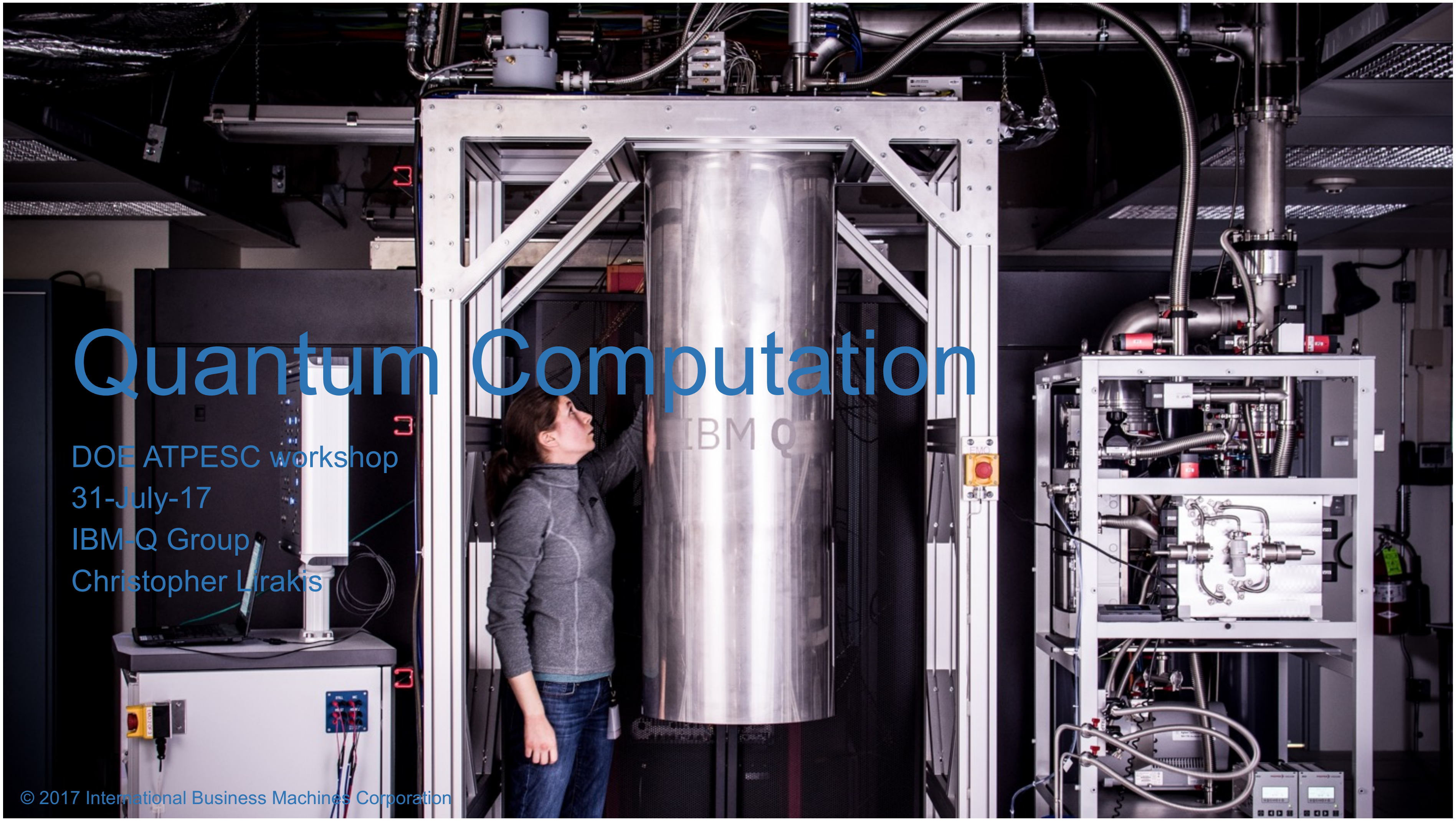


Quantum Computation

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

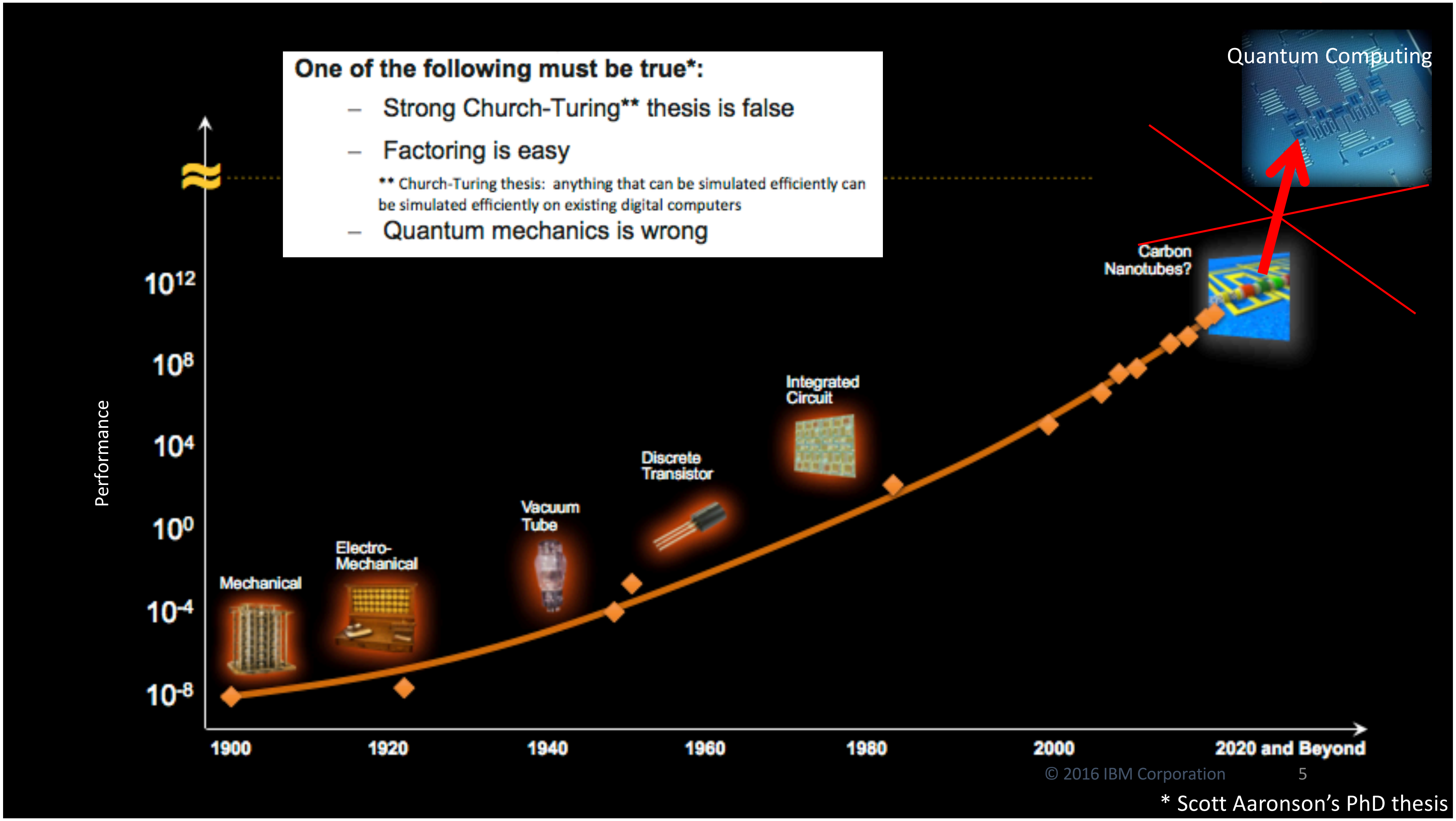
- High Level Overview – The QC promise
- Popular Modalities – Encoding of information
- IBM implementation
- Applications
- IBM Quantum Experience
- Hands on Demo

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

High Level Overview

The promise of quantum computing

ATPESC 2017


One of the following must be true*:
– Strong Church-Turing** thesis is false
– Factoring is easy
** Church-Turing thesis: anything that can be simulated efficiently can be simulated efficiently on existing digital computers
– Quantum mechanics is wrong
Quantum Computing
Carbon Nanotubes?
Integrated Circuit
Discrete Transistor
Vacuum Tube
Electro-Mechanical
Mechanical
Performance
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
1900
1920
1940
1960
1980
2000
2020 and Beyond
© 2016 IBM Corporation 5
* Scott Aaronson's PhD thesis

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"*

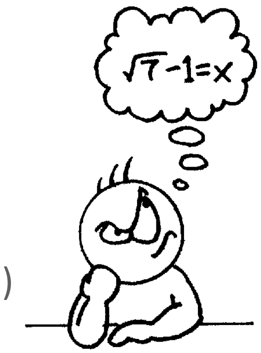
  Feynman 1982

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

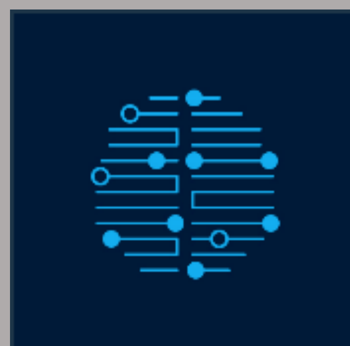
There are problems that are believed to be hard (never) for classical computers to solve

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.

Cryptography

Medicine & Materials



Machine Learning

Searching Big Data

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!

Classical Computer

n-bit intermediate state e.g. 0100

n-bit input

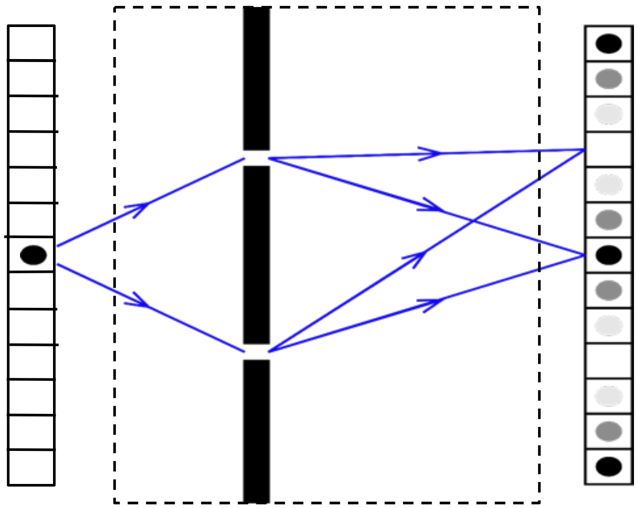
n-bit output

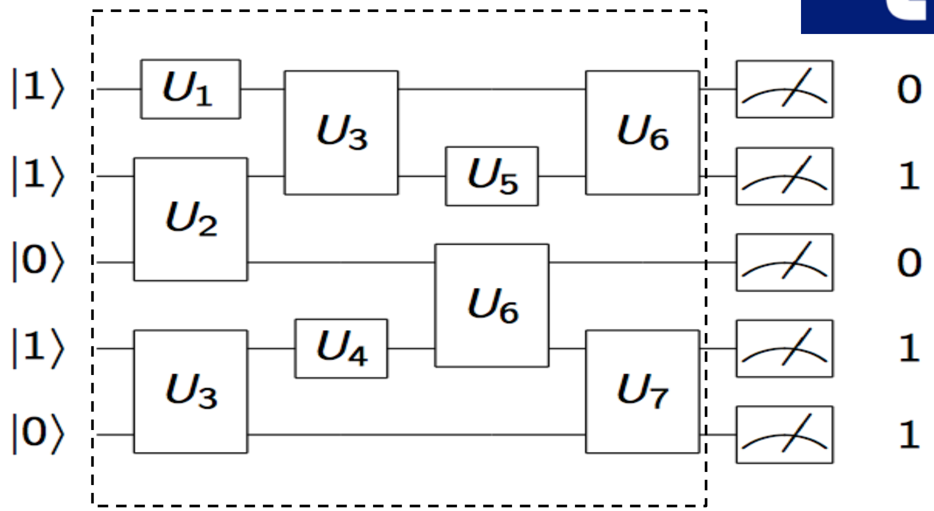
Quantum Computer

Because of the **superposition principle** and the possibility of **entanglement**, the intermediate state of an n-qubit quantum computer state requires 2^n complex numbers to describe, giving a lot more room for maneuvering

$a|0000\rangle+b|0001\rangle+c|0010\rangle+d|0011\rangle$
$+\ldots$

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

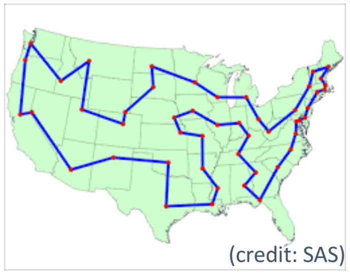
Solving computational problems requires physical *resources* (time, memory, and space).

1+1=2

"easy" problems
(polynomial ⇒ efficient)

- multiplying numbers
- word processing

"hard" problems
(exponential ⇒ 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

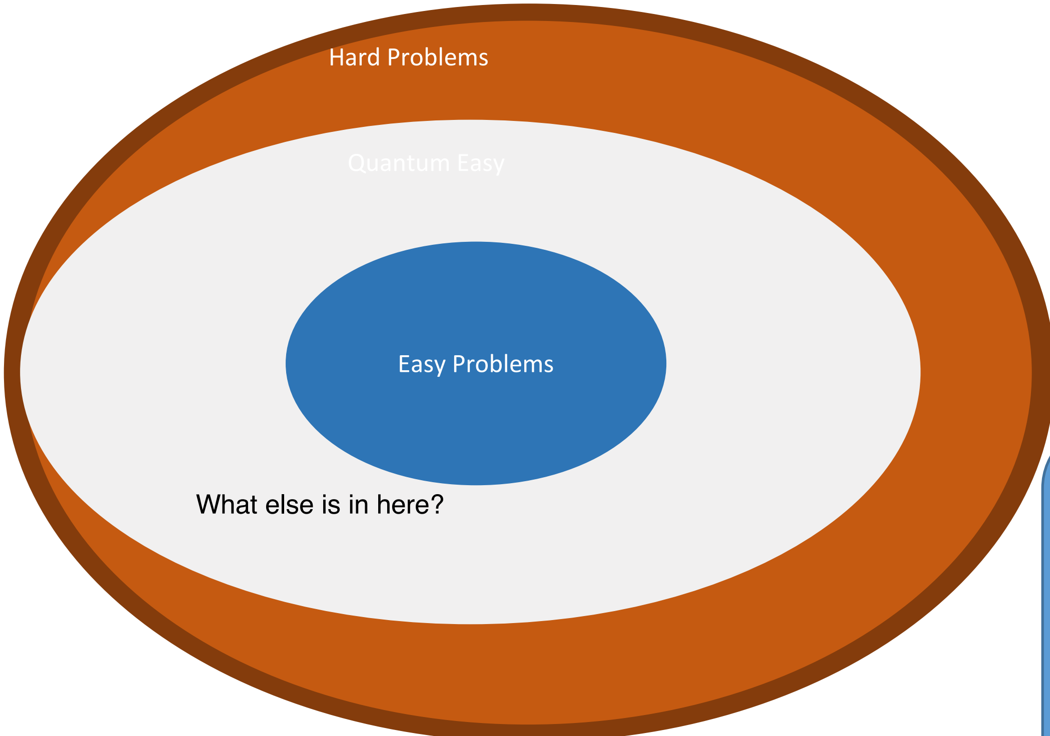
Quantum computing

Move After 7

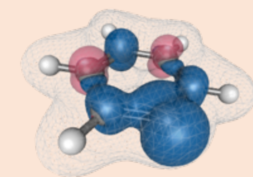
"easy" problems (polynomial ⇒ efficient)

"hard" problems (exponential ⇒ intractable)

Hardest (NP-Complete)



Molecular Dynamics, Drug Design & Materials



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

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_2	Sodium diatomic	rNaNa	3.079	2.379	-0.700

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
.	.
.	.
.	.

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

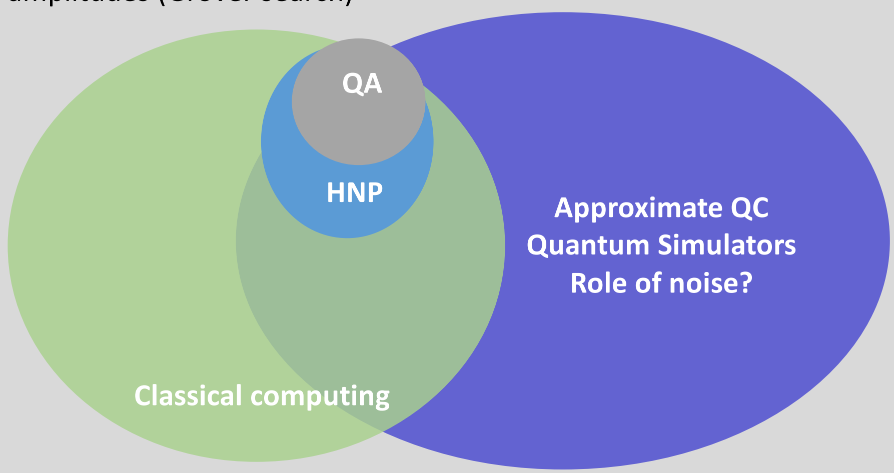
"The Quantum Zoo": http://math.nist.gov/quantum/zoo/

Types of Quantum computing

Move After 7

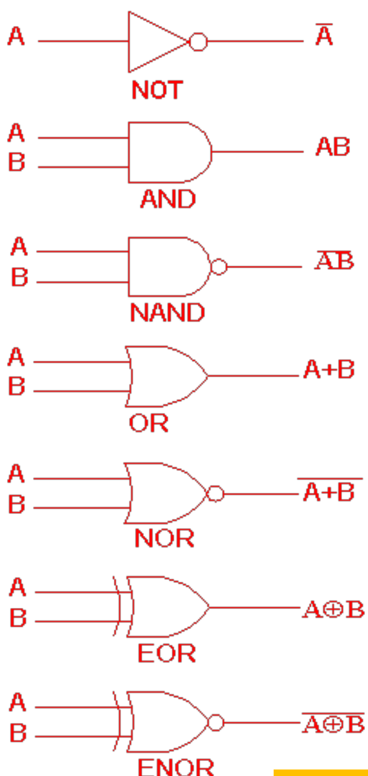
Fault Tolerant Quantum Computing:

- 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	Ā
0	1
1	0

2 Input AND gate

A	B	A.B
0	0	0
0	1	0
1	0	0
1	1	1

2 Input NAND gate

A	B	$\overline{A.B}$
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

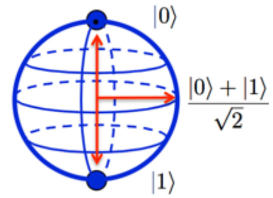
A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

2 Input EXOR gate

A	B	A⊕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**

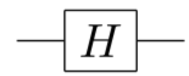
$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

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

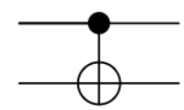
$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

2-Qubit

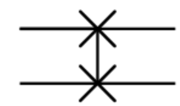
$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$



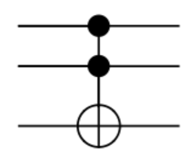
$$\text{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



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



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



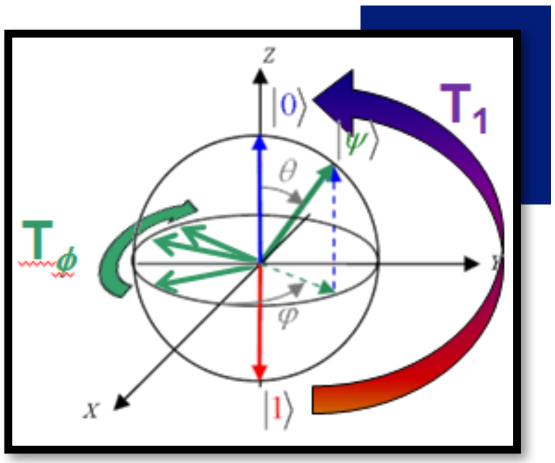
 16

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_ϕ: dephasing (randomization of ϕ)
    - 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

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

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

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

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

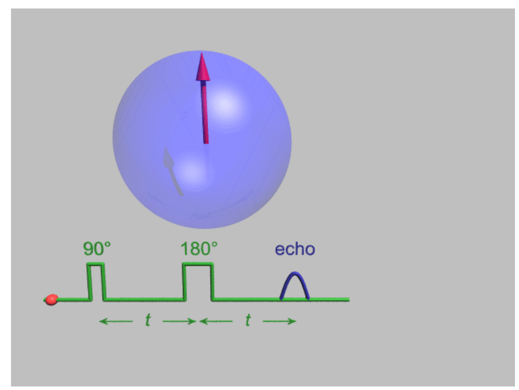
$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Dechoherence
T1 – spin flip
T2 – Dephasing -
Important to have T_{op}/T2 as large as possible

Longer Coherence

- Superconducting
- Quantum Dots
- Spin defects
- Ion Traps

Shorter Operations



Pulses to manipulate single qubit on Bloch Sphere

Implementation

Experimental Implementations

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

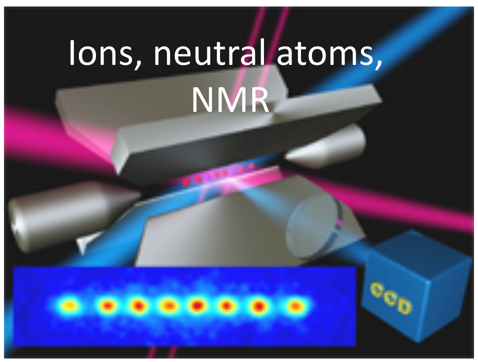


Image source: Rainer Blatt
http://www.quantumoptics.at/en/research.html

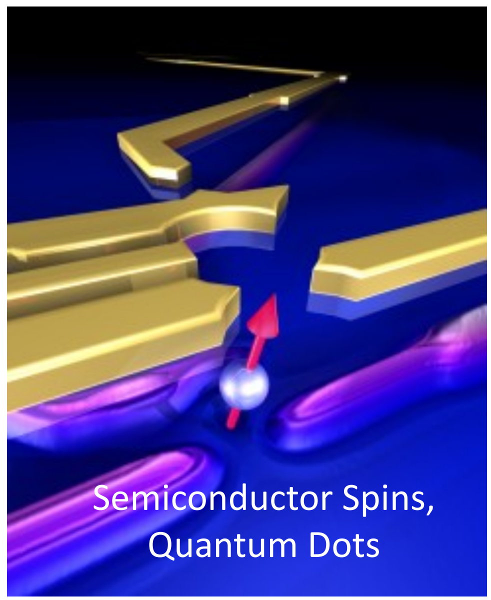
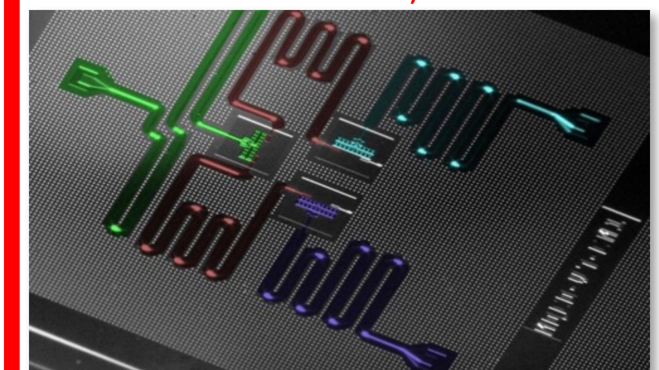
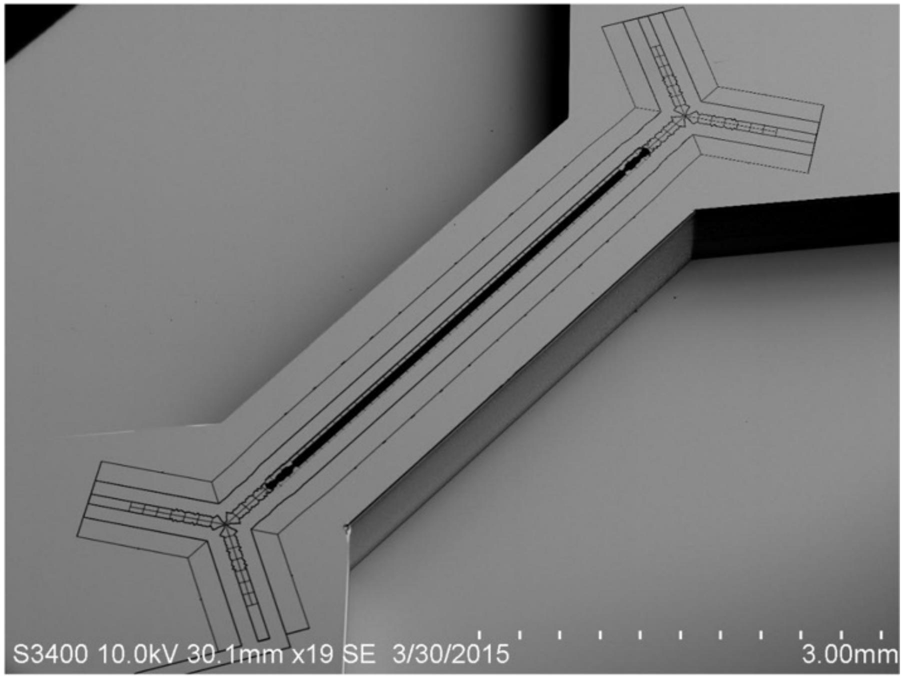


Image source: Vandersypen lab
(Illustration by Tremani)

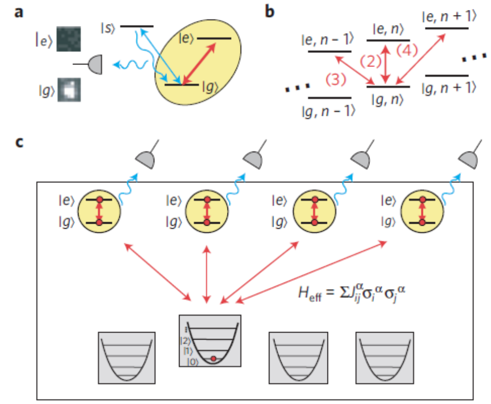
Superconducting Circuits (Josephson Junctions)



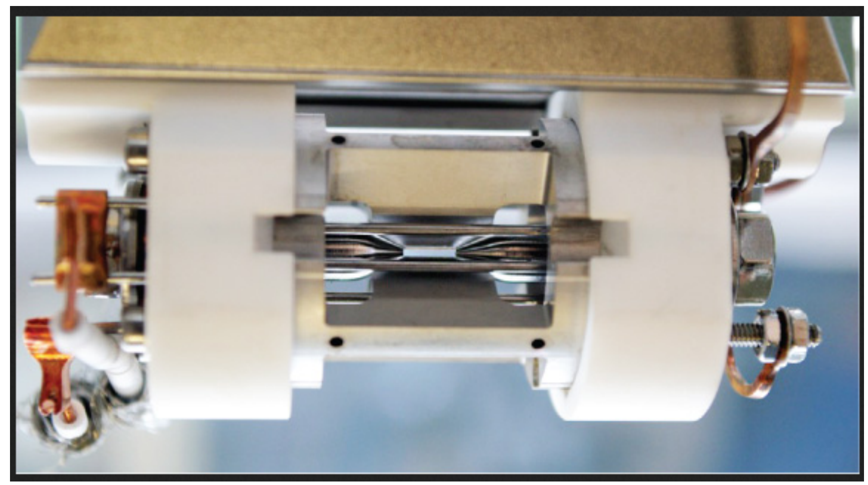
Ion Traps



HOAT 2.0 – Sandia National Laboratories



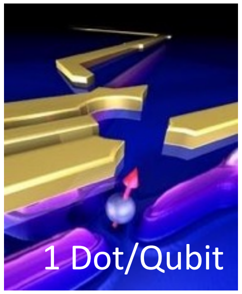
R. Blatt & C. F. Roos, Nature Physics, 8, 277 (2012)



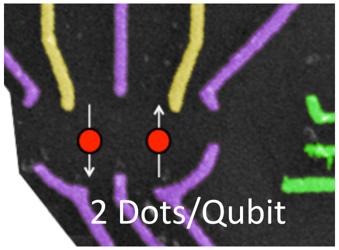
Monz, T., et al, *Science*, *351*(6277), 1068–1070.

And more: N. Linke et al., arXiv:1611.06946 (2016)

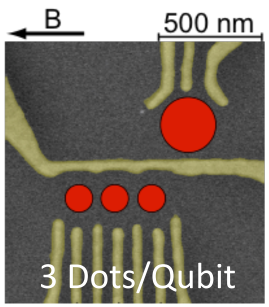
Quantum Dots



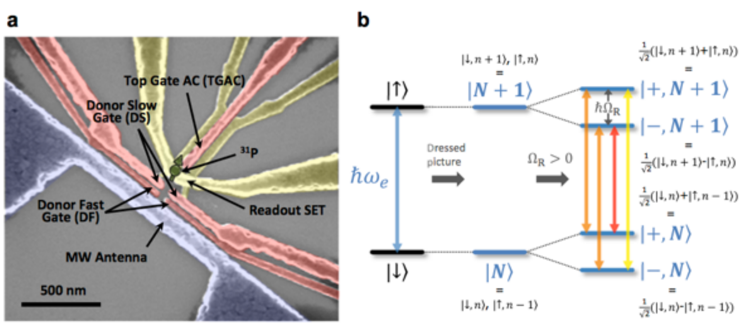
Loss and DiVincenzo, PRA 1998
Image courtesy Lieven Vandersypen



Johnson, Nature 2005
Petta, Science 2005



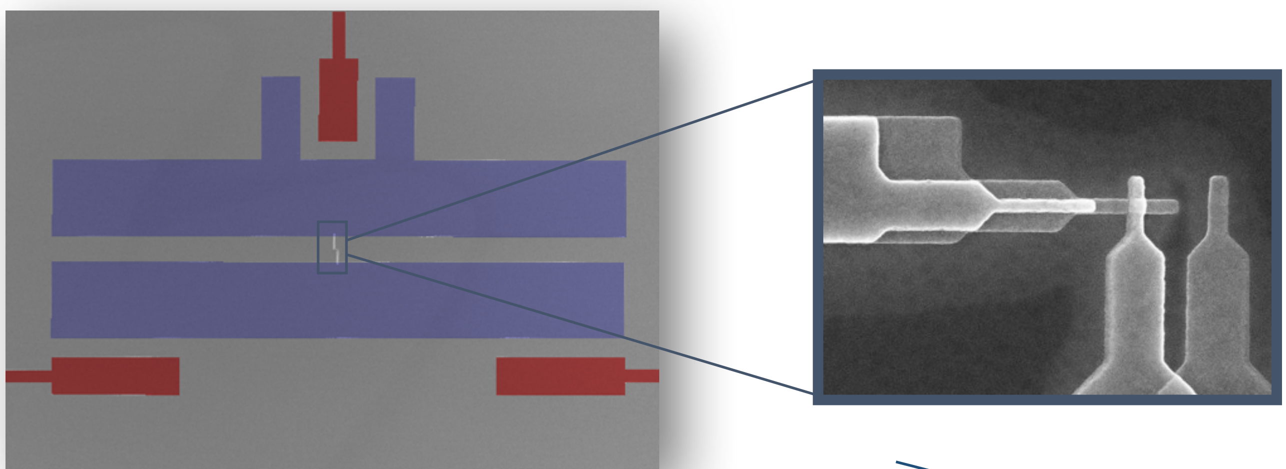
Laird et. al, PRB 2010
Image courtesy Jim Medford, Marcus Lab



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

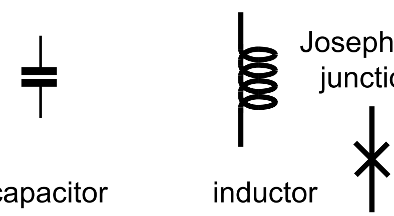
J. Nichol et al., NPJ Quant. Inf., n3:3, (2017)
P. Cerfontaine et al., arXiv:1606.01897 (2016)

Single-junction transmon qubits

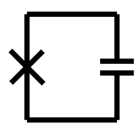


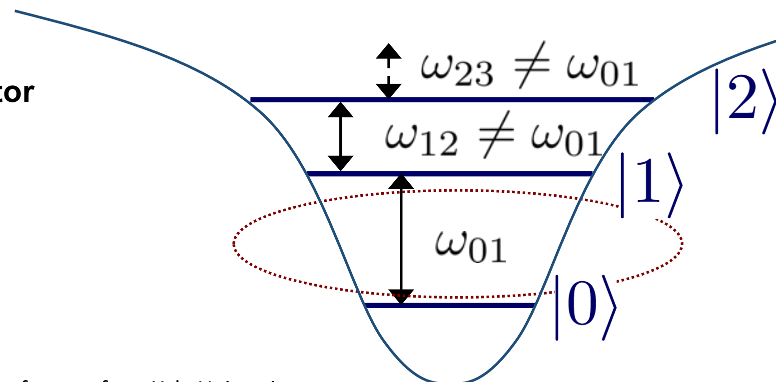
Josephson junction is a non-linear inductor

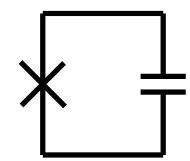
Circuit elements



'anharmonic' oscillator



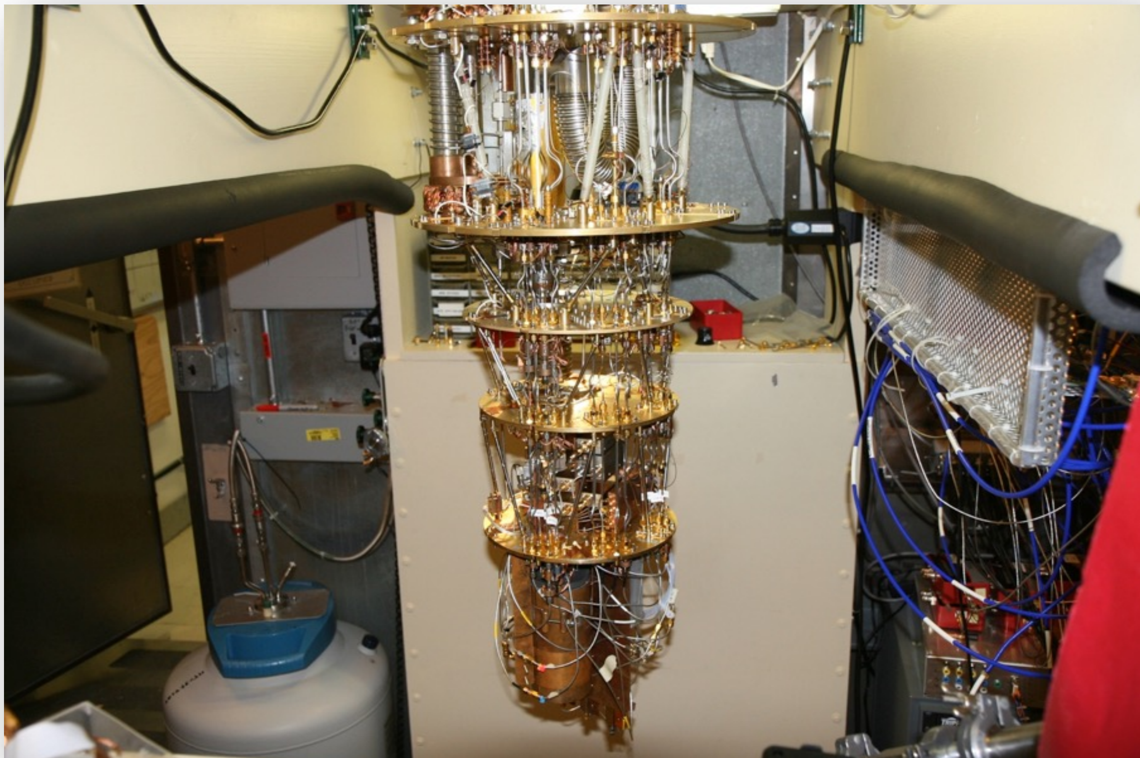


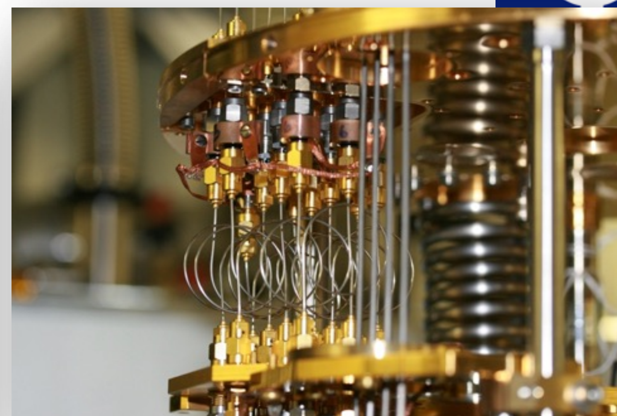


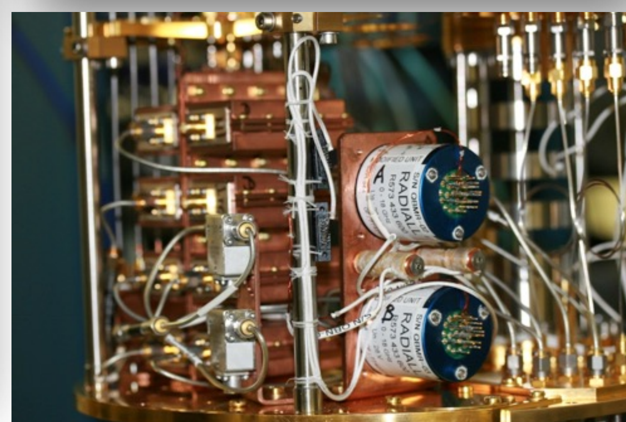
Transmon pioneered by Schoelkopf group, from Yale University
Koch et. al. PRA **76**, 04319 (2007)

Anharmonicity: $\omega_{12} - \omega_{01}$

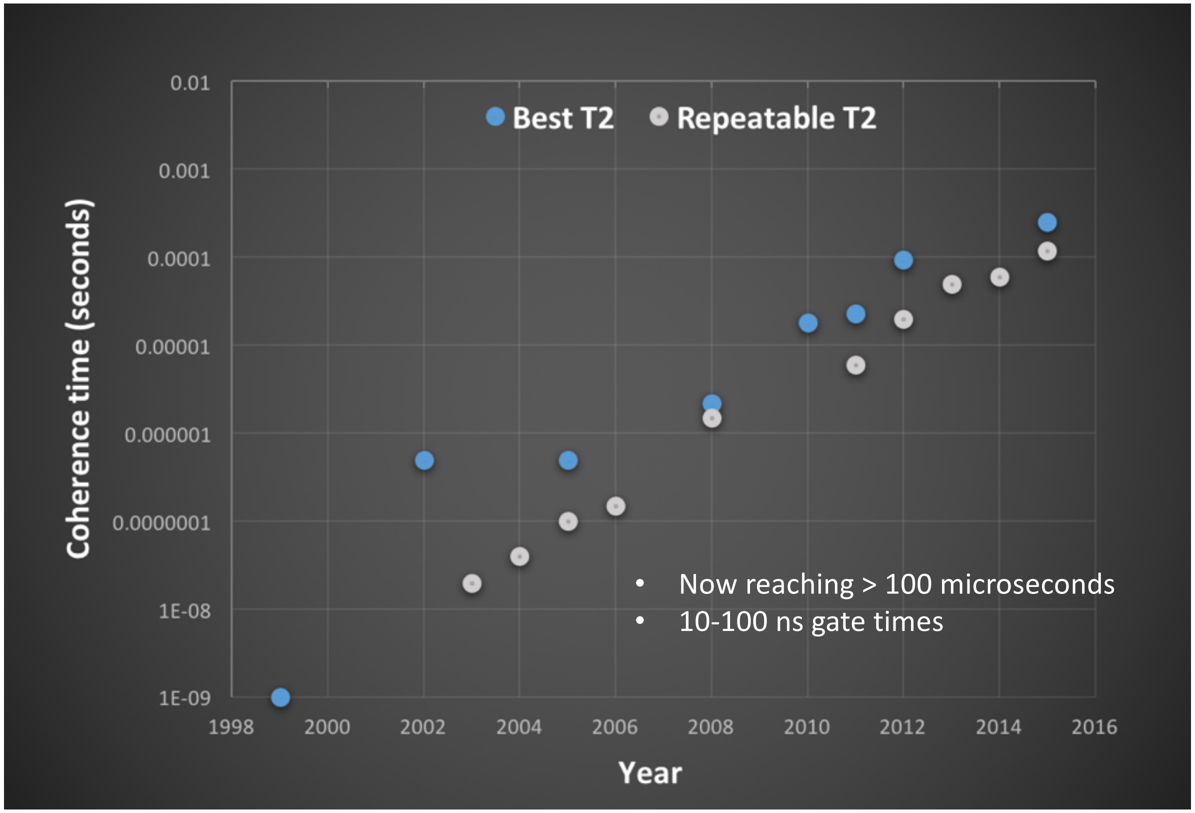
Inside one of the dilution refrigerators







Coherence times of superconducting qubits

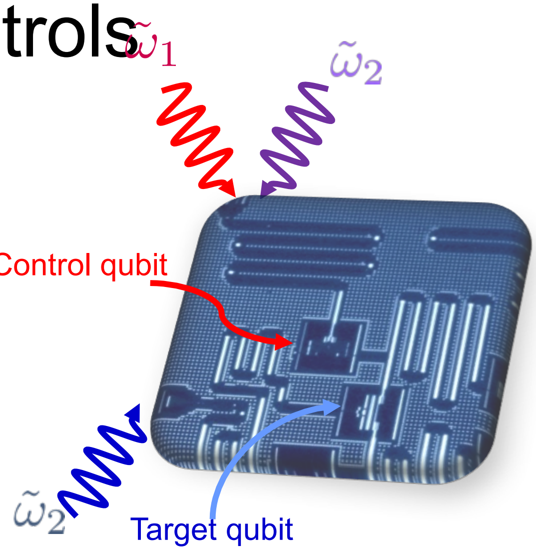


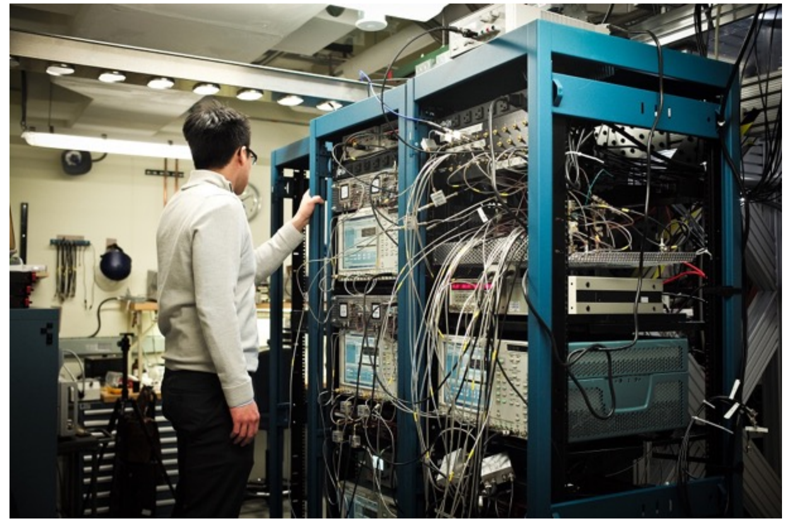
- Developments to extend coherence times
  - Materials e.g. [2]
  - Design and geometries e.g. [3]
  - 3D transmon [4]
  - IR Shielding [5,6],
  - Cold normal metal cavities and cold qubits [7]
  - High Q cavities [8]
  - Titanium Nitride (collaboration with David Pappas @ NIST Boulder) [9] …

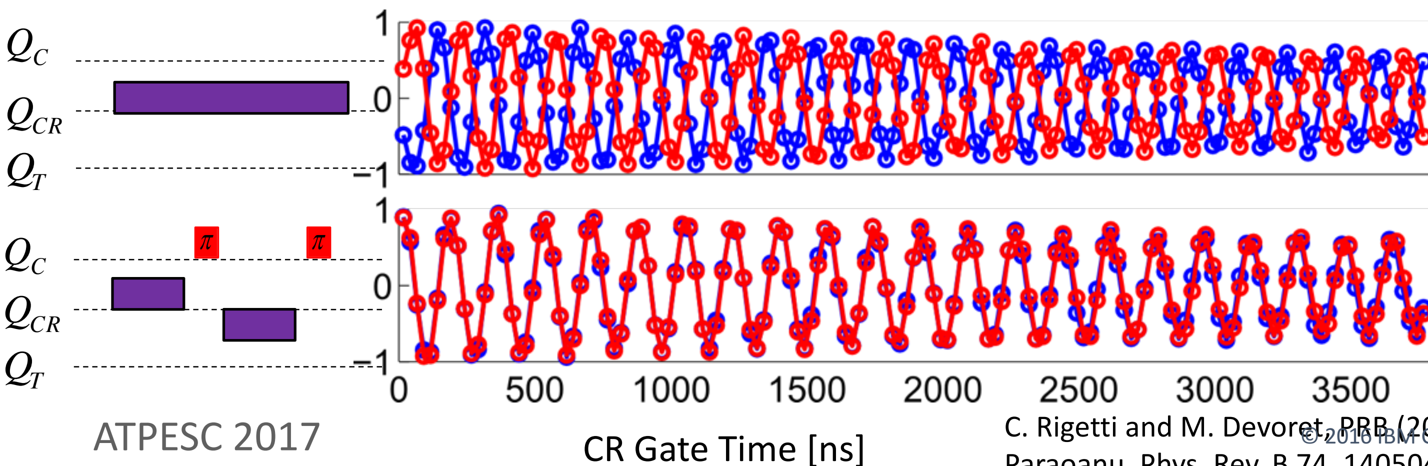
- Remarkable progress over the past decade

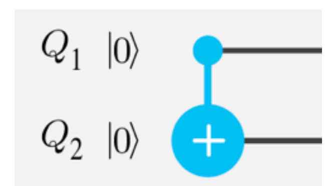
[2] J. Martinis *et al.,* PRL **95** 210503 (2005)
[3] K. Geerlings *et al*., APL 192601 (2012)
[4] H. Paik *et al*., PRL **107**, 240501 (2011)
[5] R. Barends *et al*., APL **99**, 113507 (2011)
[6] A. Corcoles *et al*., APL **99**, 181906 (2011)
[7] C. Rigetti *et al*., PRB **86**, 100506 (2012)
[8] 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 ~ 99.9 – 99.95%

- Two Qubit Gates
  - Qubit tuning, or …
  - Microwave approach
  - F ~ 95 – 99.5%
- Decoherence time
  - T1 ~ T2 ~ 40-100μs
- 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)
…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

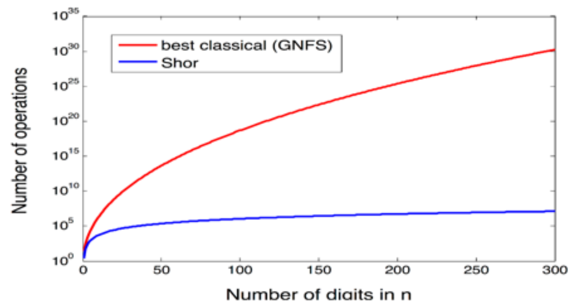
937 x 947 = N (easy)
887339 = p x q (harder)

<u>Exponential speed-up:</u>
A task taking 2^{100} seconds (**10^{25} days**) on a classical computer might take **100 seconds** on a quantum computer

<u>public key from google.com</u>

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 × 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)



Classical Record: 230 digits

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

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

- Quantum mechanics is wrong

Shor's algorithm jumpstarted the interest in quantum computing

* Scott Aaronson, PhD thesis, UC Berkeley

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

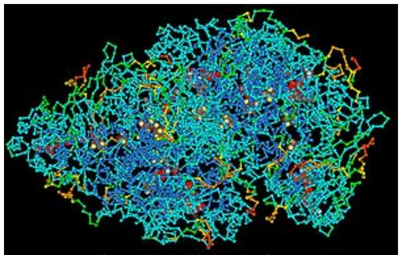
A quantum device which does not need fault tolerance, with the goal of demonstrating a useful application by interacting with a classical computing system, e.g. quantum chemistry, optimization

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

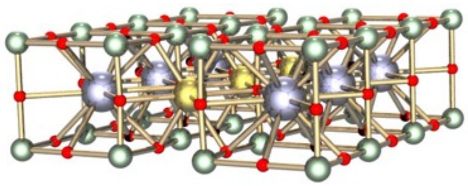


(credit: wikipedia)

Molecule simulation

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

Condensed Matter Physics

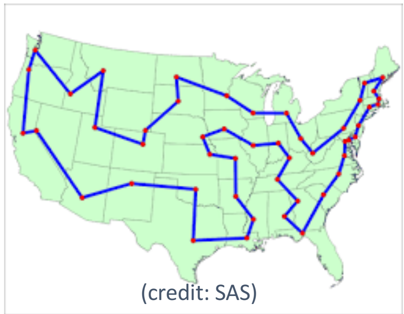


(credit: wikipedia)

High Tc materials

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

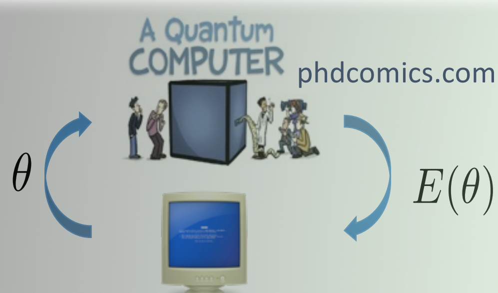
Quantum enhanced optimization



(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

"The Quantum Zoo": http://math.nist.gov/quantum/zoo/

The experiment: Short depth, device oriented quantum circuit

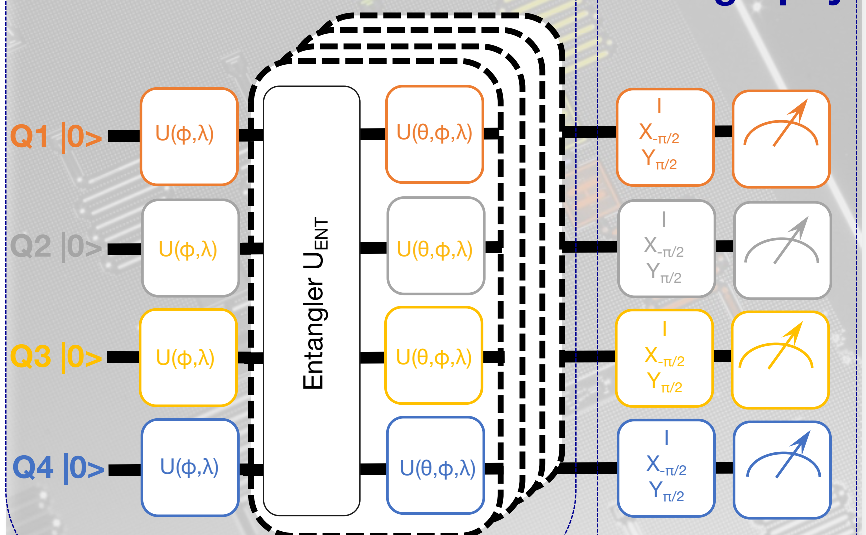
Map fermionic Hamiltonian to qubits

H=
-(0.206)IIII
-(0.002)XZXZ
+(0.028)XXXX
…..

Generate controls (θ,ϕ,λ…)

Trial state preparation

Partial state tomography



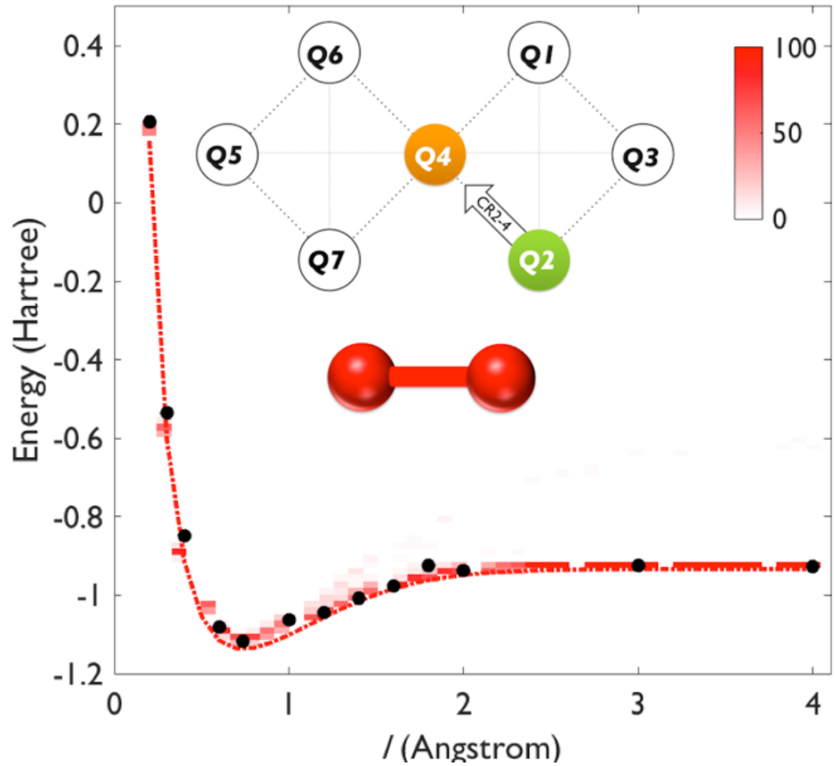
Calculate trial state energy

E(θ,ϕ,λ…)=
-0.206<IIII>
-0.002<XZXZ>
+0.028<XXXX>
…..

Optimize

The interatomic potential of H

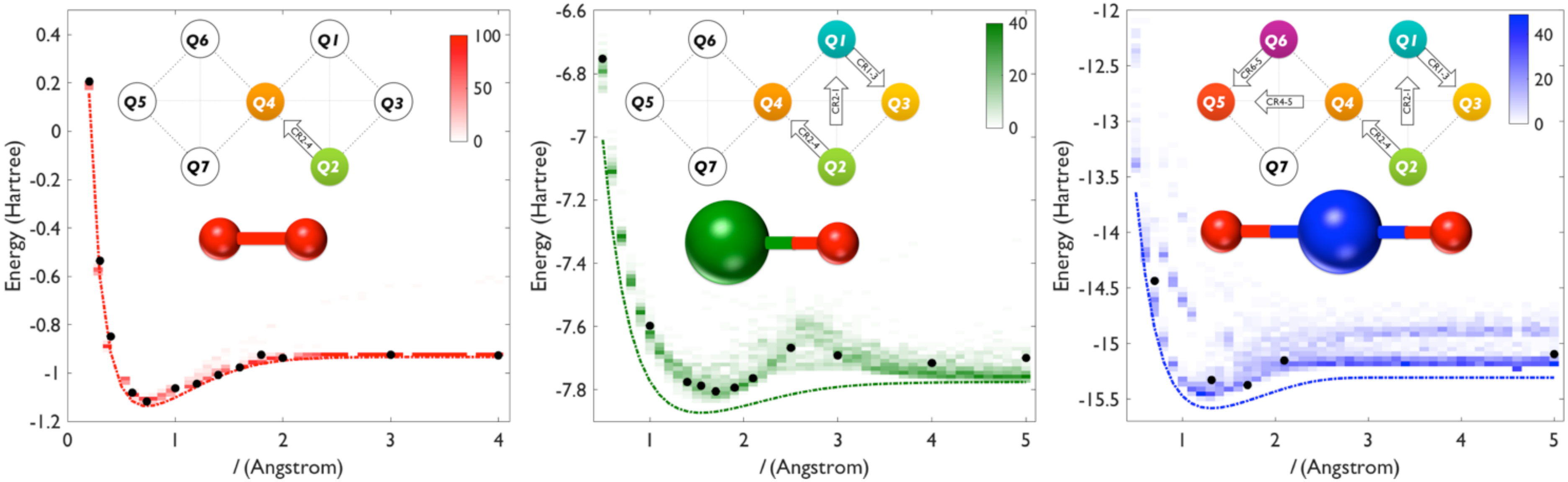
	Equilibrium Separation (0.735 A)	Dissociation Separation (4.0 A)
Exact	-1.138	-0.9348
QC	-1.116 ±0.00089	-0.9272±0.00019



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

Quantum chemistry



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

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

Quantum Volume - Metrics

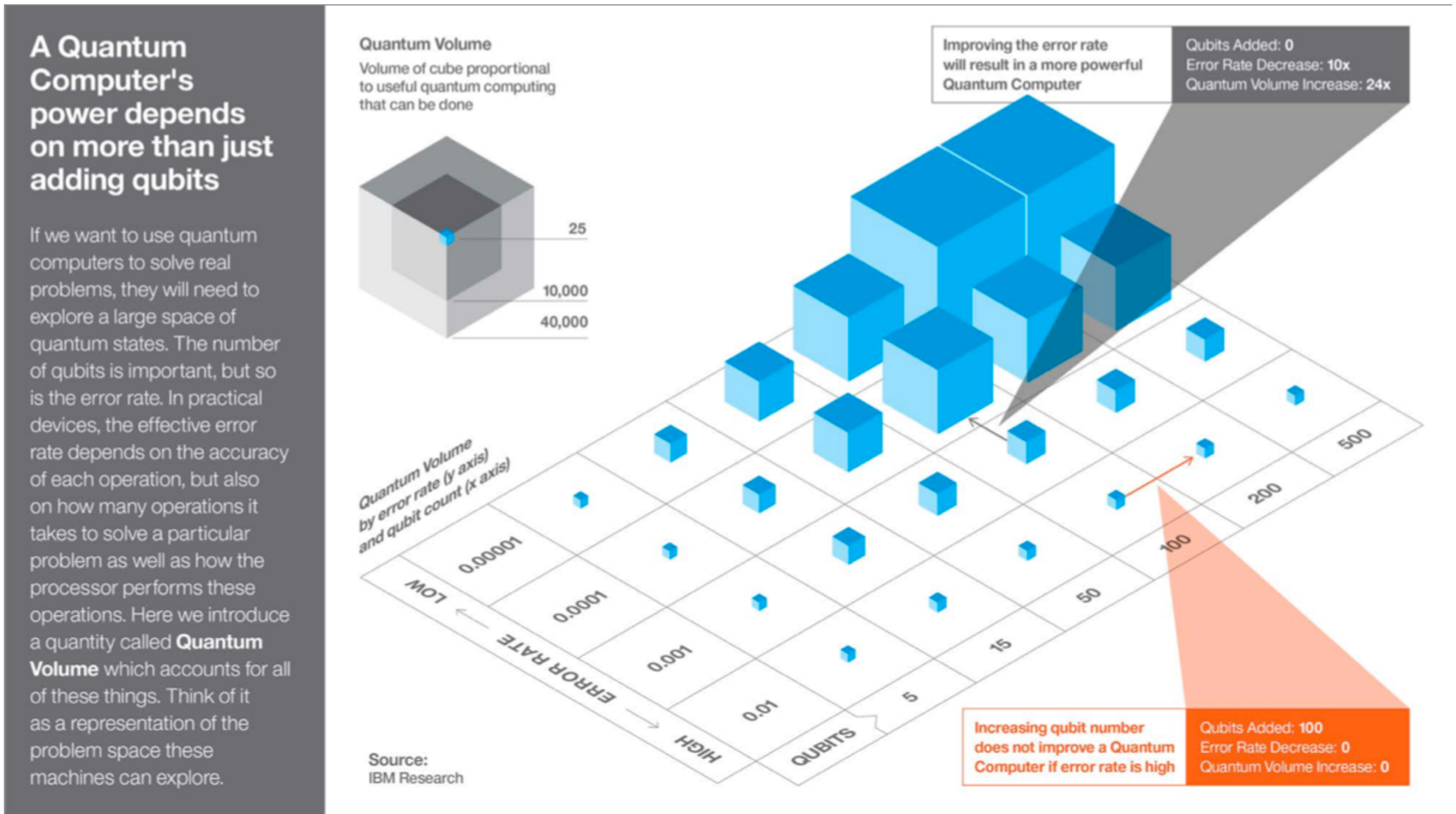
Number of qubits (more is better)

Connectivity (more is better)

Gates set (more is better)

Errors (less is better)

Quantum volume



Demonstration – IBM QX

Developing a quantum community

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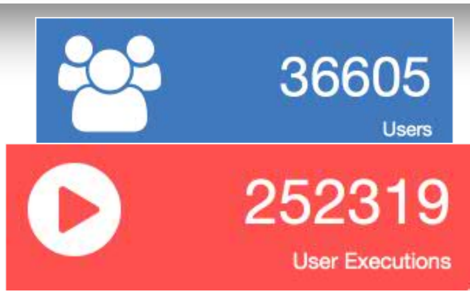
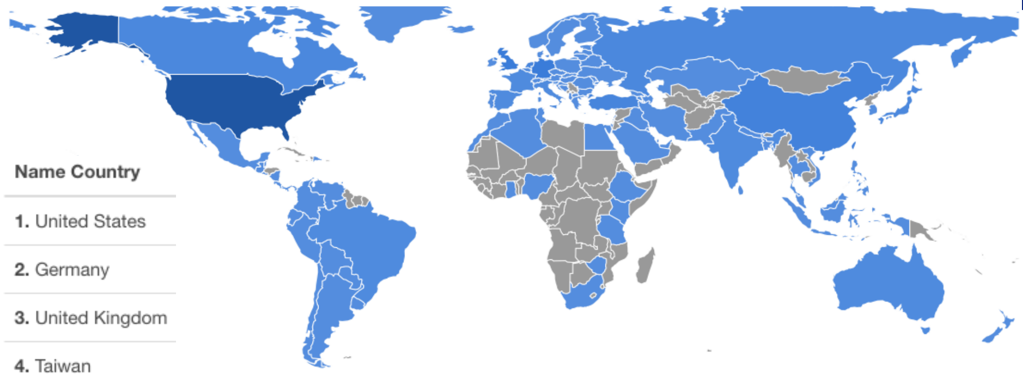
IBM Quantum Experience

Launched May 4, 2016



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

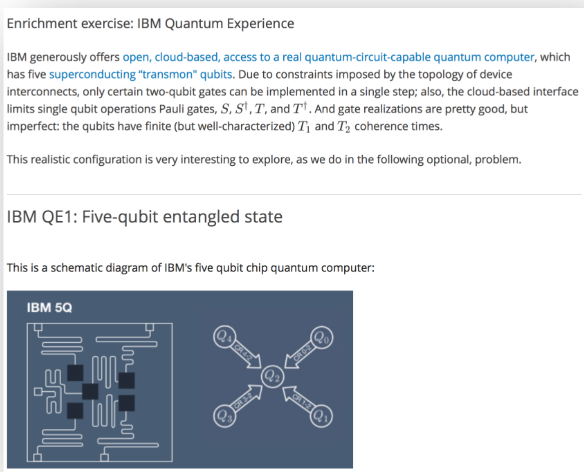


Over 121 countries have joined the Experience
Now can log-in with
Linkedin, Github, or Google accounts

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



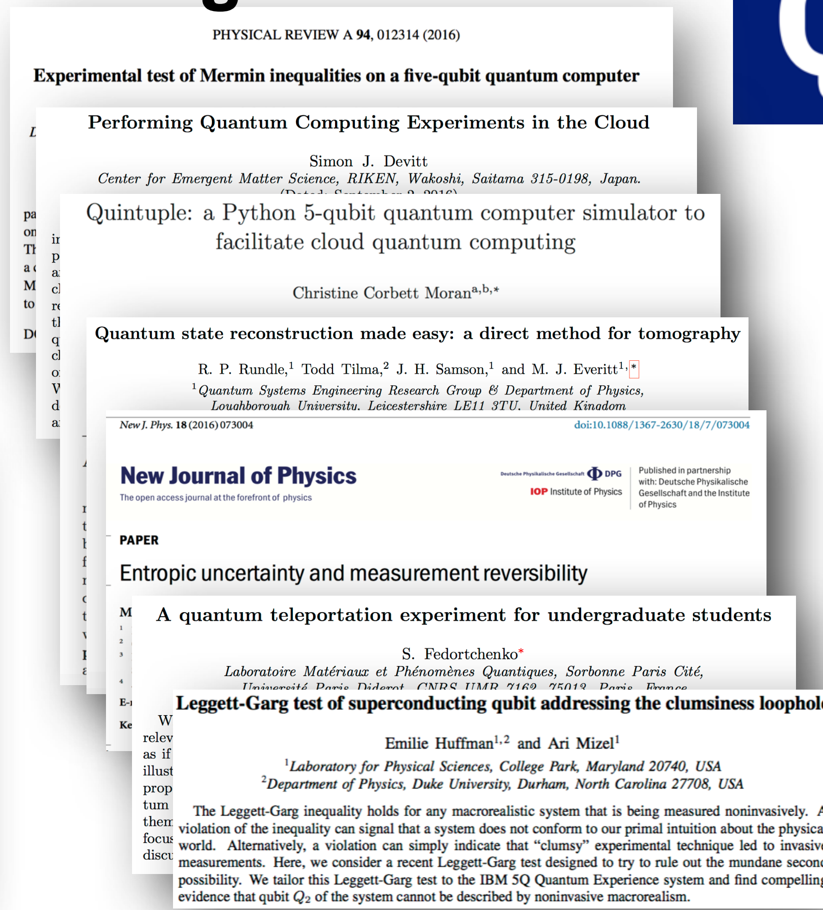
Enrichment exercise: IBM Quantum Experience

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.

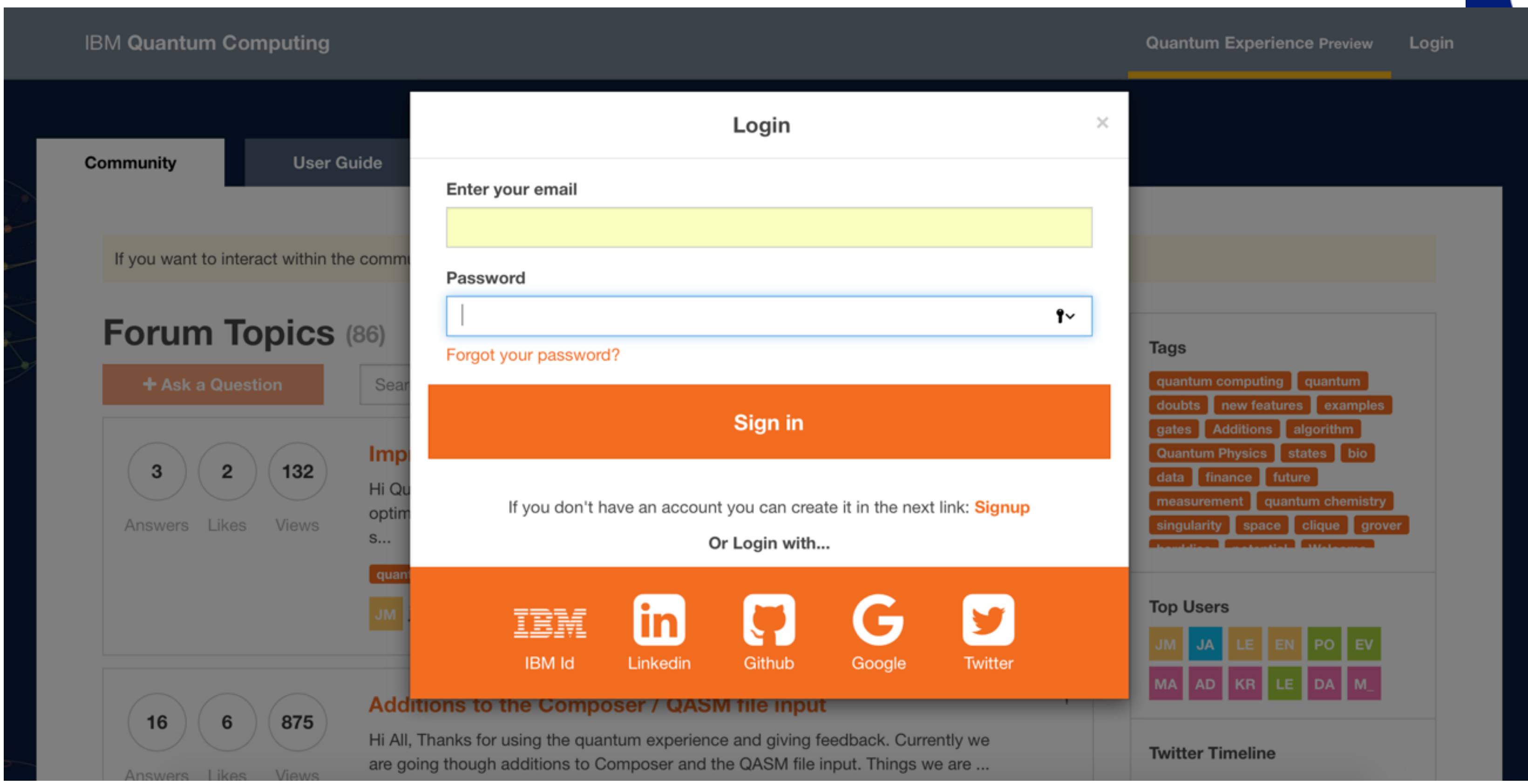
This realistic configuration is very interesting to explore, as we do in the following optional, problem.

IBM QE1: Five-qubit entangled state

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

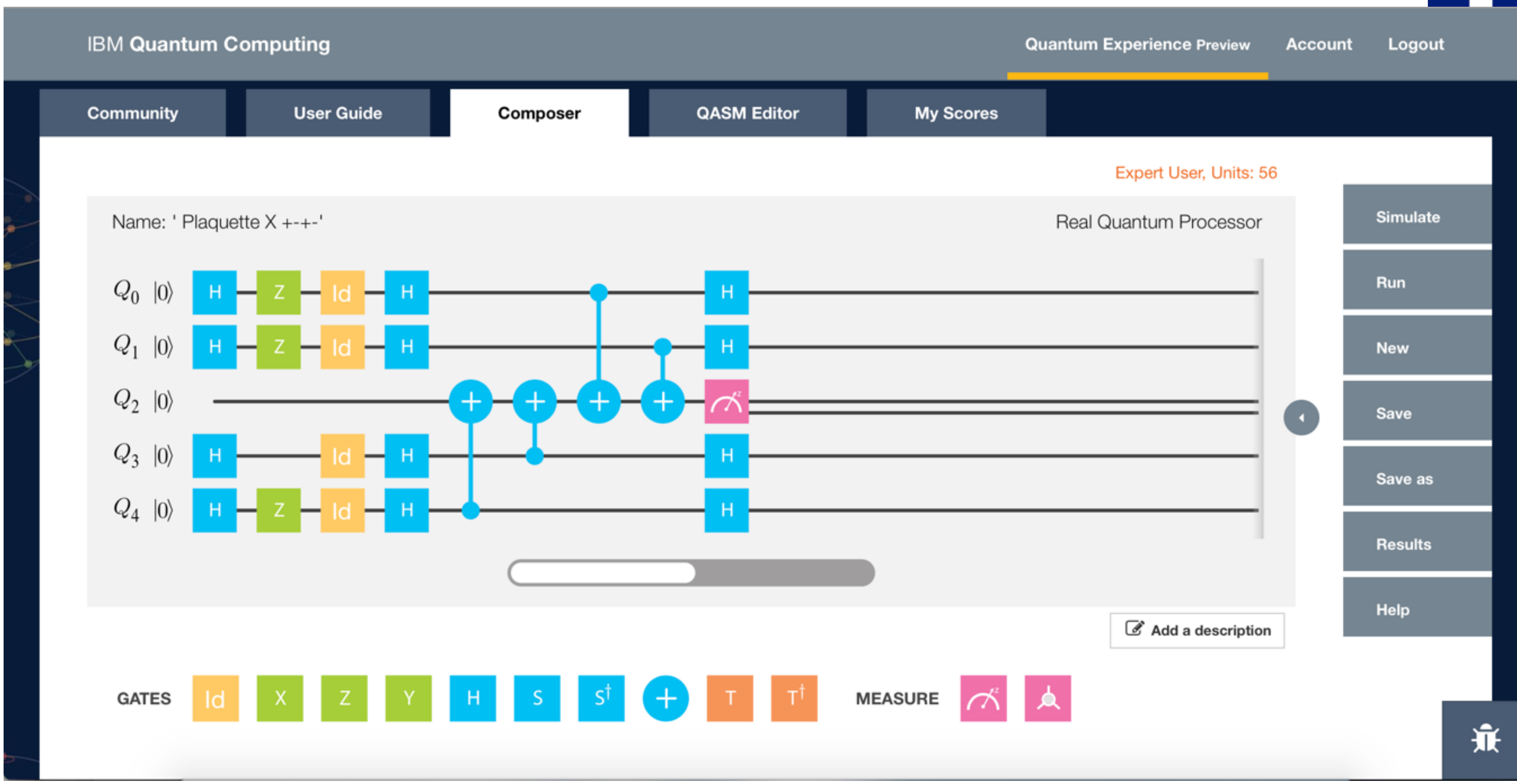


IBM Quantum Experience



www.ibm.com/quantumcomputing

IBM Quantum Experience



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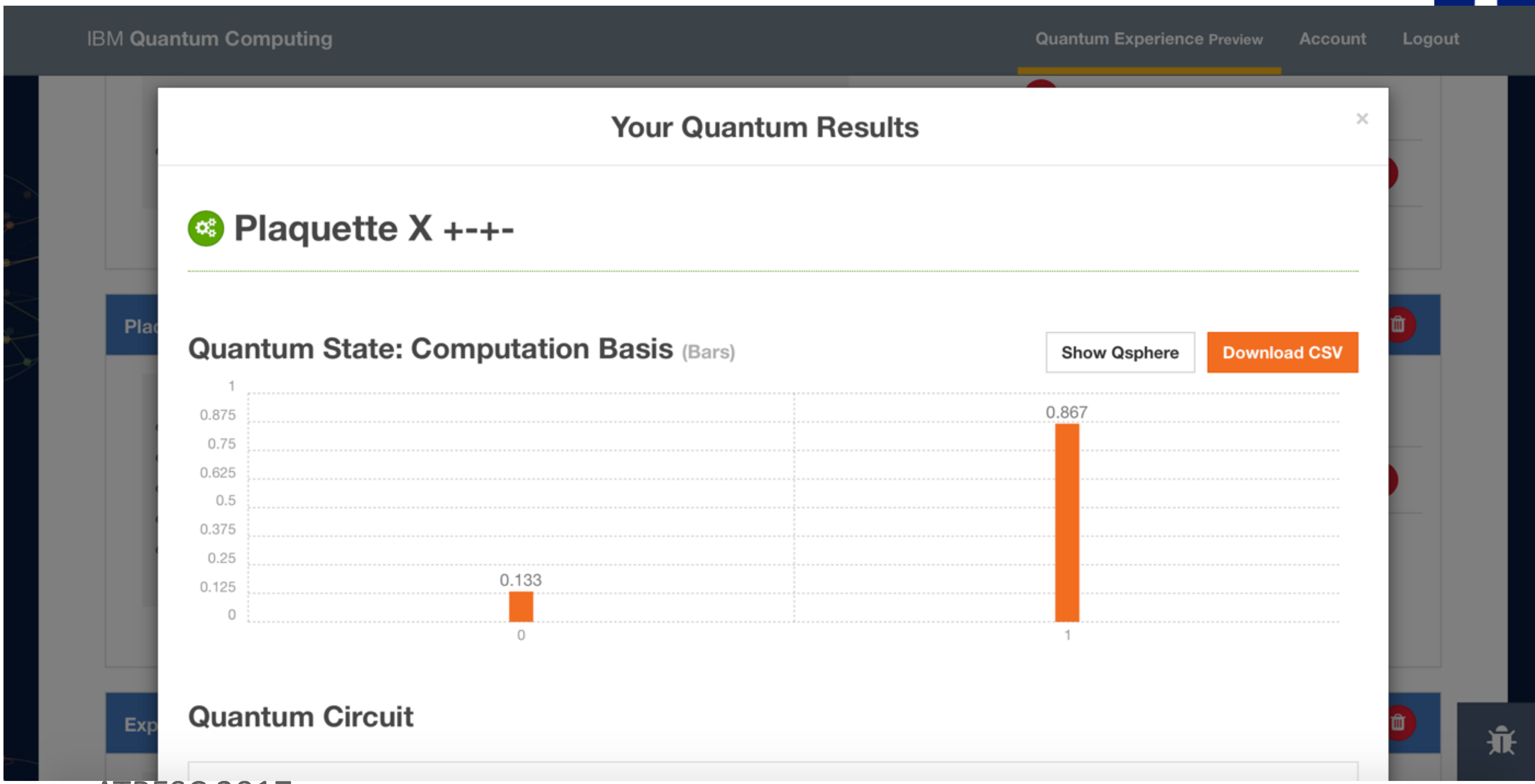
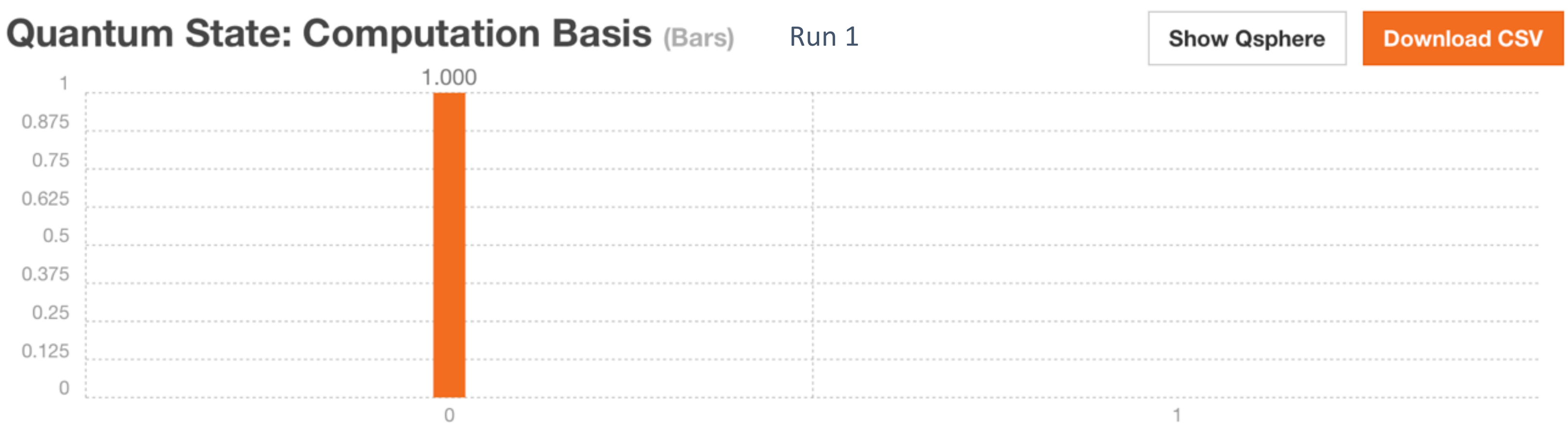
IBM Quantum Experience



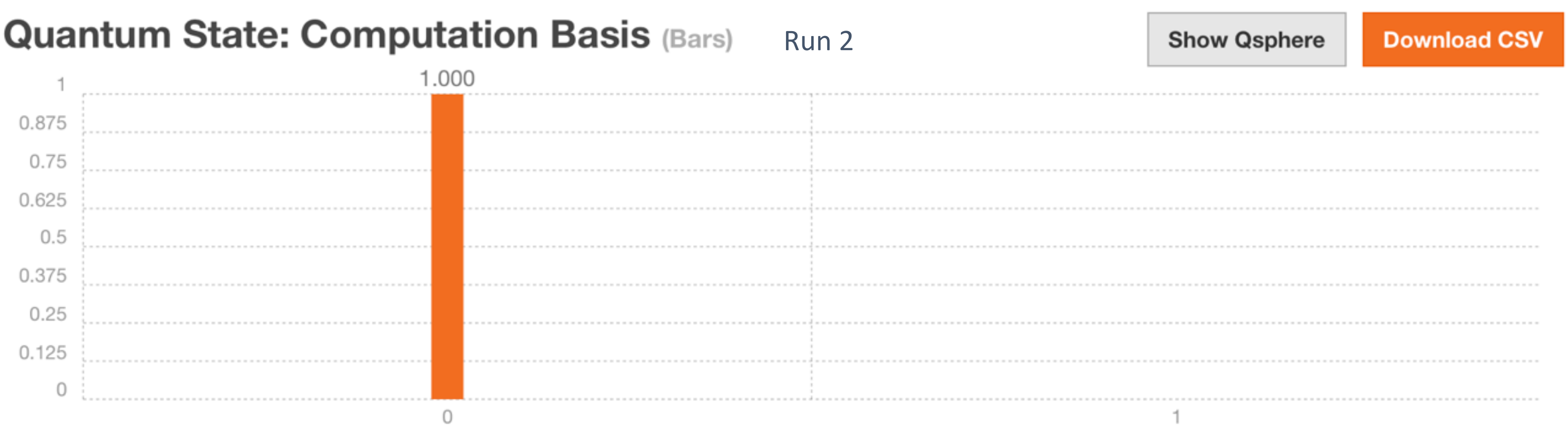
Single qubit states

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



Single qubit states

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



Single qubit states

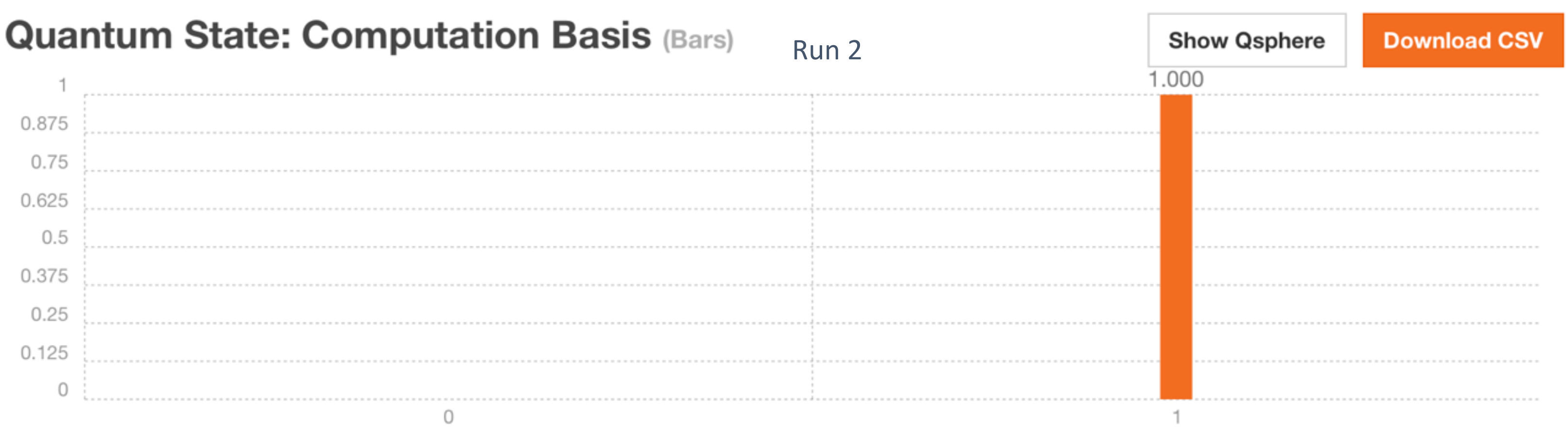
Exp 1. Preparing the qubit in the "0" state

Single qubit states

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

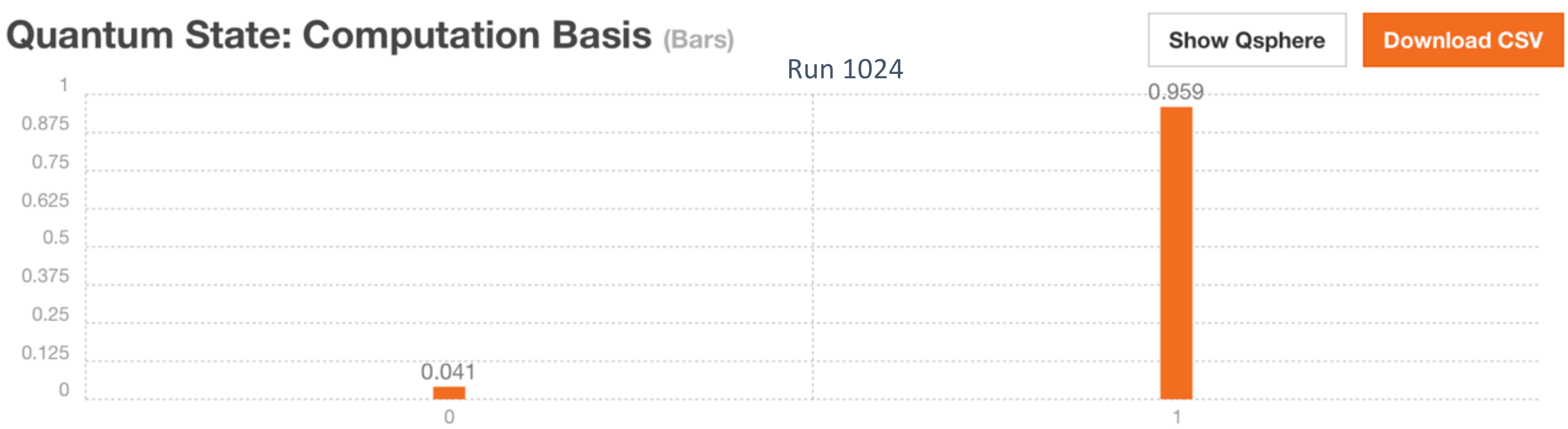
Single qubit states

Exp 2. Preparing the qubit in the “1” state



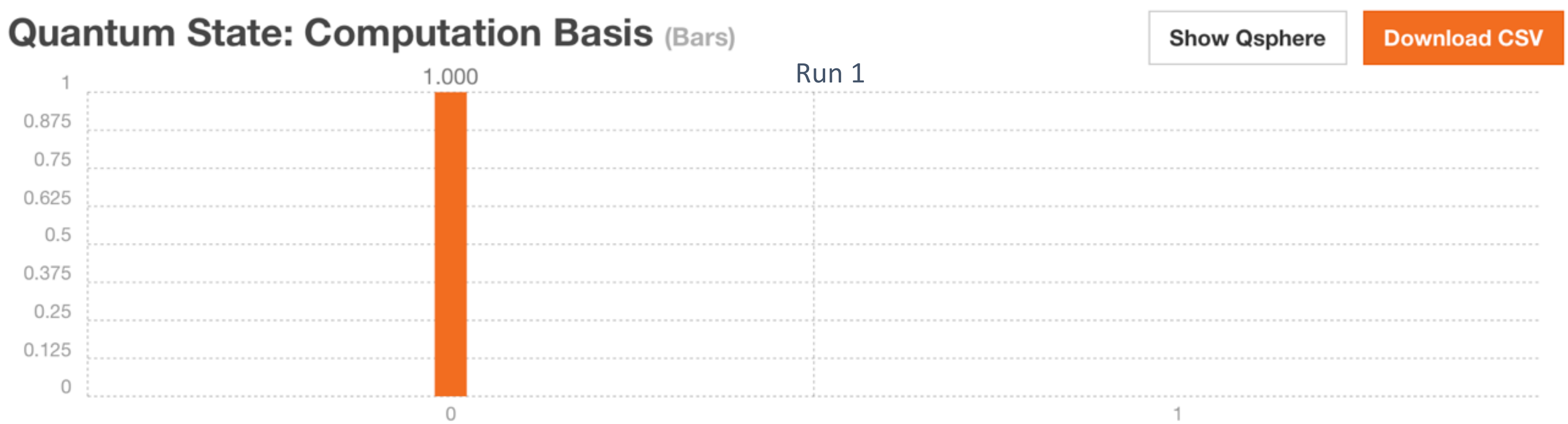
Single qubit states

Exp 2. Preparing the qubit in the “1” state



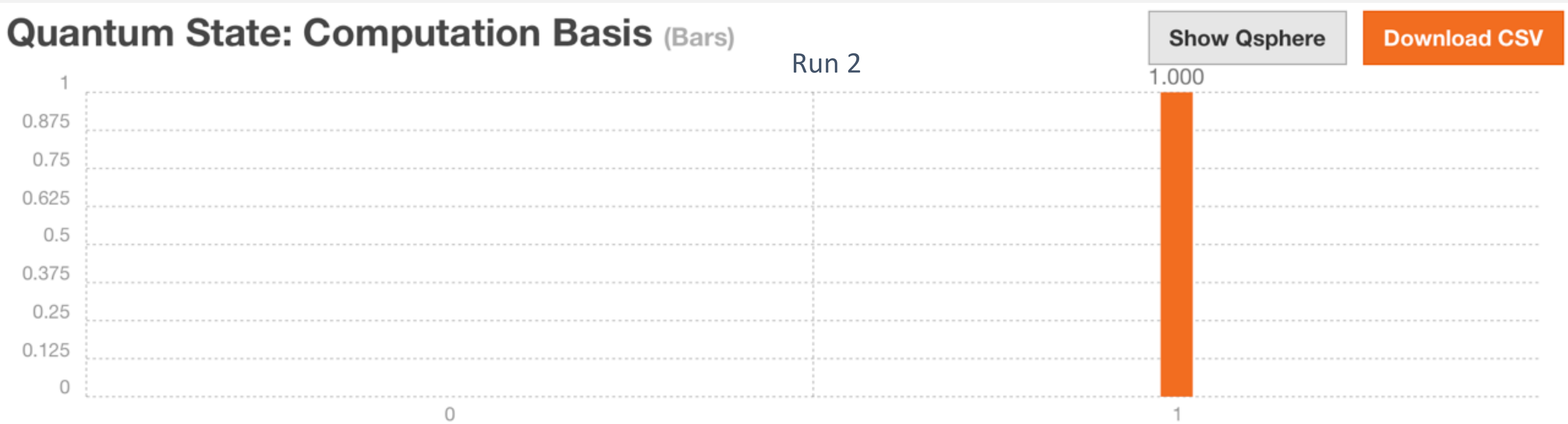
Single qubit states

Exp 3. Preparing the qubit in the "0+1" state



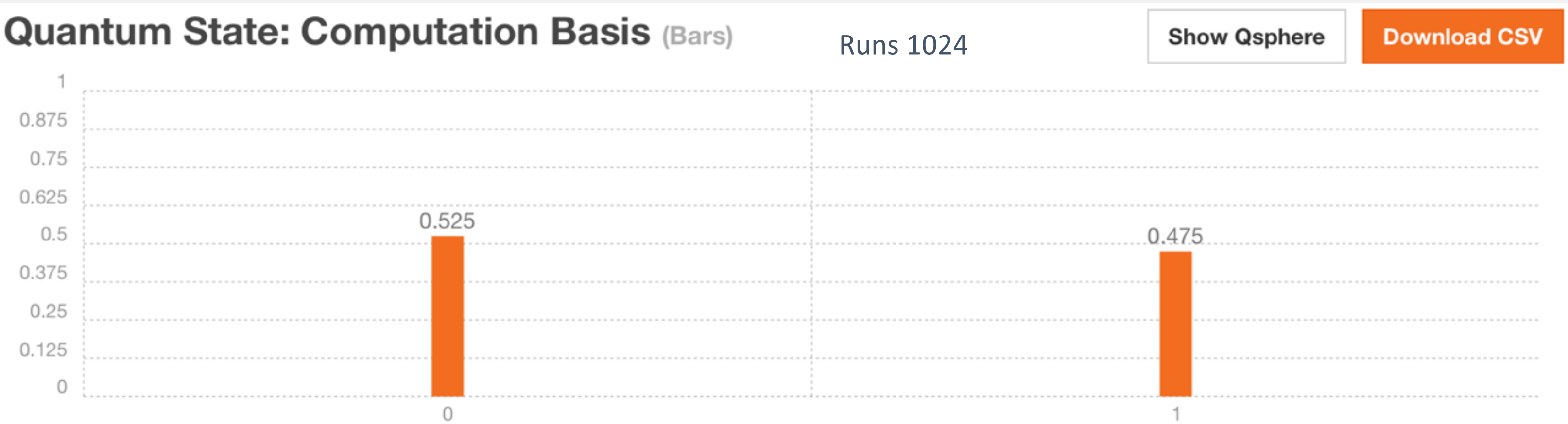
Single qubit states

Exp 3. Preparing the qubit in the "0+1" state



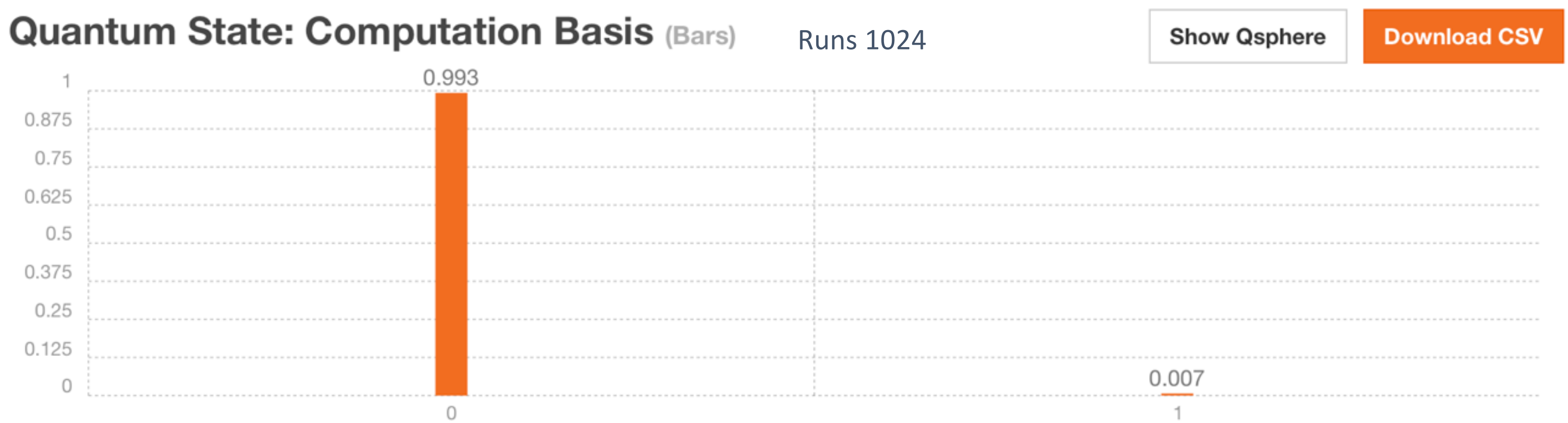
Single qubit states

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

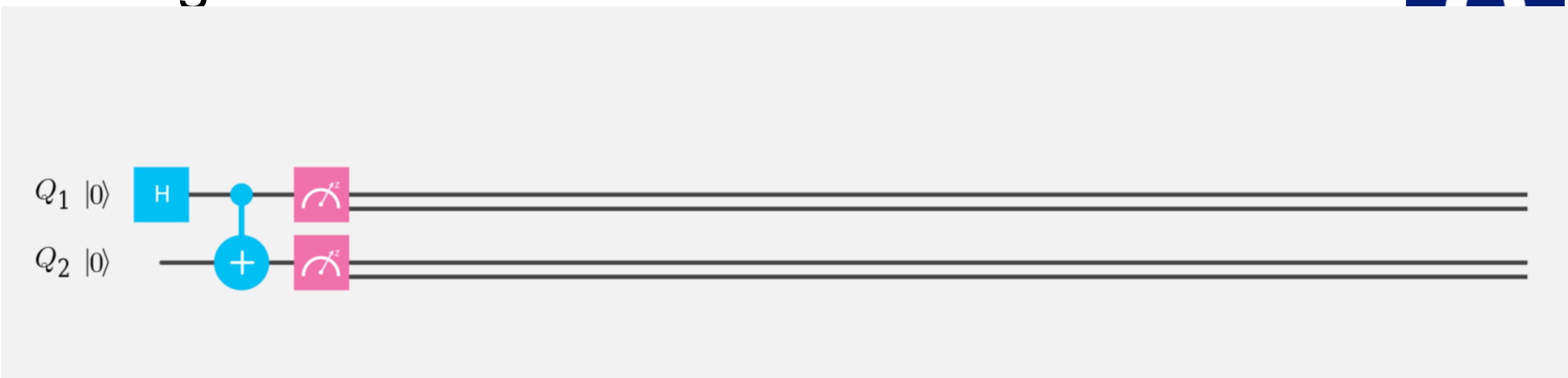


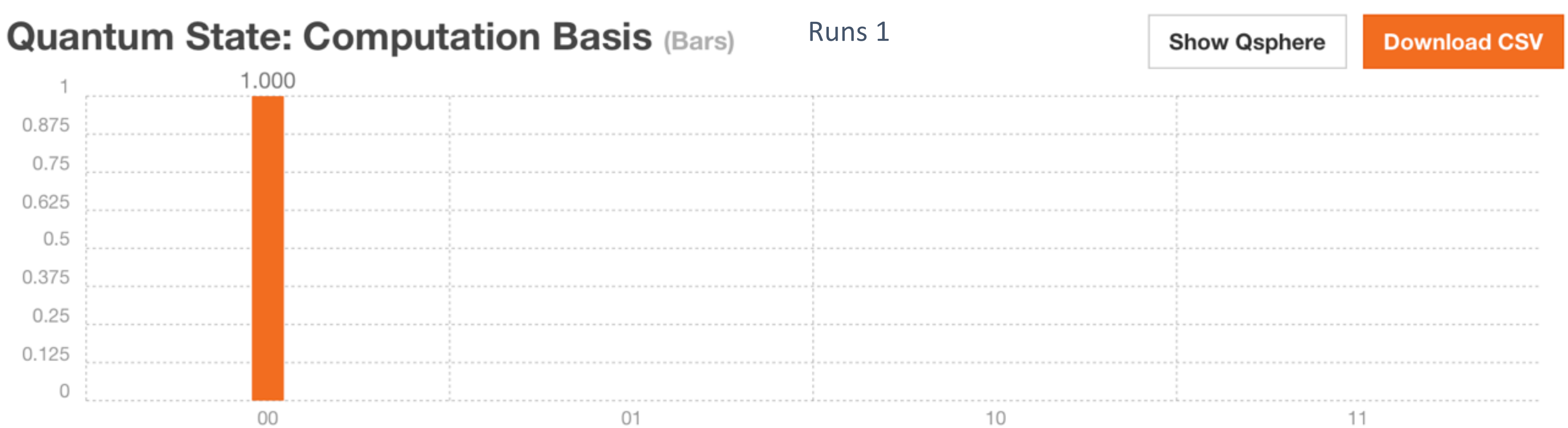
Single qubit states

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

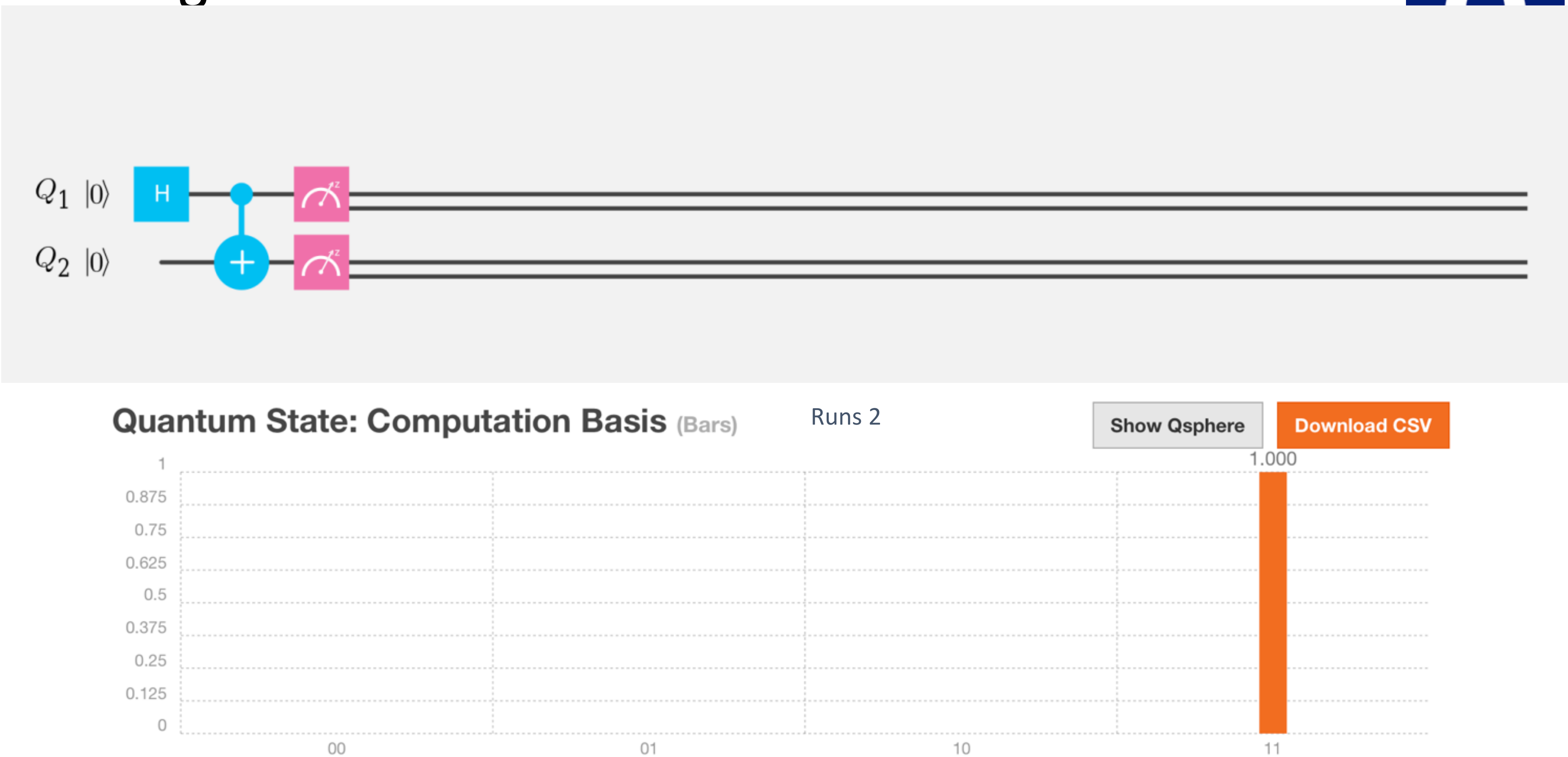


Entanglement

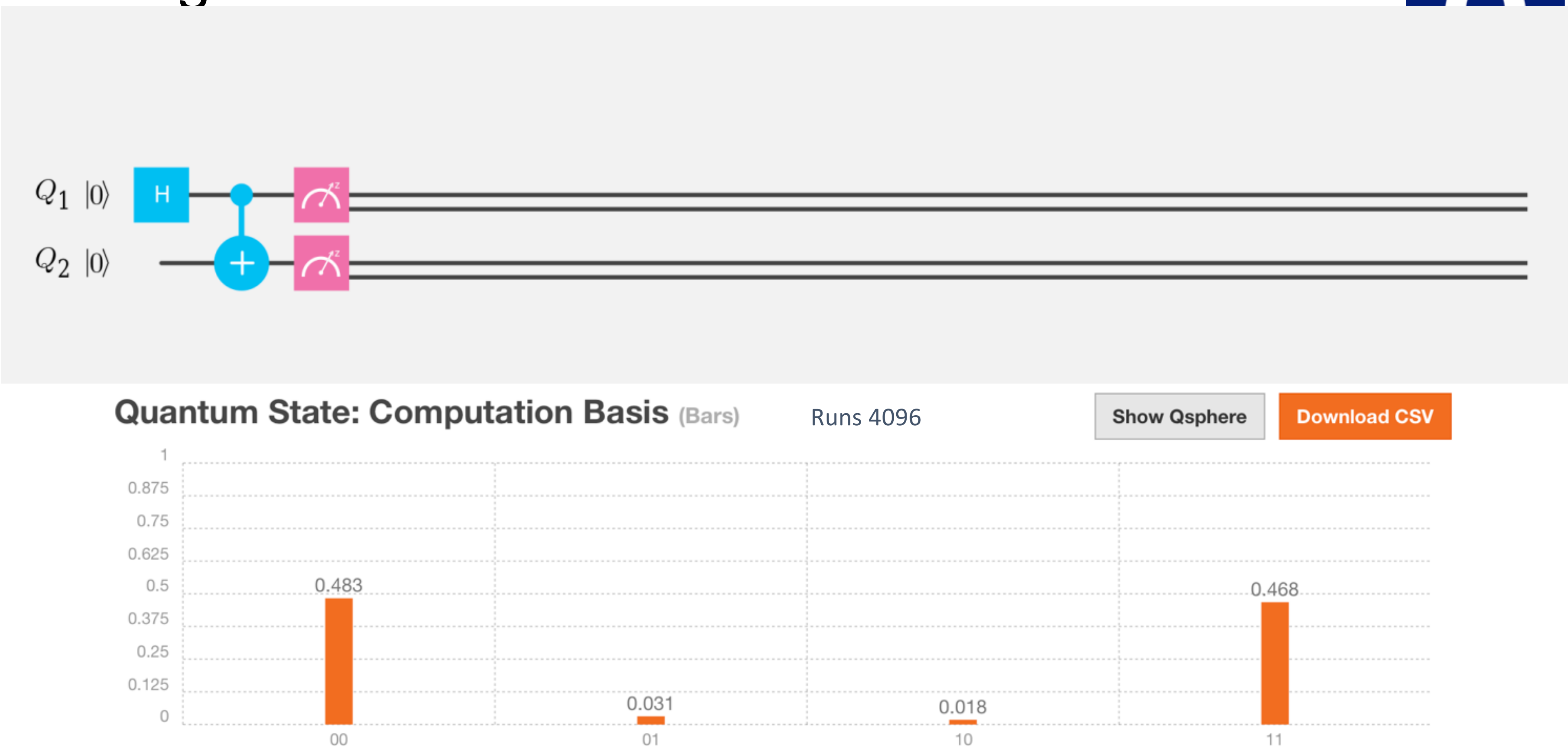




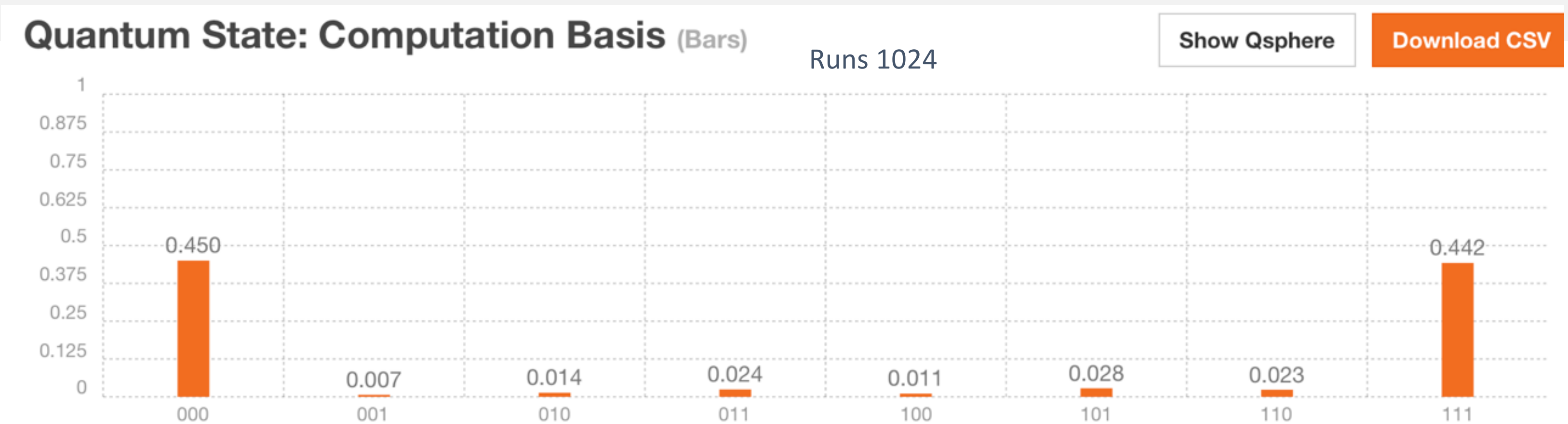
Entanglement



Entanglement



Entanglement



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

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Branch: master qiskit-sdk-py / tutorial / index.ipynb

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jaygambetta fixing links. 236f52e on May 22

1 contributor

150 lines (149 sloc) 5.54 KB

Raw Blame History

QISKit

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.

IBM

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