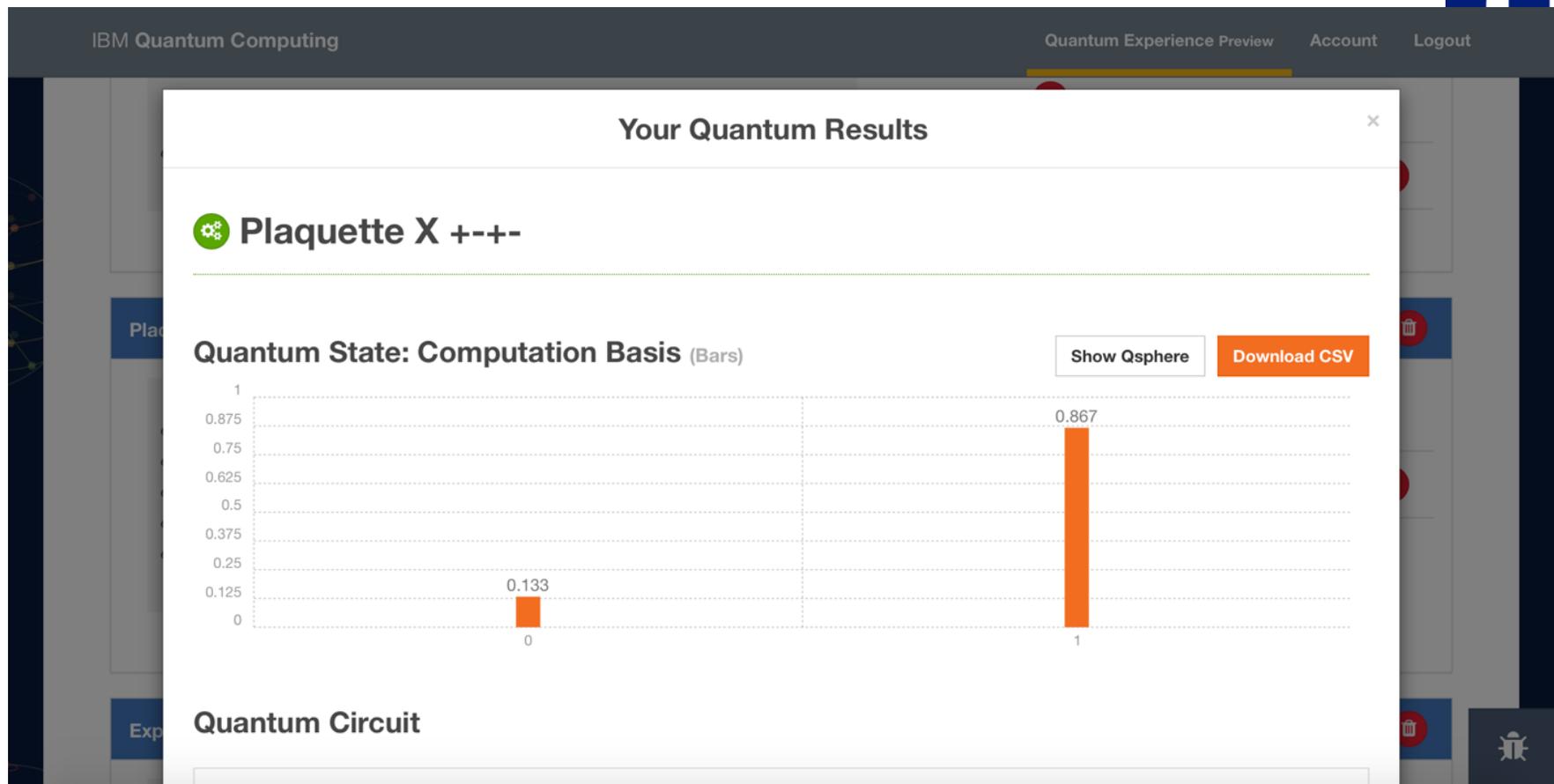
The main workspace shows a quantum circuit named "Plaquette X +++" for a "Real Quantum Processor". The circuit involves five qubits,  $Q_0$  through  $Q_4$ , each starting in the  $|0\rangle$  state. The gates and operations are as follows:

- $Q_0$ : H, Z, Id, H, followed by a CNOT gate with  $Q_4$  as control and  $Q_0$  as target.
- $Q_1$ : H, Z, Id, H, followed by a CNOT gate with  $Q_4$  as control and  $Q_1$  as target.
- $Q_2$ : Four CNOT gates with  $Q_4$  as control and  $Q_2$  as target, followed by a MEASURE gate.
- $Q_3$ : H, Id, H, followed by a CNOT gate with  $Q_4$  as control and  $Q_3$  as target.
- $Q_4$ : H, Z, Id, H.

At the bottom, a "GATES" palette includes Id, X, Z, Y, H, S, S†, CNOT, T, and T†. A "MEASURE" palette includes two measurement symbols. A right-hand sidebar contains buttons for "Simulate", "Run", "New", "Save", "Save as", "Results", and "Help". A "Add a description" button is located at the bottom right of the circuit area.

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# IBM Quantum Experience



# Single qubit states



Exp 1. Preparing the qubit in the "0" state



Quantum State: Computation Basis (Bars)

Run 1

Show Qsphere

Download CSV



# Single qubit states



Exp 1. Preparing the qubit in the "0" state

$Q_1$   $|0\rangle$



Quantum State: Computation Basis (Bars)

Run 2

Show Qsphere

Download CSV



# Single qubit states



Exp 1. Preparing the qubit in the "0" state

$Q_1$   $|0\rangle$



## Quantum State: Computation Basis (Bars)

Shots 4096

Show Qsphere

Download CSV



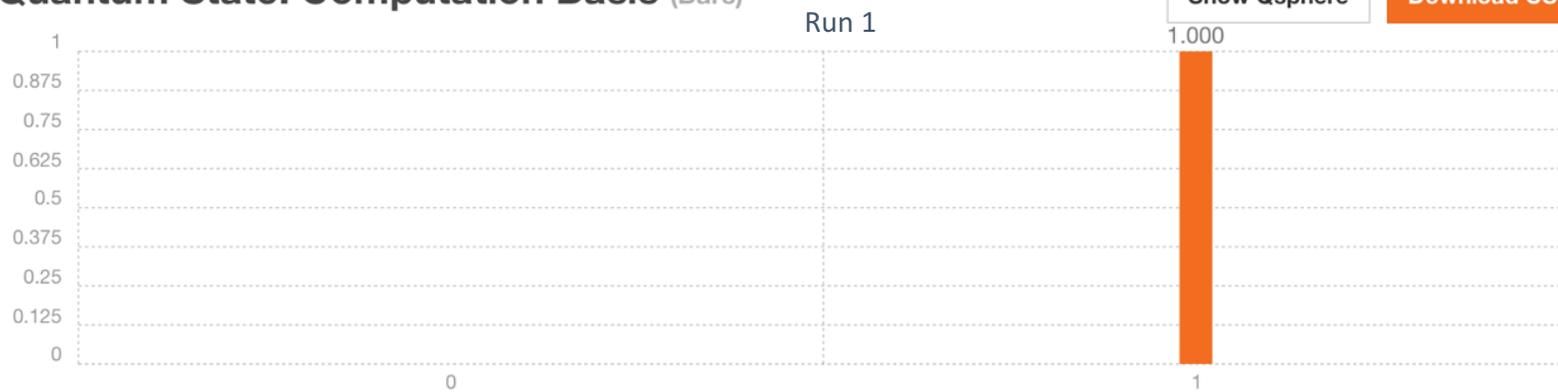
# Single qubit states



Exp 2. Preparing the qubit in the "1" state



Quantum State: Computation Basis (Bars)



# Single qubit states



Exp 2. Preparing the qubit in the "1" state



Quantum State: Computation Basis (Bars)

Run 2

Show Qsphere

Download CSV



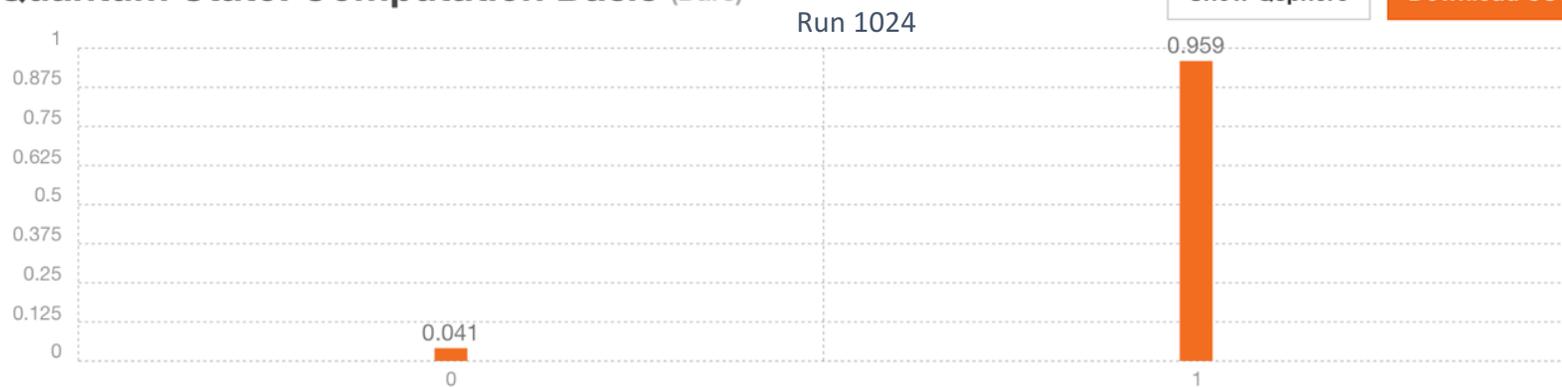
# Single qubit states



Exp 2. Preparing the qubit in the "1" state



Quantum State: Computation Basis (Bars)



Show Qsphere

Download CSV

# Single qubit states



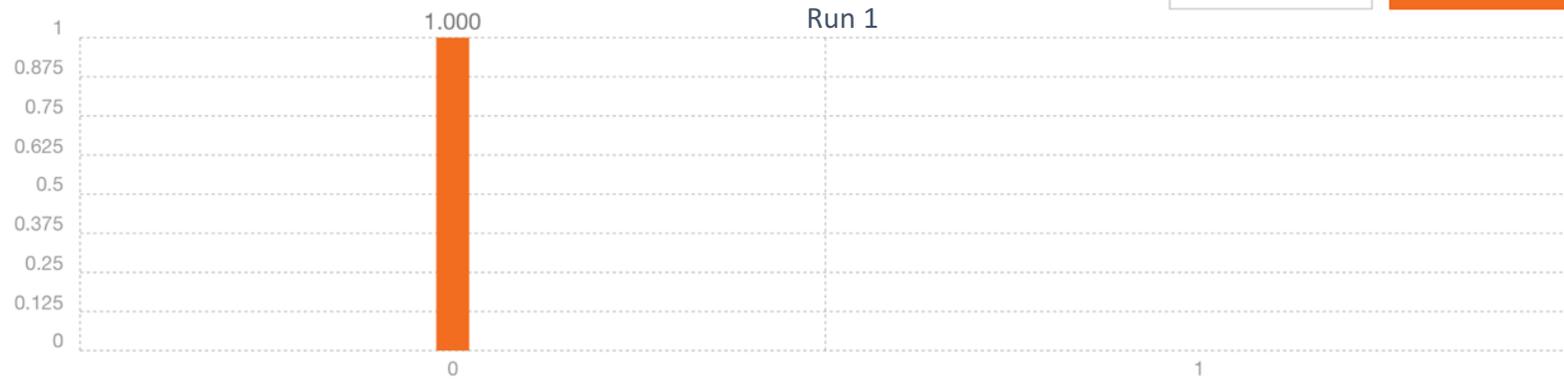
Exp 3. Preparing the qubit in the “0+1” state



Quantum State: Computation Basis (Bars)

Show Qsphere

Download CSV



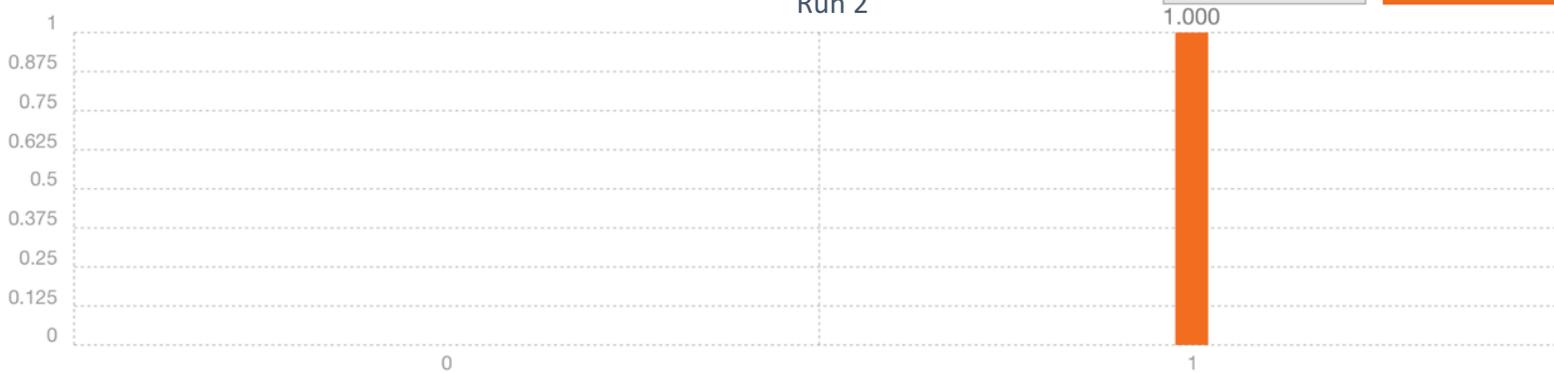
# Single qubit states



Exp 3. Preparing the qubit in the “0+1” state



Quantum State: Computation Basis (Bars)



# Single qubit states



Exp 3. Preparing the qubit in the “0+1” state



Quantum State: Computation Basis (Bars)

Runs 1024

Show Qsphere

Download CSV



# Single qubit states



Exp 4. Preparing the qubit in the “0+1” state and applying twice



Quantum State: Computation Basis (Bars)

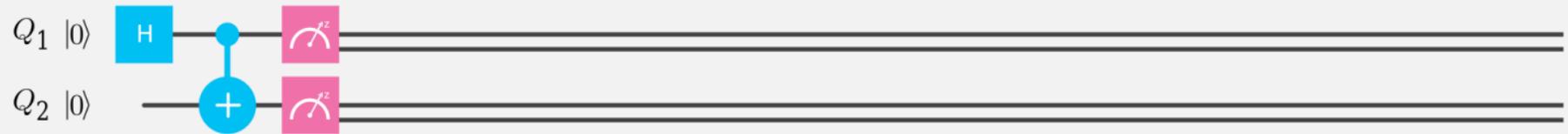
Runs 1024

Show Qsphere

Download CSV



# Entanglement

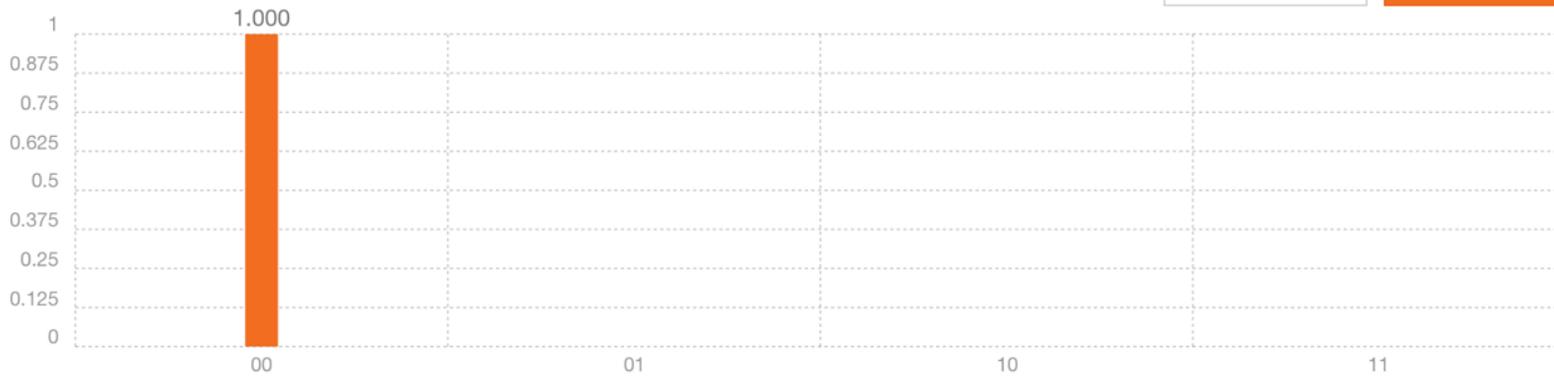


Quantum State: Computation Basis (Bars)

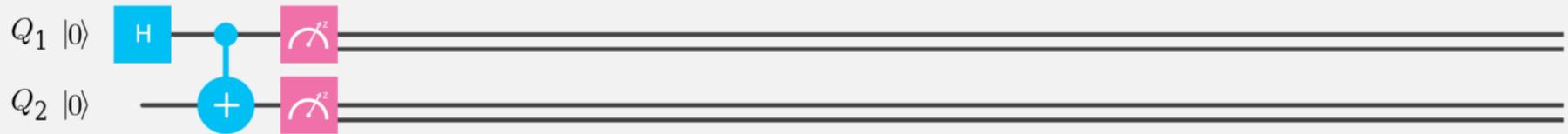
Runs 1

Show Qsphere

Download CSV



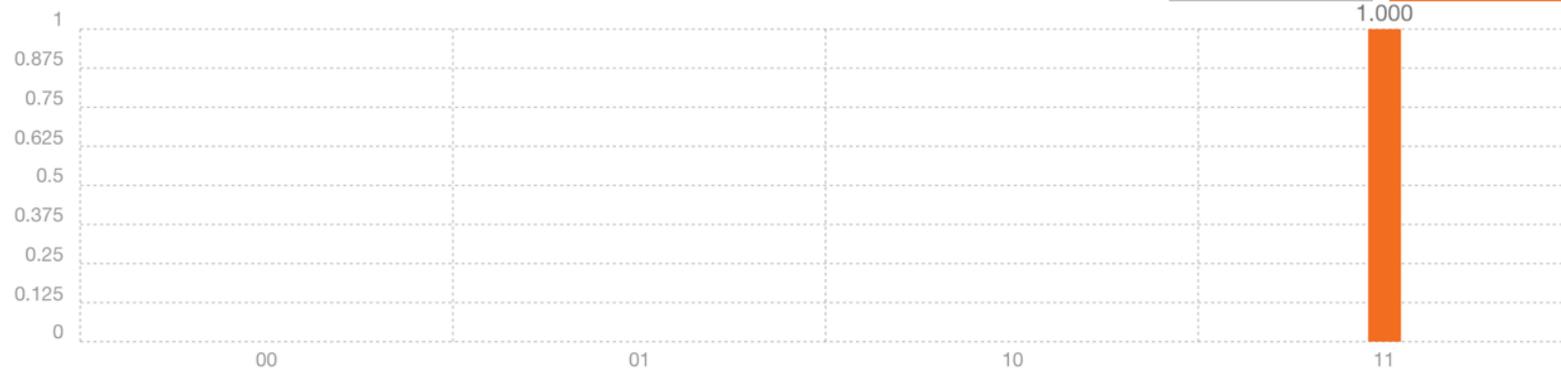
# Entanglement



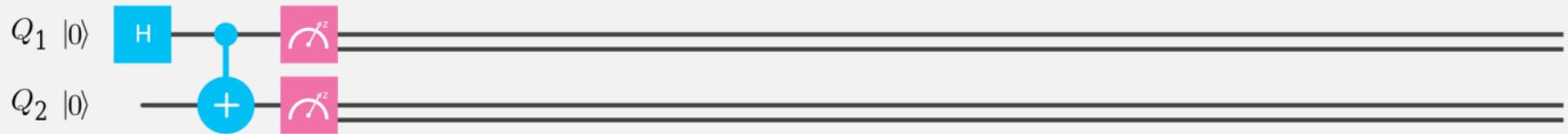
Quantum State: Computation Basis (Bars)

Runs 2

Show Qsphere [Download CSV](#)



# Entanglement

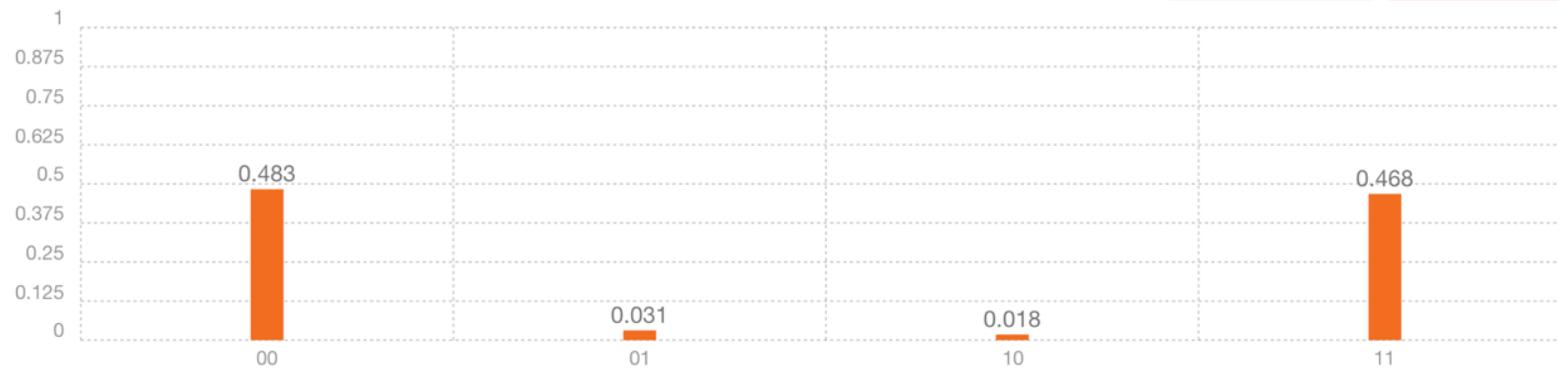


Quantum State: Computation Basis (Bars)

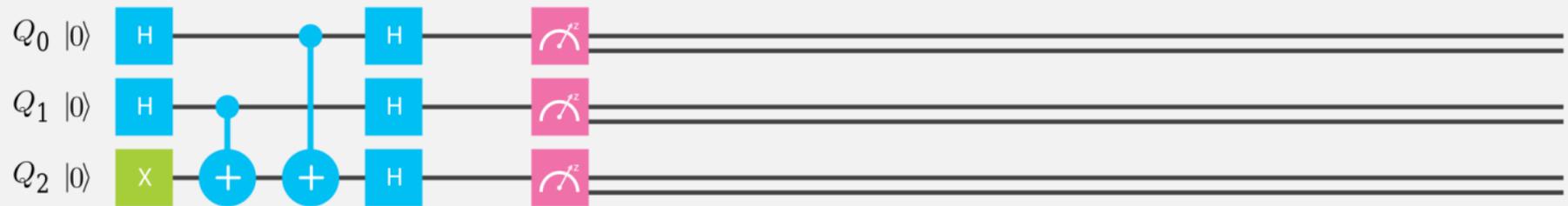
Runs 4096

Show Qsphere

Download CSV



# Entanglement

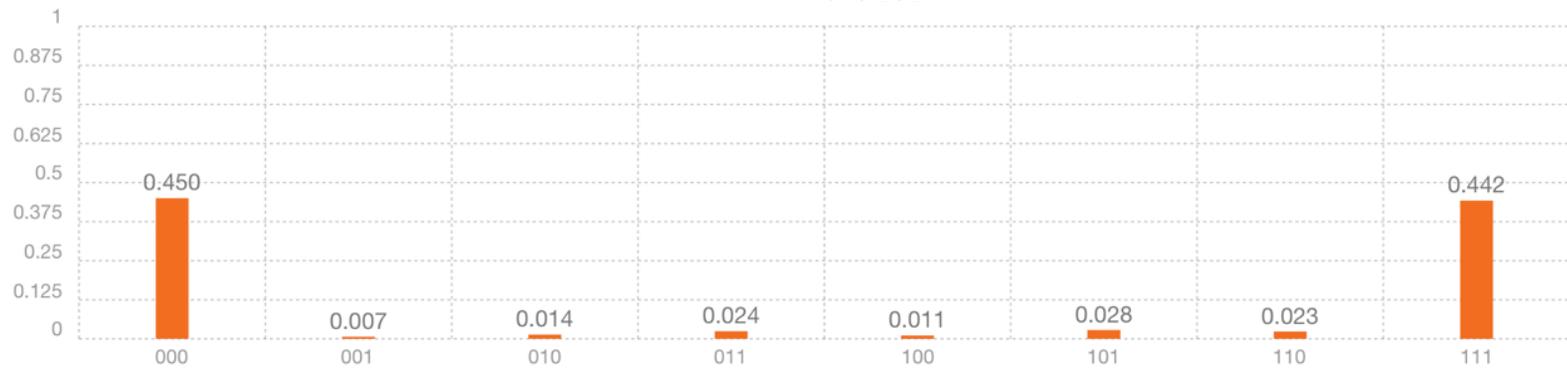


Quantum State: Computation Basis (Bars)

Runs 1024

Show Qsphere

Download CSV



https://github.com/IBM/qiskit-sdk-py/blob/master/tutorial/index.ipynb



GitHub navigation bar: Features, Business, Explore, Marketplace, Pricing, This repository, Search, Sign in or Sign up

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Branch: master | qiskit-sdk-py / tutorial / index.ipynb | Find file | Copy path

jaygambetta fixing links. 236f52e on May 22

1 contributor

150 lines (149 sloc) | 5.54 KB | Raw | Blame | History



### QISKit (Quantum Information Software Kit)

The latest version of this notebook is available on <https://github.com/IBM/qiskit-sdk-py/tree/master/scripts>.

For more information about how to use the IBM Q experience (QX), consult the [tutorials](#), or check out the [community](#).

---

#### Contributors (alphabetical)

Antonio Córcoles, Jerry Chow, Abigail Cross, Andrew Cross, Ismael Faro, Andreas Fuhrer, Jay Gambetta

In future releases, anyone who contributes to the tutorial can include their name here.

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