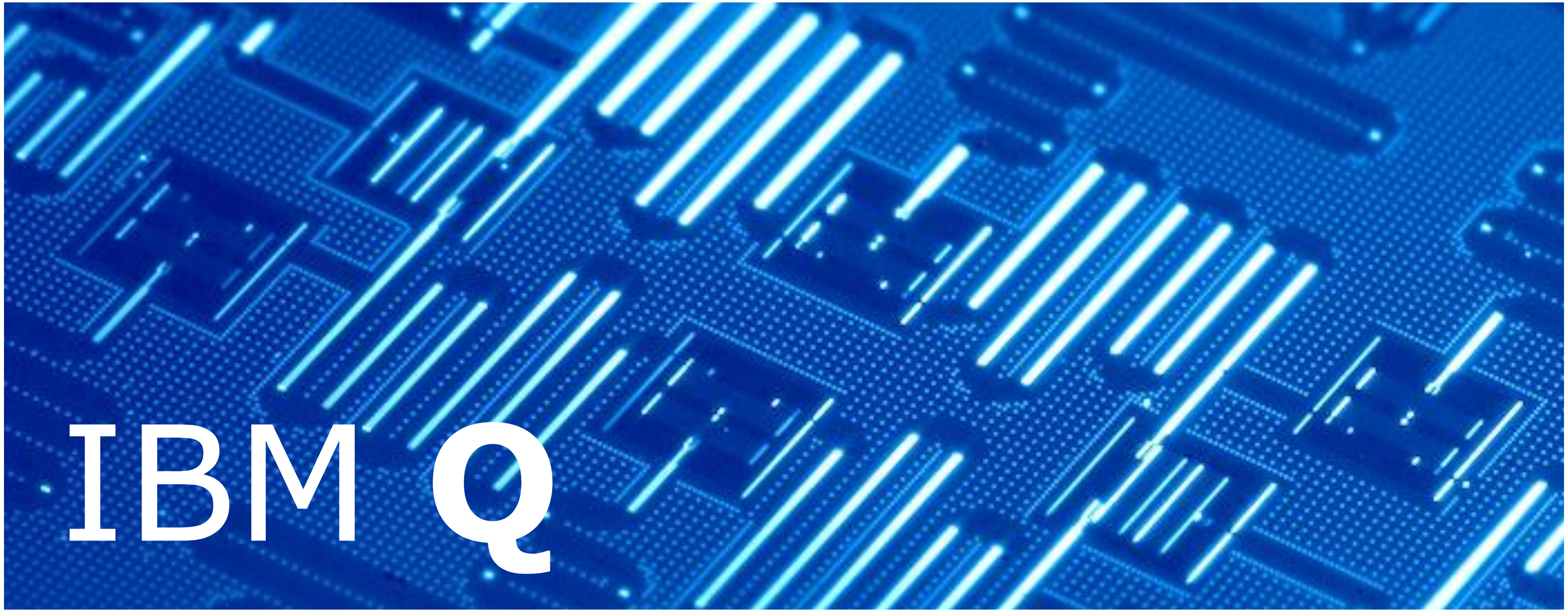
IBM®



Quantum Computing

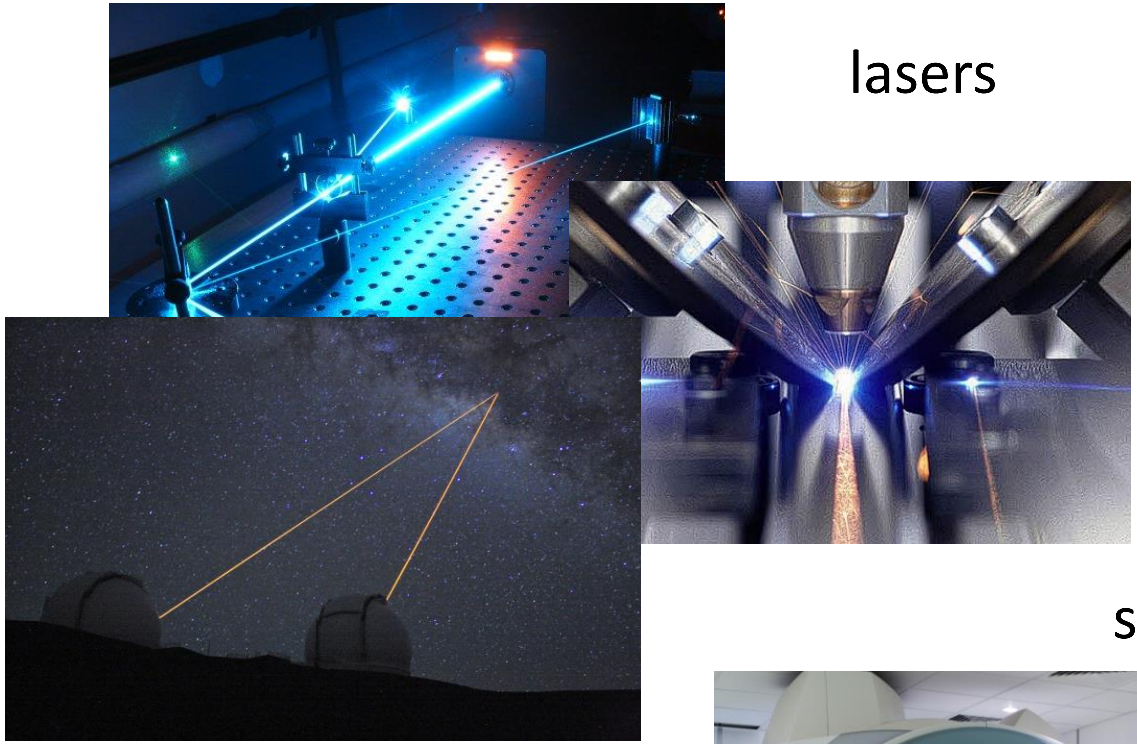
GI - Treffen der Fachgruppe Betriebssysteme – 29th of September 2017
Albert Frisch, PhD - albert.frisch@de.ibm.com

Waves of Quantum Revolution

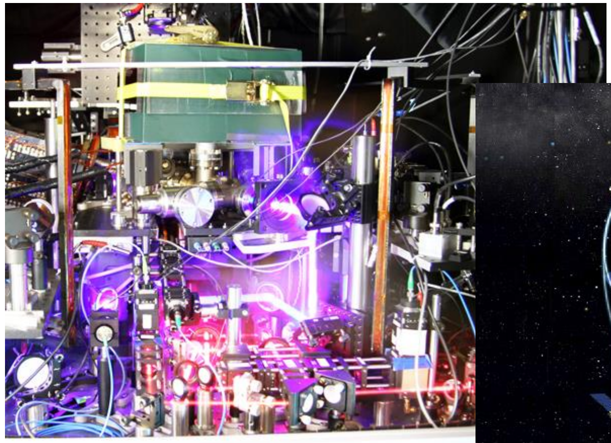
Waves of Quantum Revolution

IBM Q

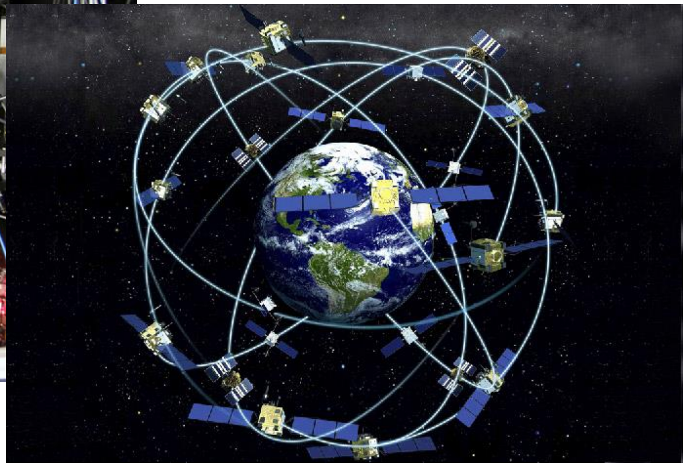
lasers



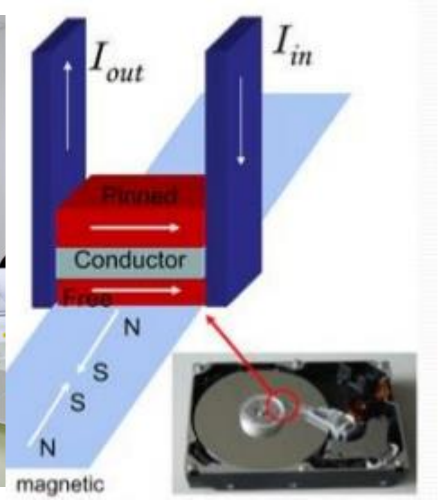
atomic clocks



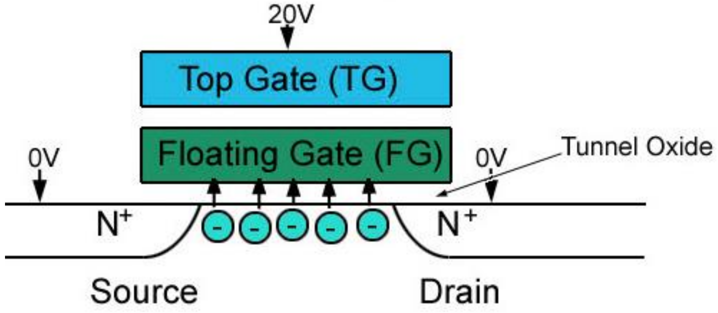
GPS



sensors



flash memory



quantum computing

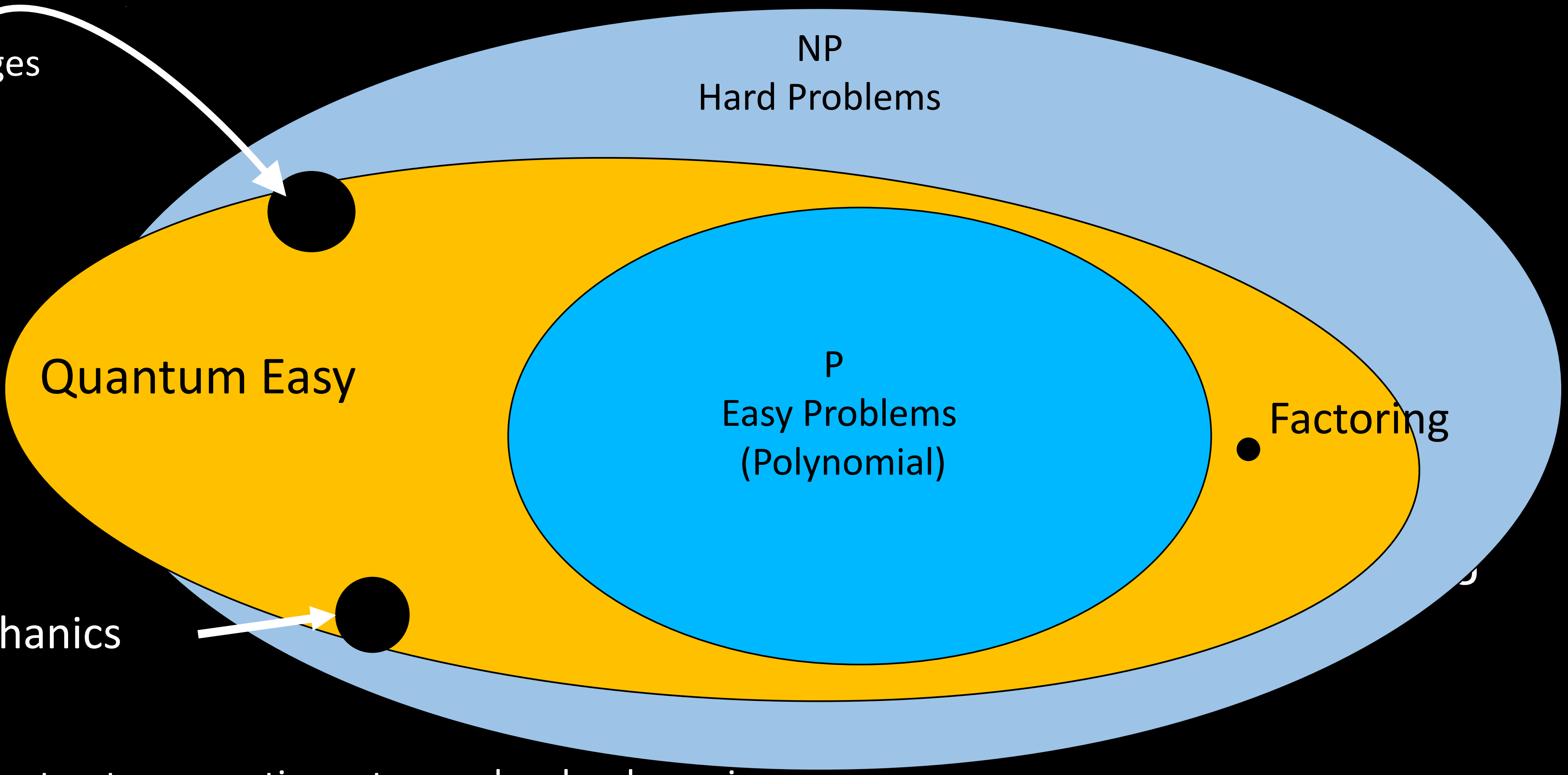
Quantum Heuristic Algorithms

IBM Q

…Quantum computers are the only known game-changer

Optimization Problems:

- Max cut with weighted edges
- Travelling Salesman
- Scheduling problems
- Portfolio analysis
- Map coloring problems
- Vehicle routing problems
- Supply chain optimization
- Other hard problems



Simulating Quantum Mechanics

- e.g. CaF, FeS
- High Tc Superconductors
- Generally: drugs, molecular structure, reaction rates, molecular dynamics

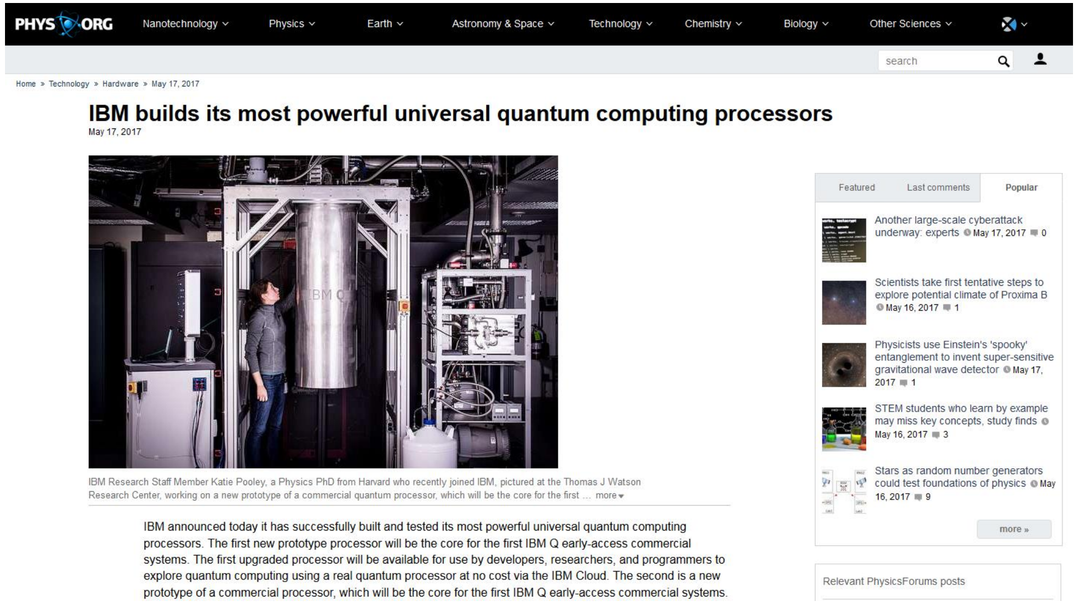
IBM Q in the press

press anouncement on 6th of March 2017:

„The First Universal Quantum Computers for Business and Science"

press anouncement on 17th of May 2017:

16- and 17-qubit processors



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Home » Technology » Hardware » May 17, 2017

IBM builds its most powerful universal quantum computing processors

May 17, 2017

IBM Research Staff Member Katie Pooley, a Physics PhD from Harvard who recently joined IBM, pictured at the Thomas J Watson Research Center, working on a new prototype of a commercial quantum processor, which will be the core for the first ... more

IBM announced today it has successfully built and tested its most powerful universal quantum computing processors. The first new prototype processor will be the core for the first IBM Q early-access commercial systems. The first upgraded processor will be available for use by developers, researchers, and programmers to explore quantum computing using a real quantum processor at no cost via the IBM Cloud. The second is a new prototype of a commercial processor, which will be the core for the first IBM Q early-access commercial systems.

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Relevant PhysicsForums posts

IBM aims at constructing commercial IBM Q systems with **~50 qubits in the next few years** to demonstrate capabilities beyond today's classical systems

➡ **quantum advantage**

The Road to Quantum Advantage

IBM **Q**

Quantum Science

Fundamentals of quantum information science

Create and scale qubits with increasing coherence

Create error detection and mitgation schemes

Launch of IBM **Q** Experience

~1900

Quantum Ready

Core algorithm development

Increase quantum volume

Standardize performance benchmarks

System infrastructure and software enablement

2016

~2020

Quantum Advantage

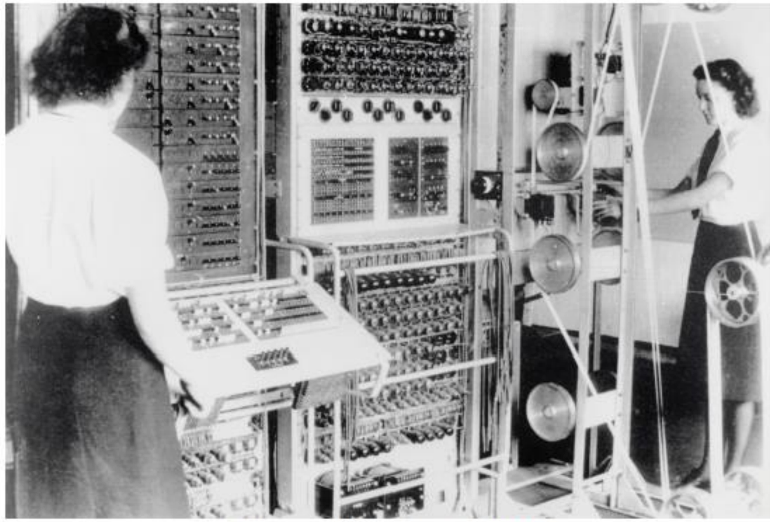
Demonstrate an advantage to using QC for real problems of interest

Extract commercial value

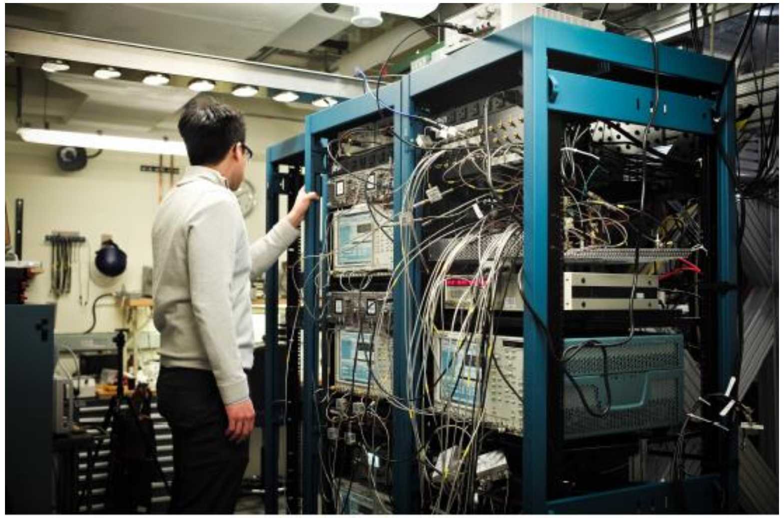
Enable scientific discovery

The Quantum World

IBM **Q**



Classical Computer, 1940s



Quantum Computer, 2010s

classical computer

is in a **deterministic state** at any time
defined by all bits of the computer

$\boldsymbol{n}$ **bits** $\rightarrow 2^n$ **possible states, one at a time**

quantum computer

uses **qubits** to take advantage of quantum speedup

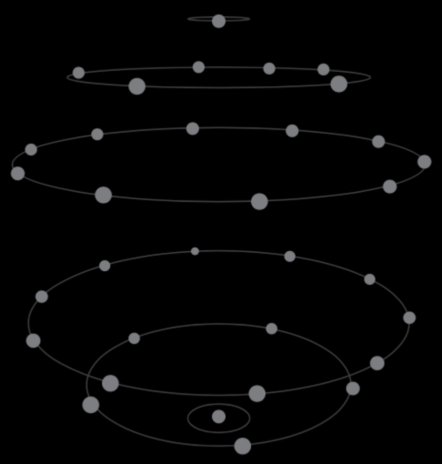
superposition of states possible
„all states at the same time“

50 qubits $\rightarrow$ **10^{15} states simultaneously available**

e.g. $|\psi\rangle = a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + \cdots$

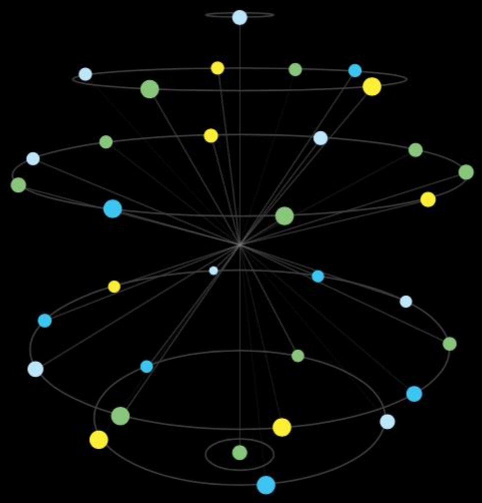
A Quantum Algorithm

IBM Q



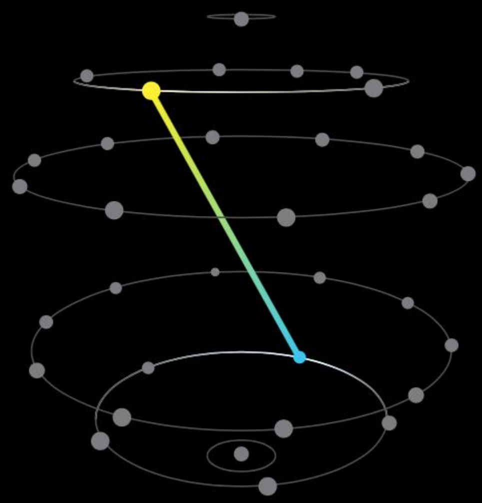
The spread

First part of the algorithm is to make an equal superposition of all 2^n states by applying H gates



The problem

The second part is to encode the problem into this states; put phases on all 2^n states



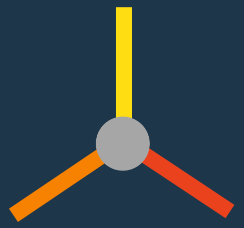
The magic

The magic of quantum algorithms is to interfere all these states back to a few outcomes containing the solution

Three Steps of Development

IBM Q

1. Quantum Annealer

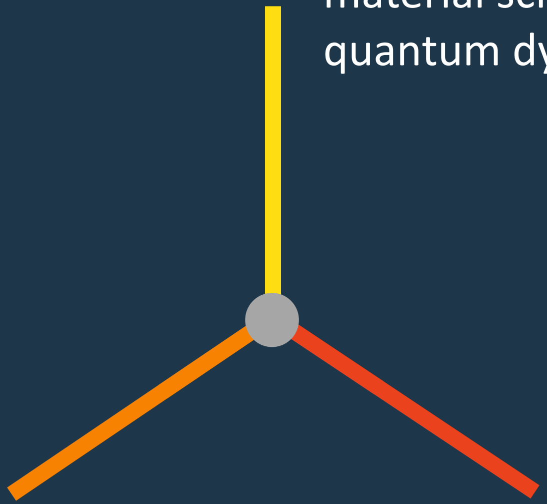


Three Steps of Development

2. Approximate Quantum Computer

applications

optimization
quantum chemistry
material sciences
quantum dynamics



generality
partial

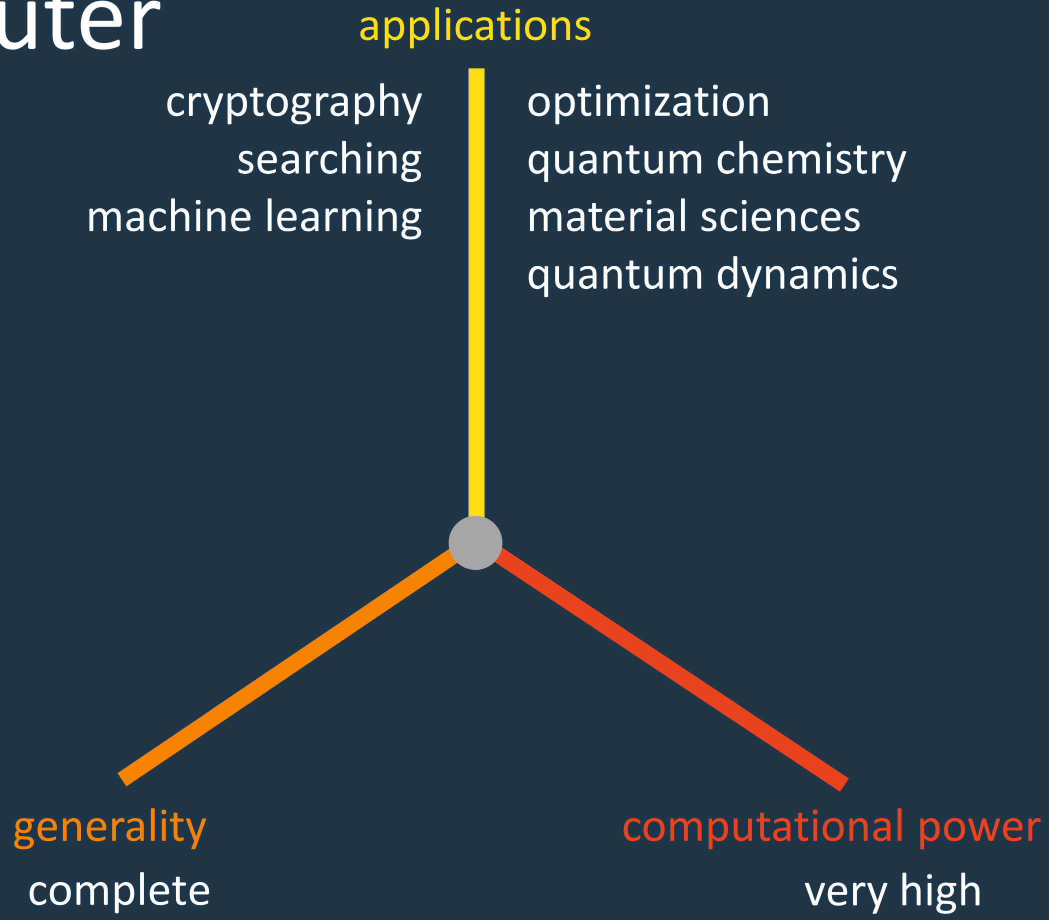
computational power
high

Three Steps of Development

IBM Q

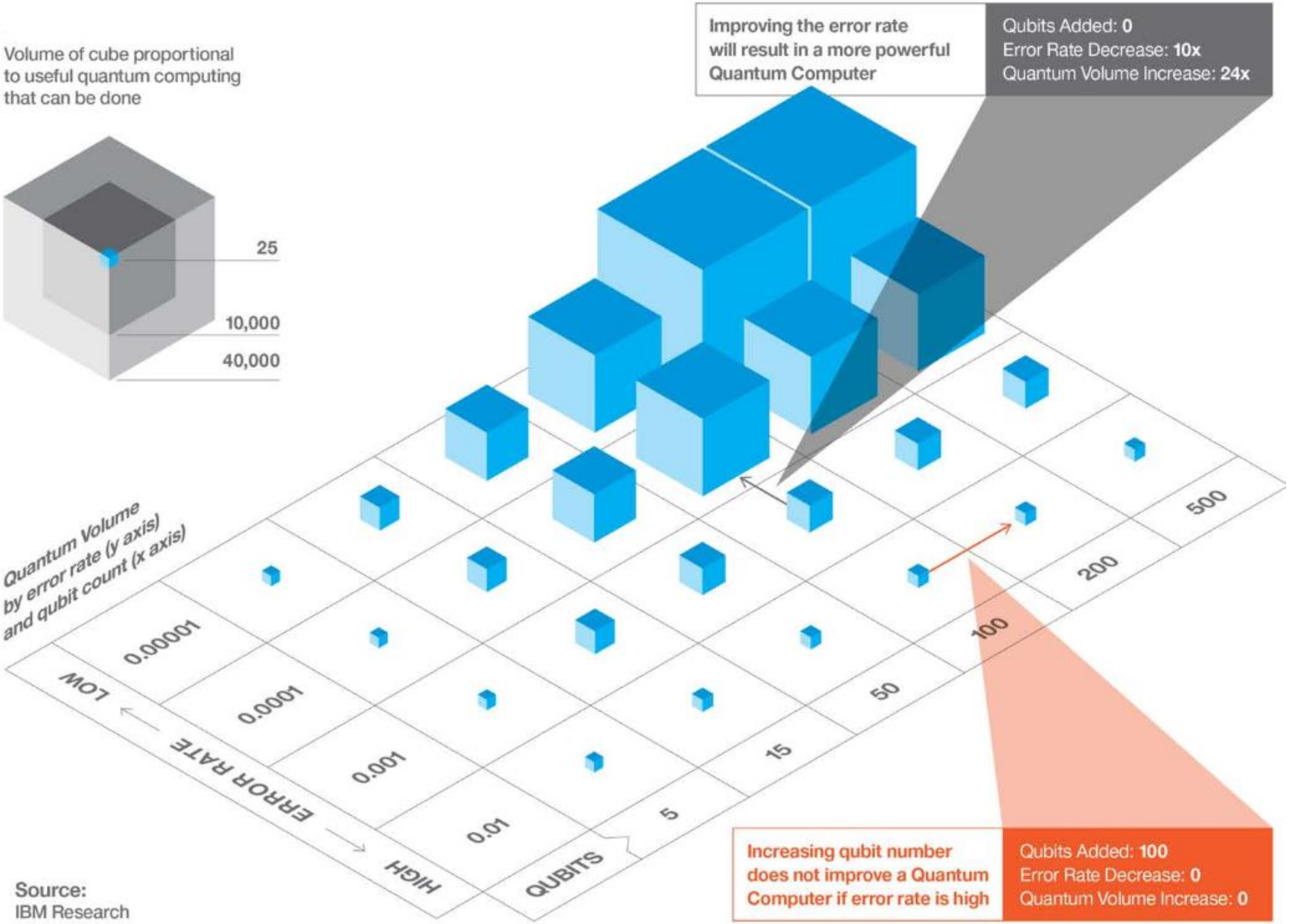
3. Fault-tolerant Quantum Computer

>100.000 qubits



Quantum Volume

IBM Q

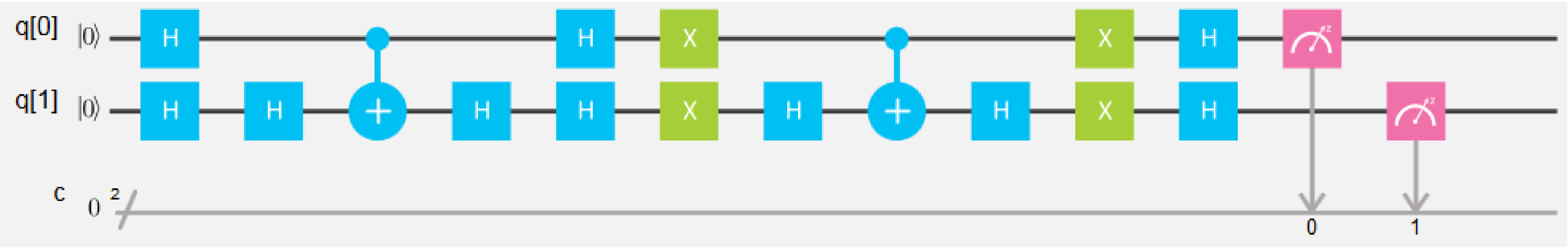


Source:
IBM Research

quantum algorithm

Quantum Score

1. 2. 3.



1. **initialization** of all qubits in $|0\rangle$
2. sequence of **operations** on single or multiple qubits
3. **measurement** (read-out) concludes algorithm

multiple repetitions for **statistical claims** necessary

Qubits

IBM **Q**

$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

superposition

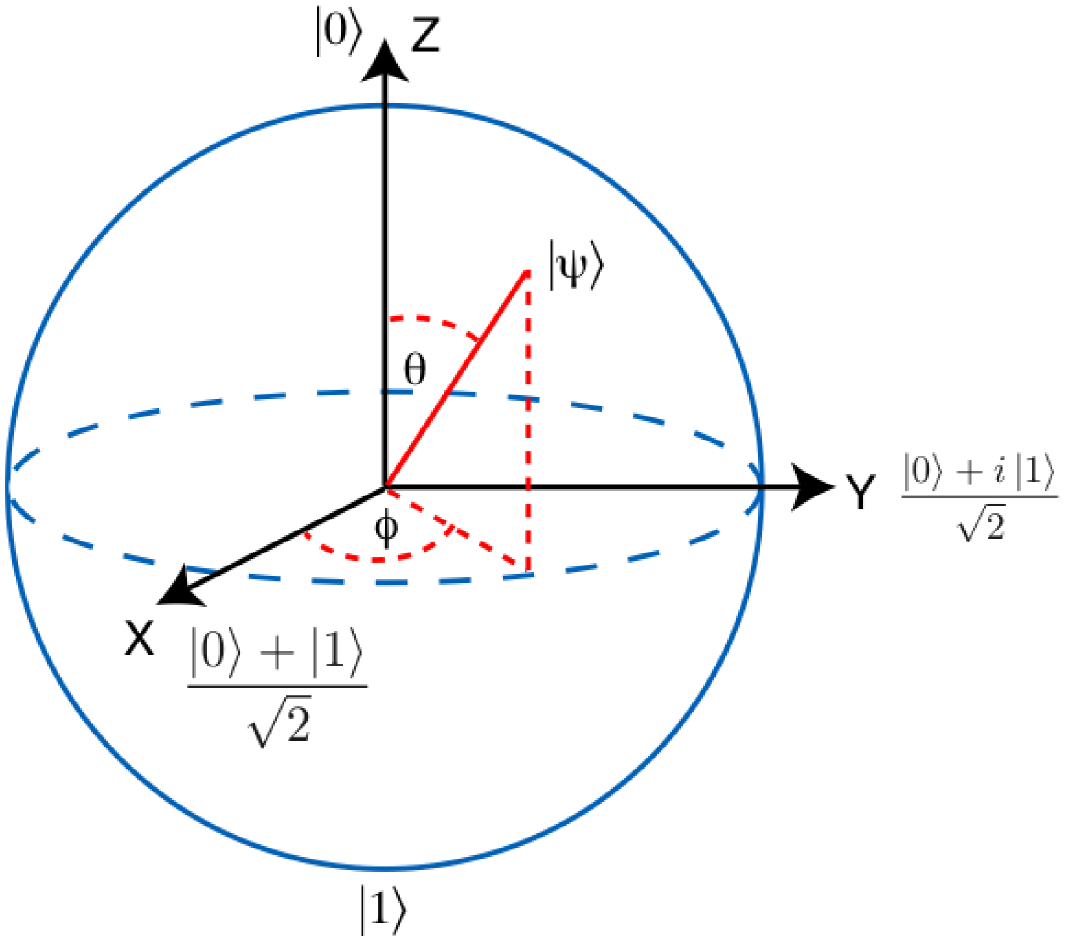
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

z.B.

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

$$|\circlearrowright\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle) \qquad |\circlearrowleft\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$$

Bloch sphere

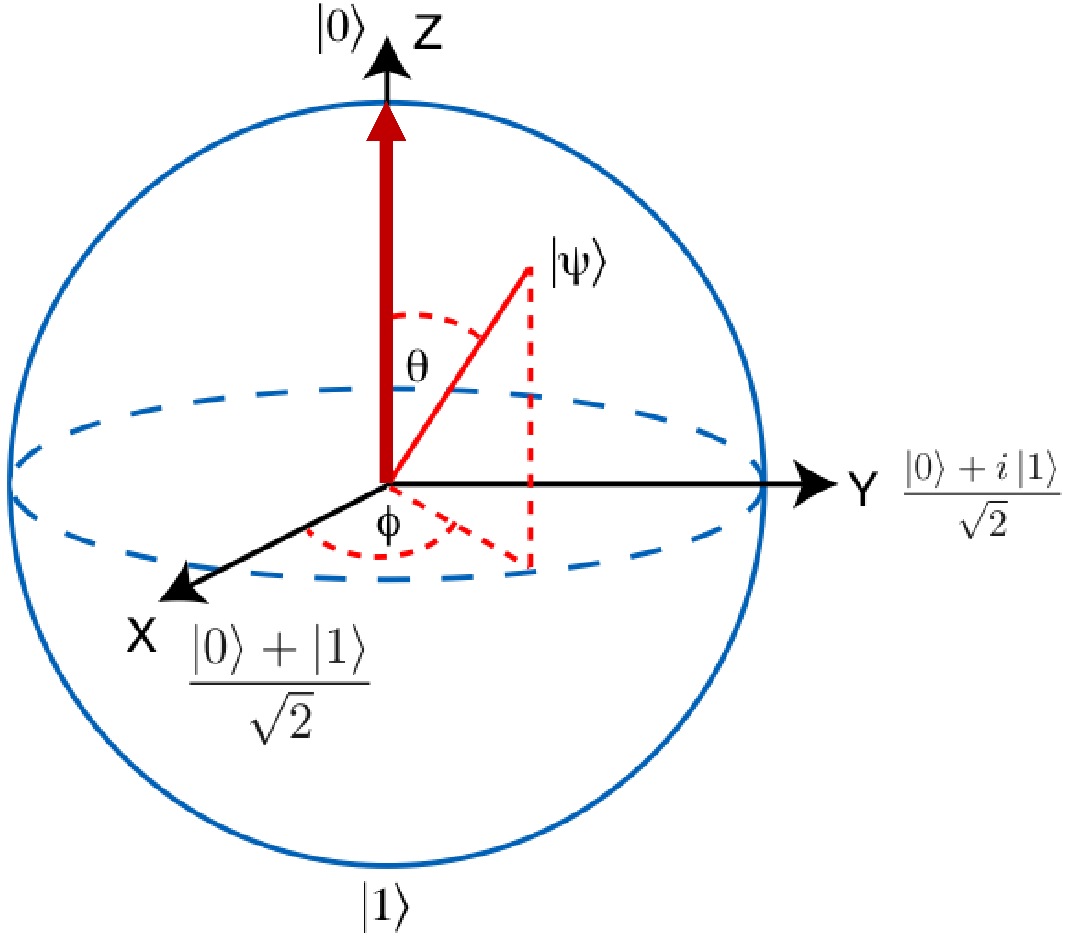


IBM Quantum Experience - quantumexperience.ng.bluemix.net/

Qubits

$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Bloch sphere



superposition

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

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$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

$$|\circlearrowright\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle) \qquad |\circlearrowleft\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$$

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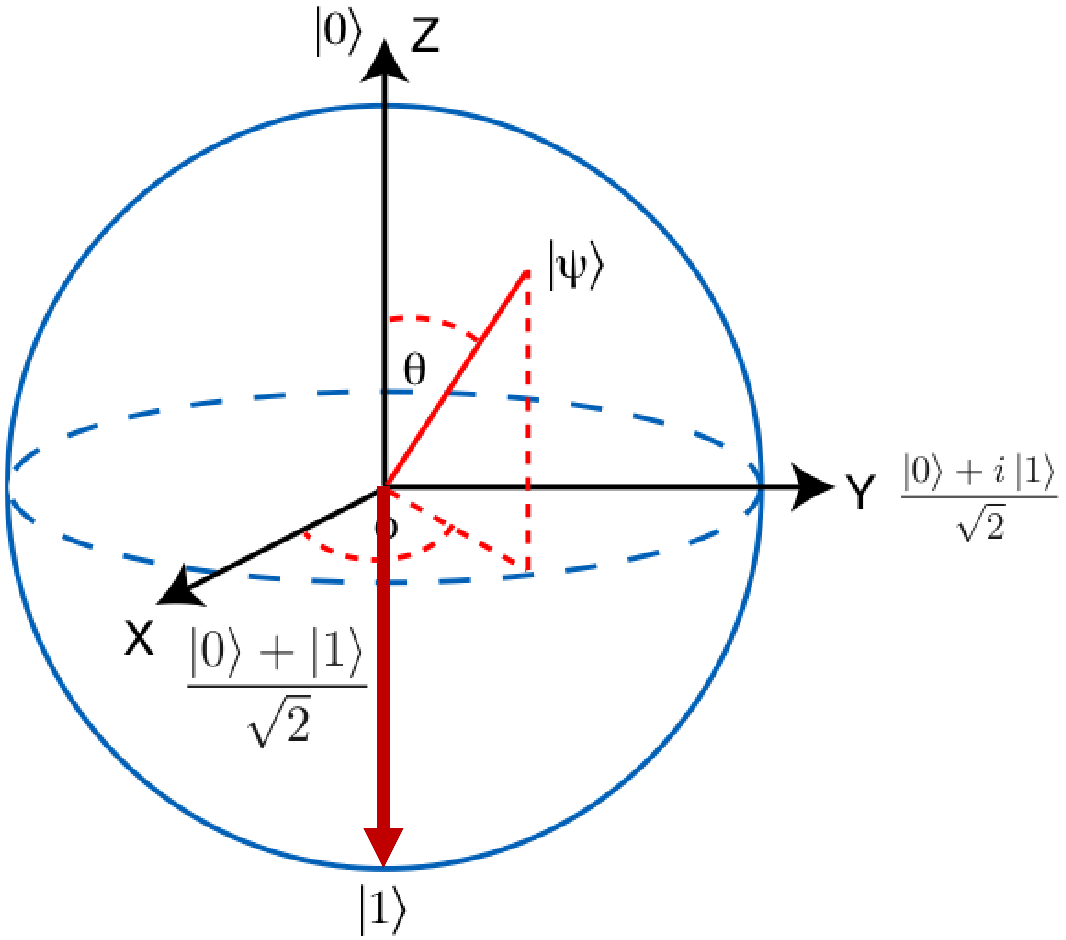
Qubits

IBM **Q**

$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Bloch sphere



superposition

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

z.B.

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

$$|\circlearrowright\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle) \qquad |\circlearrowleft\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$$

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Qubits

IBM Q

$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

superposition

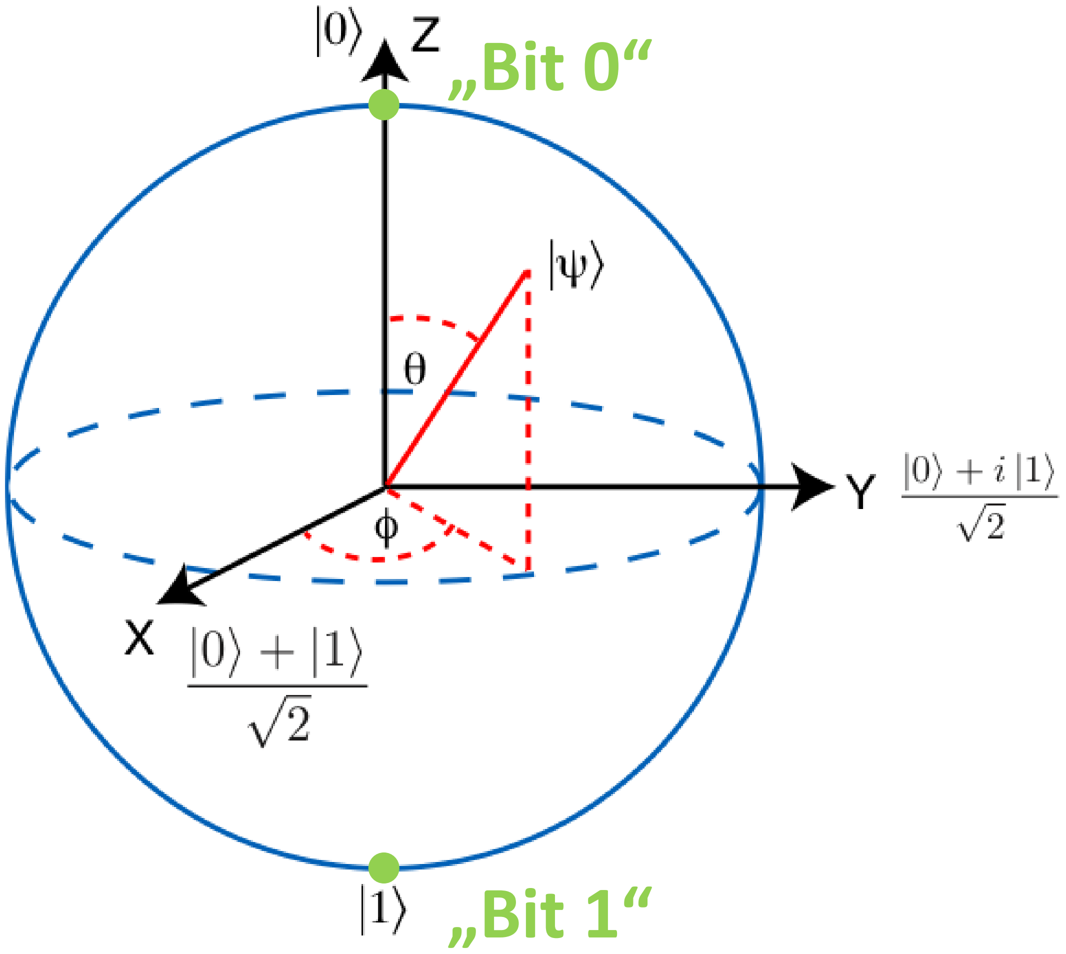
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

z.B.

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \qquad |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

$$|\circlearrowright\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle) \qquad |\circlearrowleft\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$$

Bloch sphere



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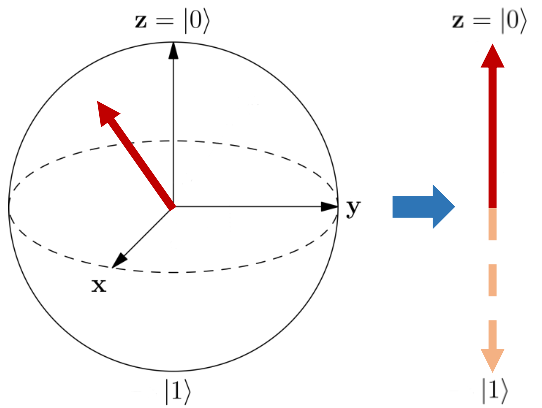
Measurement and Quantum Gates

IBM **Q**

measurement $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$



probability

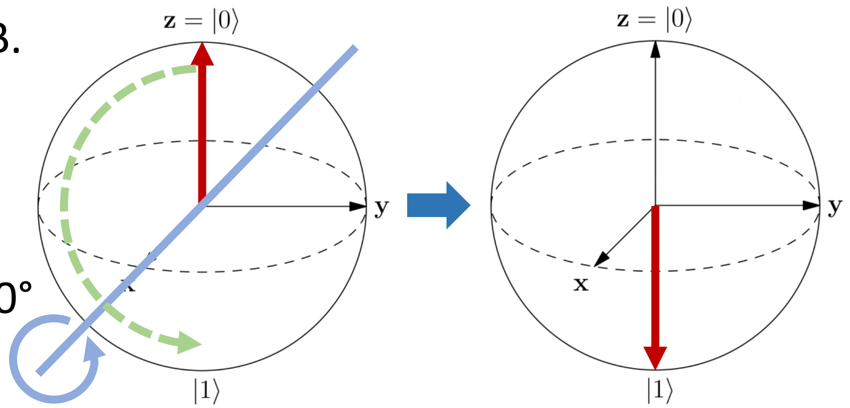
either $|0\rangle$ $|\alpha|^2$

or $|1\rangle$ $|\beta|^2$

rotations

X Z Y

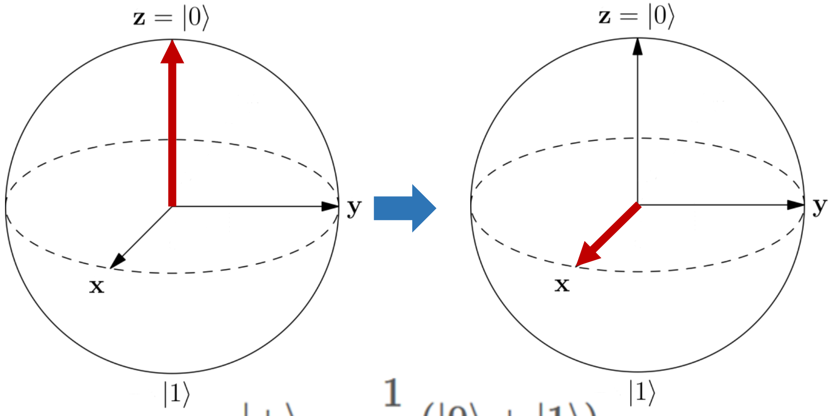
z.B.



180°

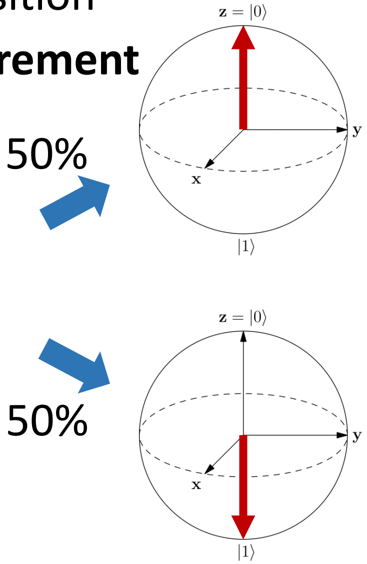
Hadamard

creates superposition



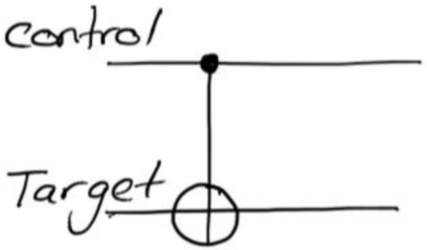
$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

measurement



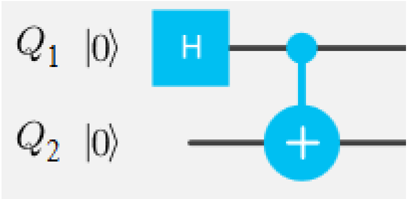
controlled-NOT

„quantum XOR“



for entanglement

e.g.



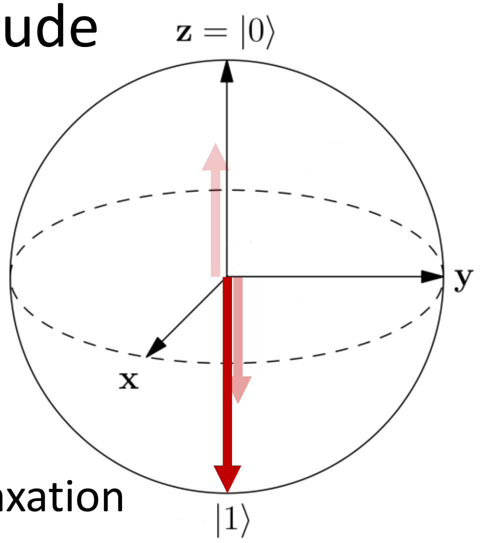
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

→ **no classical equivalent exists**

Decoherence

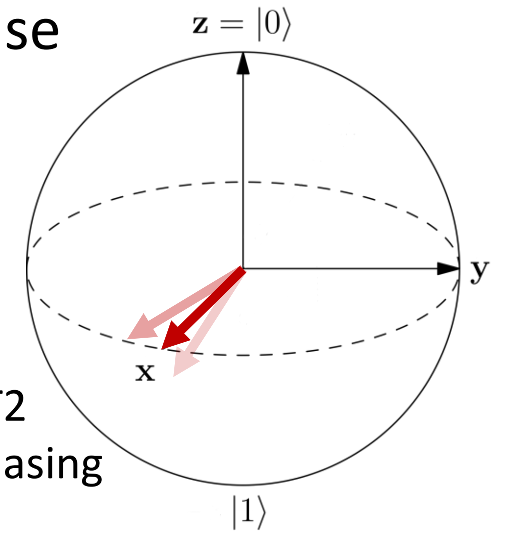
loss of quantum information

amplitude

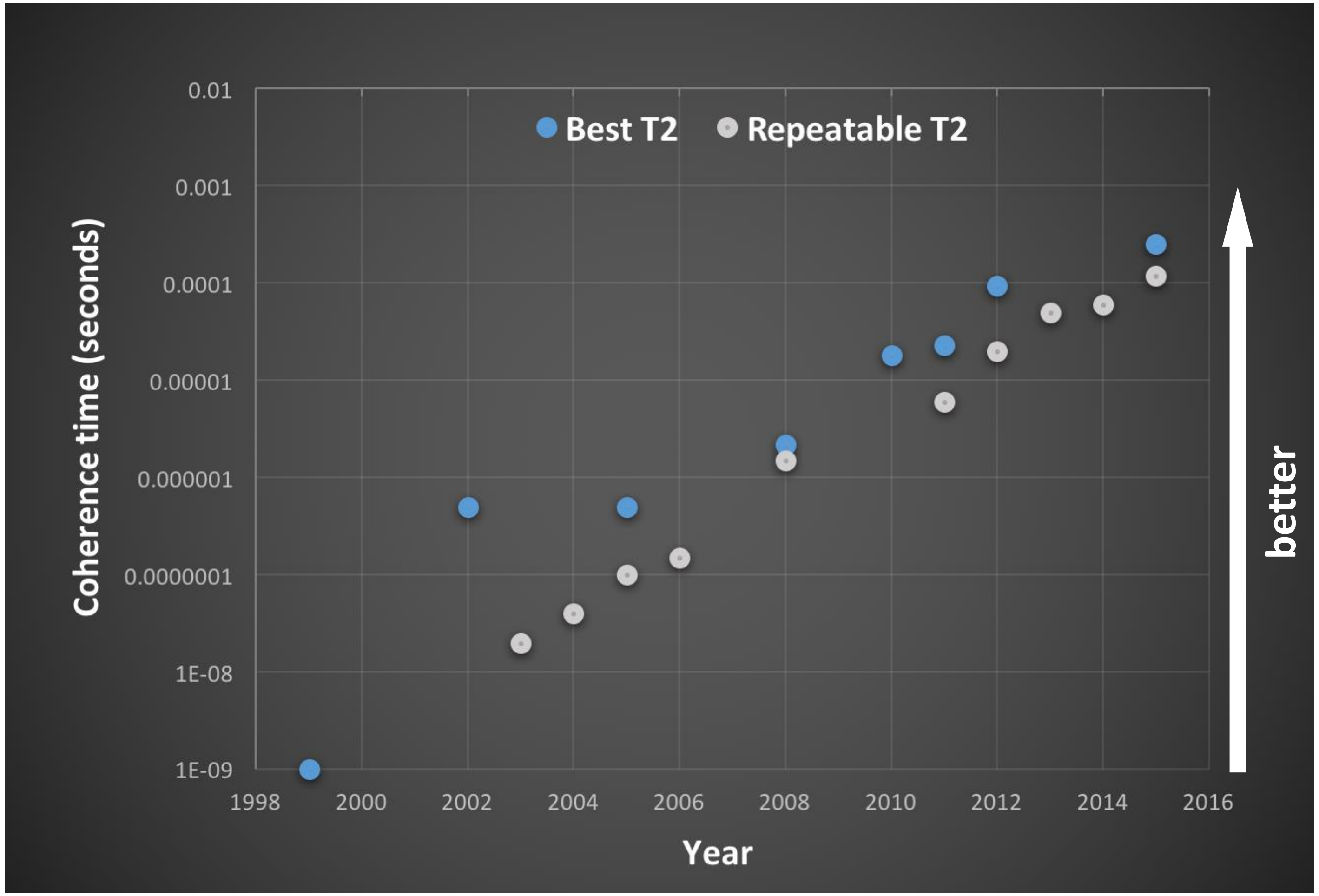


T1
energy relaxation

phase



T2
dephasing



longer coherence times mean lower error rates

which allows more time to compute

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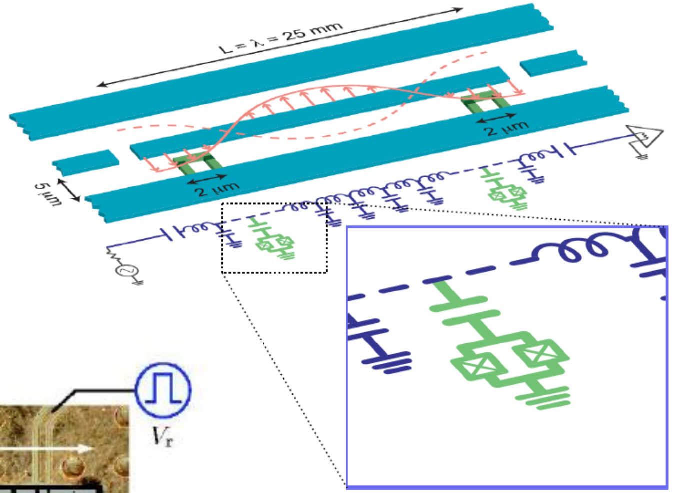
Quantum Architectures

IBM Q

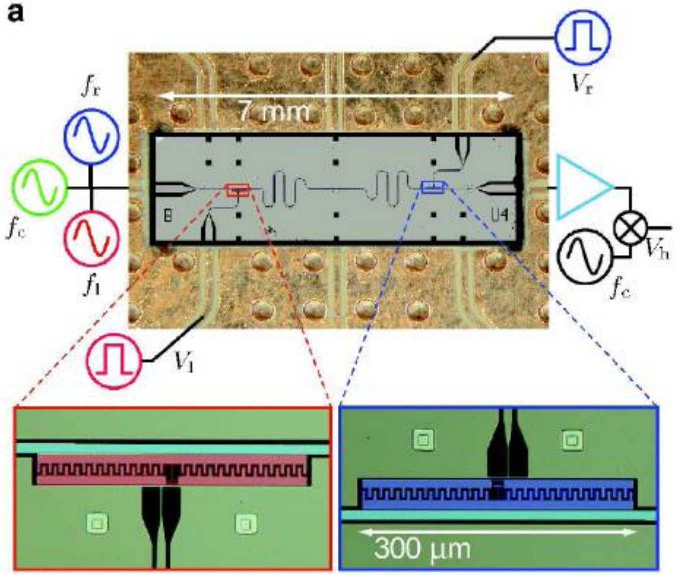
superconducting qubits

„artificial atoms“

cQED
(circuit quantum electrodynamics)

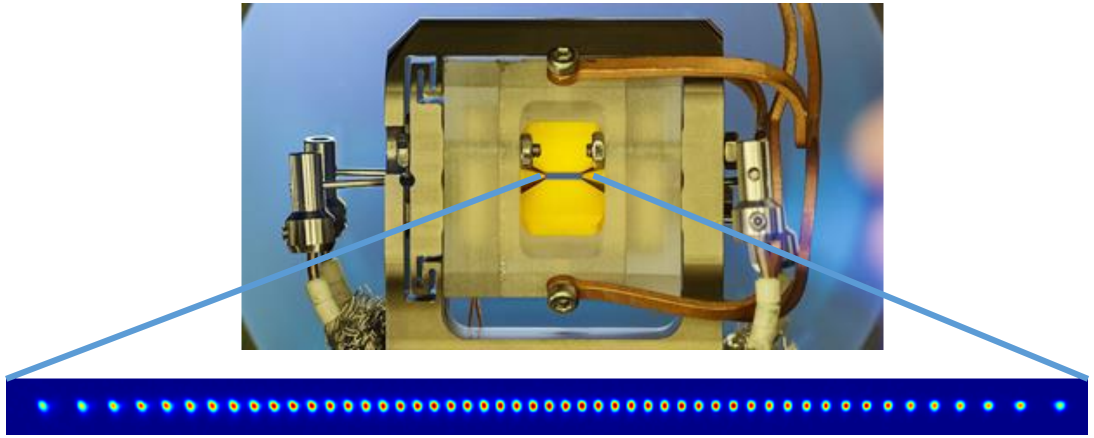


a



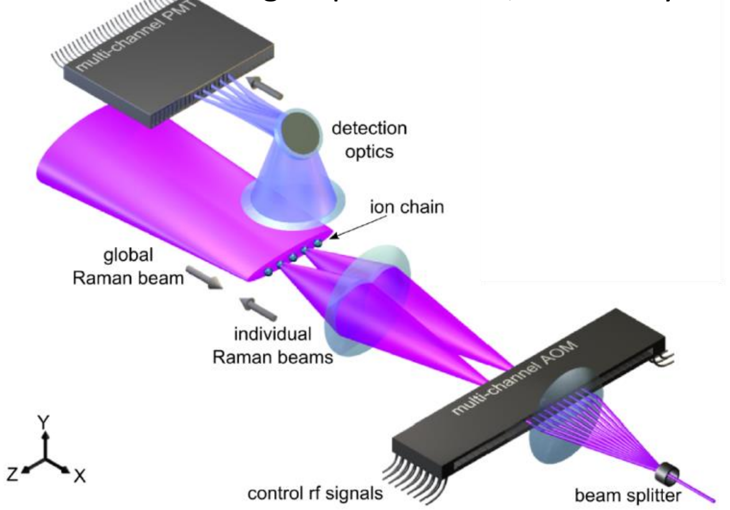
group of R. Schoelkopf, Yale University

ion-trap qubits



group of R. Blatt, University of Innsbruck

b



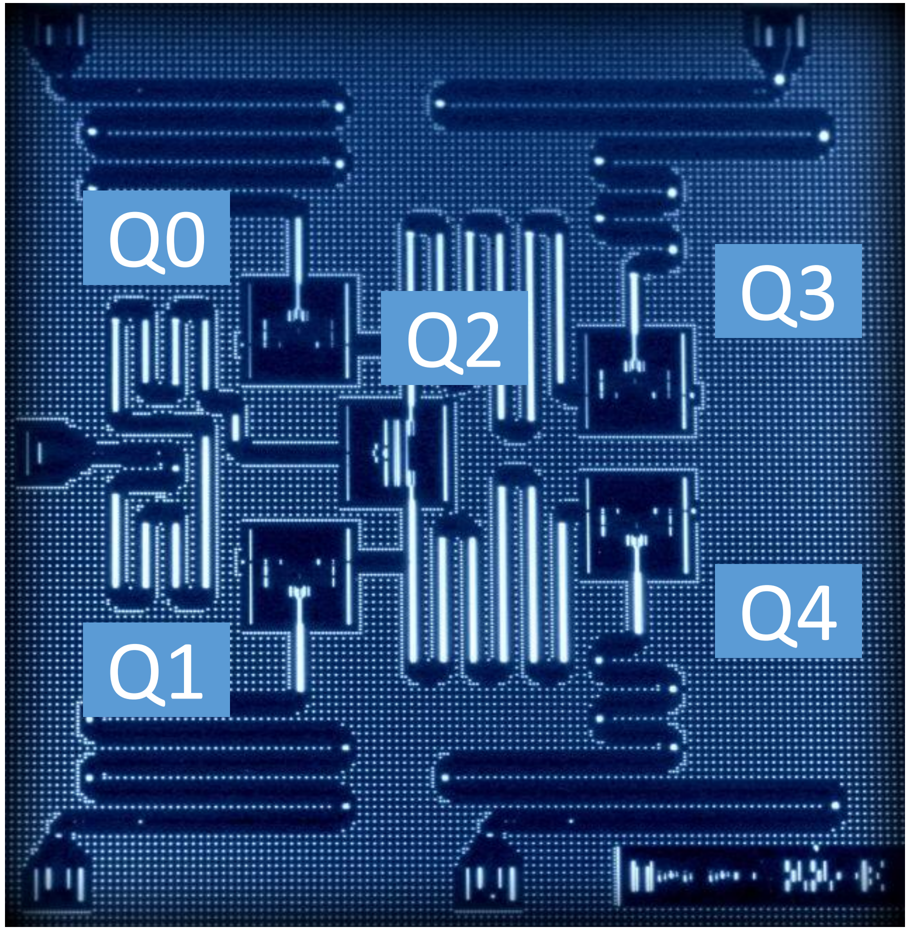
group of C. Monroe, University of Maryland

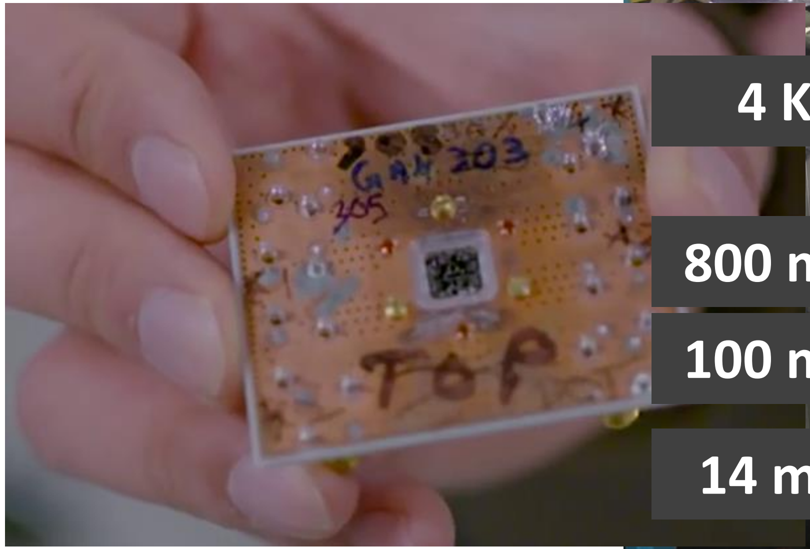
“Experimental Comparison of Two Quantum Computing Architectures”, Linke et al, 2017. https://arxiv.org/abs/1702.01852

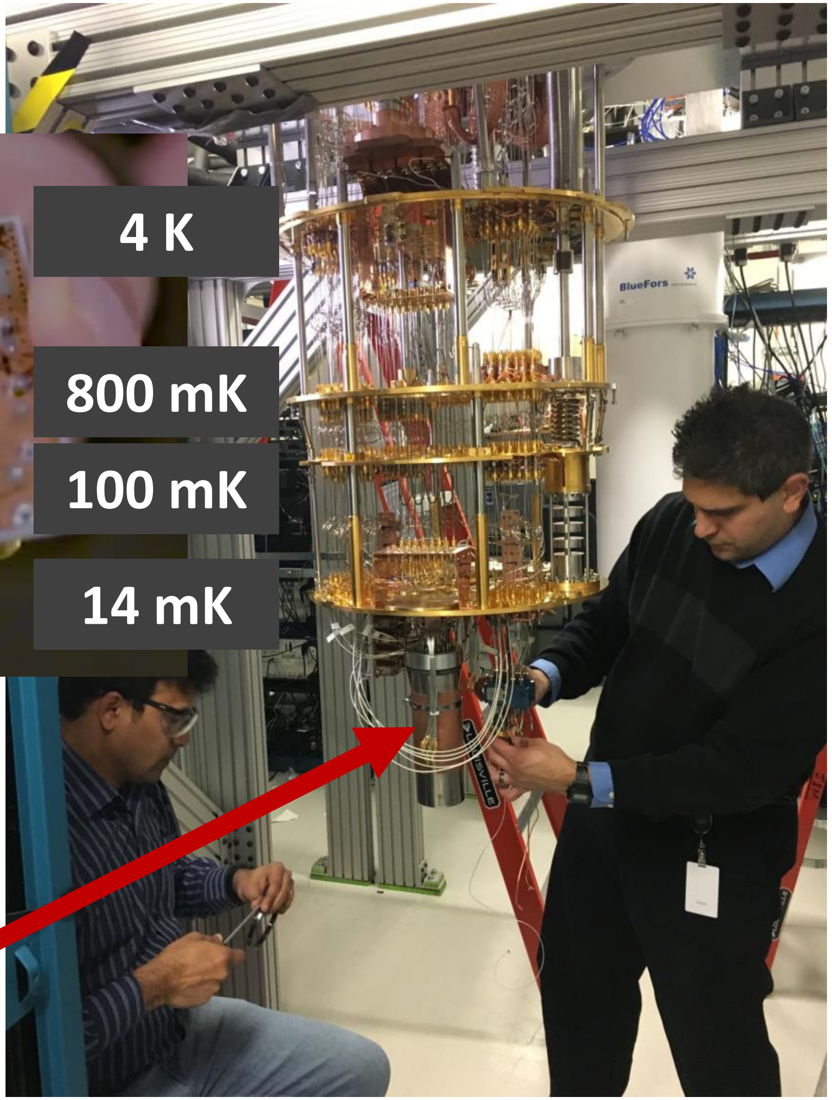
developments at IBM

IBM 5-qubit Quantum Computer

IBM Q







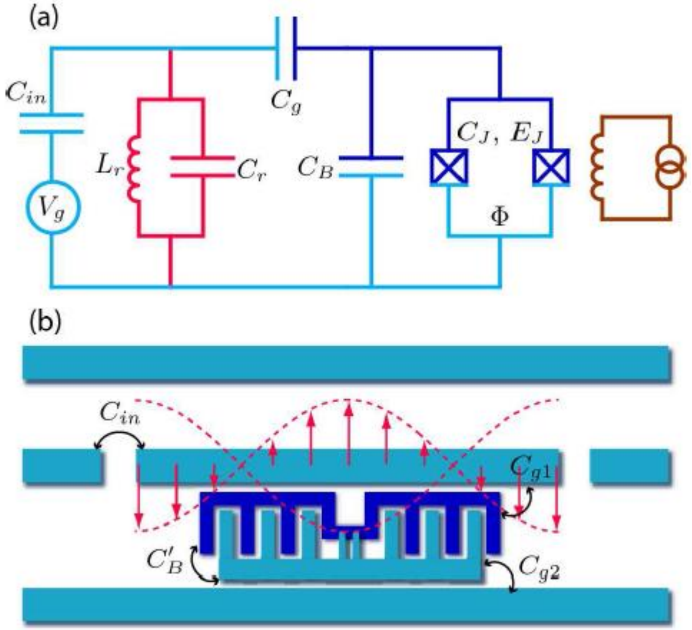
cryostat
temperature
0.014K

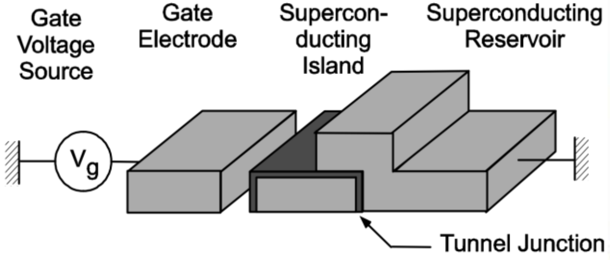
"Demonstration of a quantum error detection code using a square lattice of four superconducting qubits", A.D. Córcoles et al., **Nat. Comm.**, 6:6979 (2015)

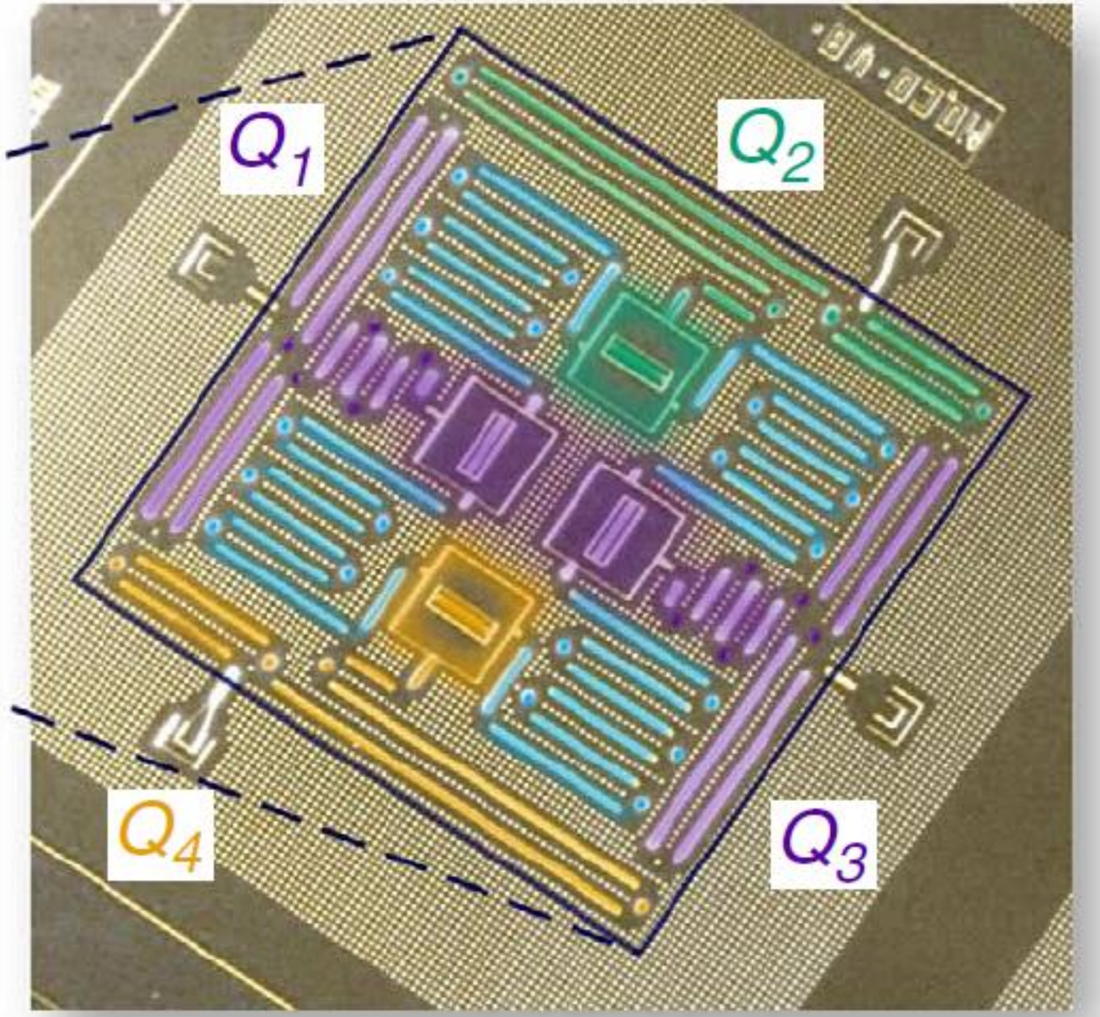
Transmon Qubit

IBM **Q**

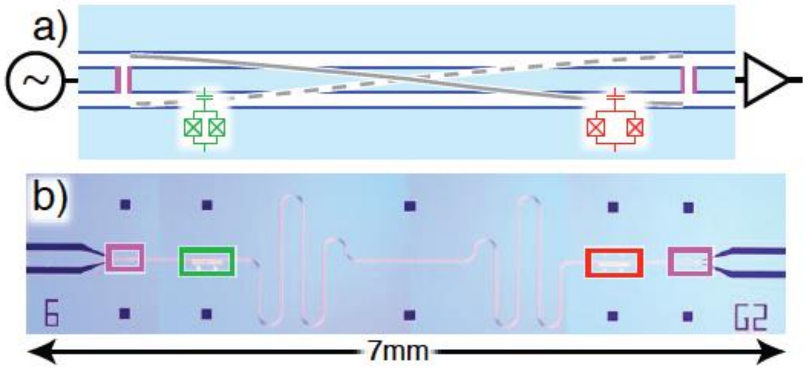
a „transmission-line shunted plasma oscillation qubit“ [1]







taken from [3]



coupling qubits via cavity bus [2]

[1] “Charge insensitive qubit design derived from the Cooper pair box”, J. Koch et al., Phys. Rev. A 76, 042319 (2007)
[2] “Coupling Superconducting Qubits via a Cavity Bus”, J. Majer et al., Nature 449, 443-447 (2007)
[3] “Demonstration of a quantum error detection code using a square lattice of four superconducting qubits”, A.D. Córcoles et al., Nat. Comm., 6:6979 (2015)

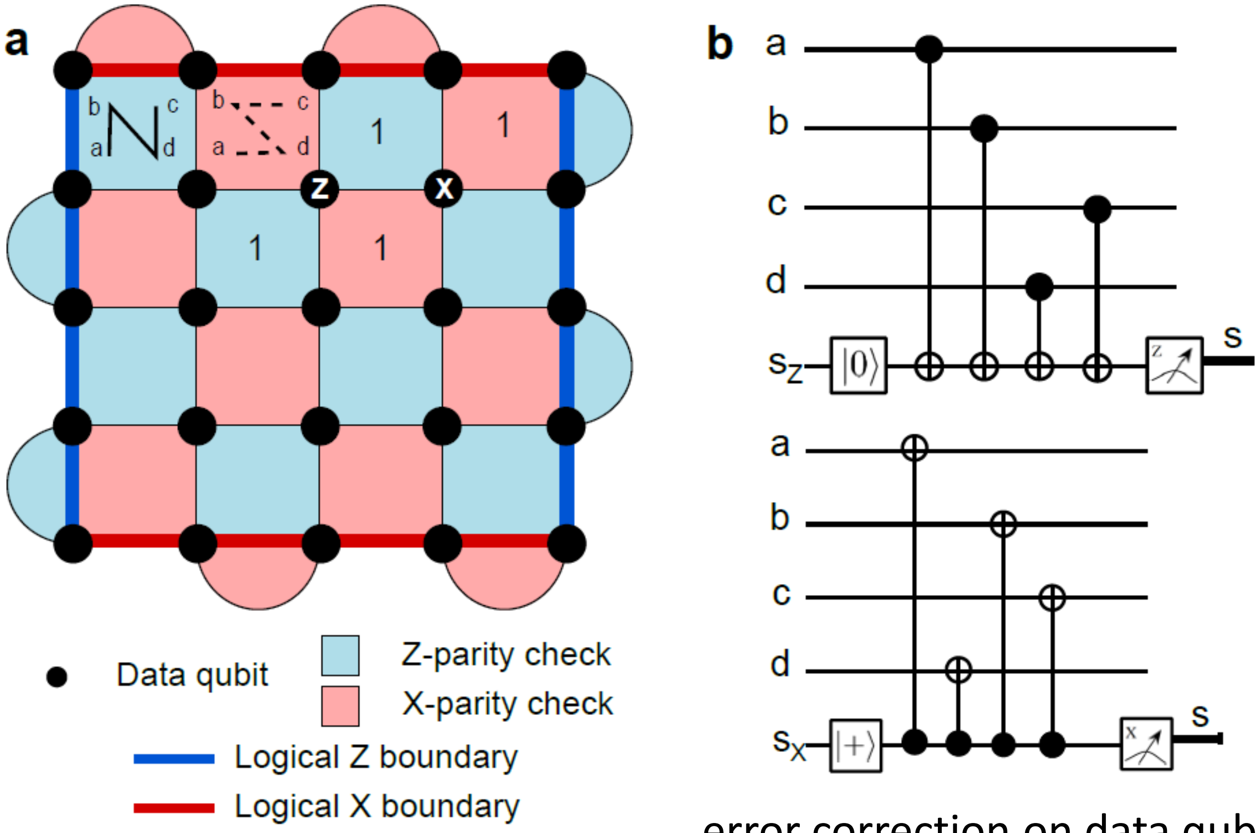
A Scalable Quantum Chip Architecture

IBM Q

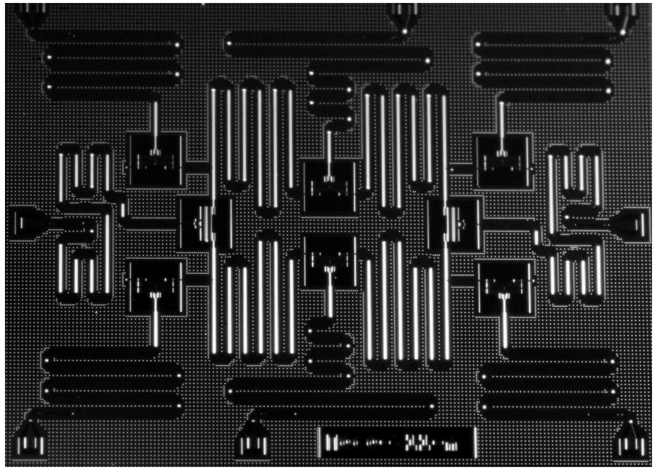
fault-tolerant quantum computing via the surface code

topological quantum computing

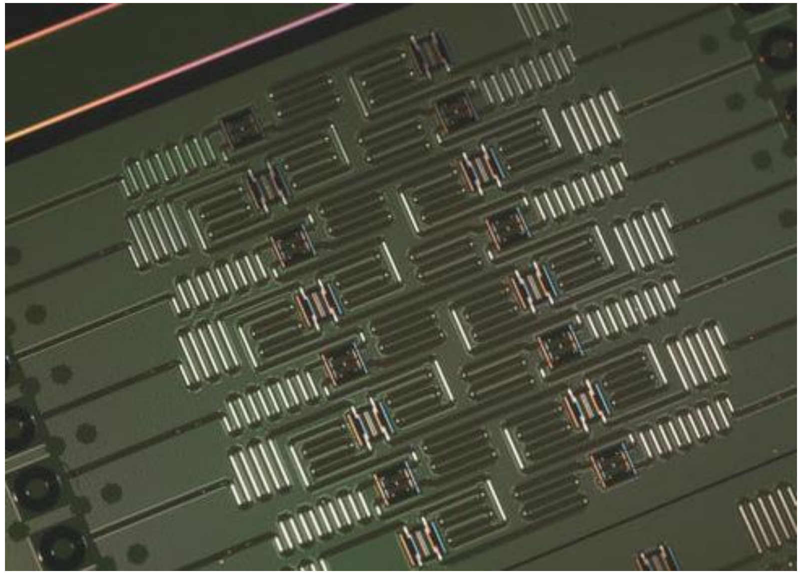
logical qubits formed by delocalized states of data qubits



error correction on data qubits



8 Qubits / 4 Buses / 8 Readouts



16 Qubits / 22 Buses / 16 Readouts

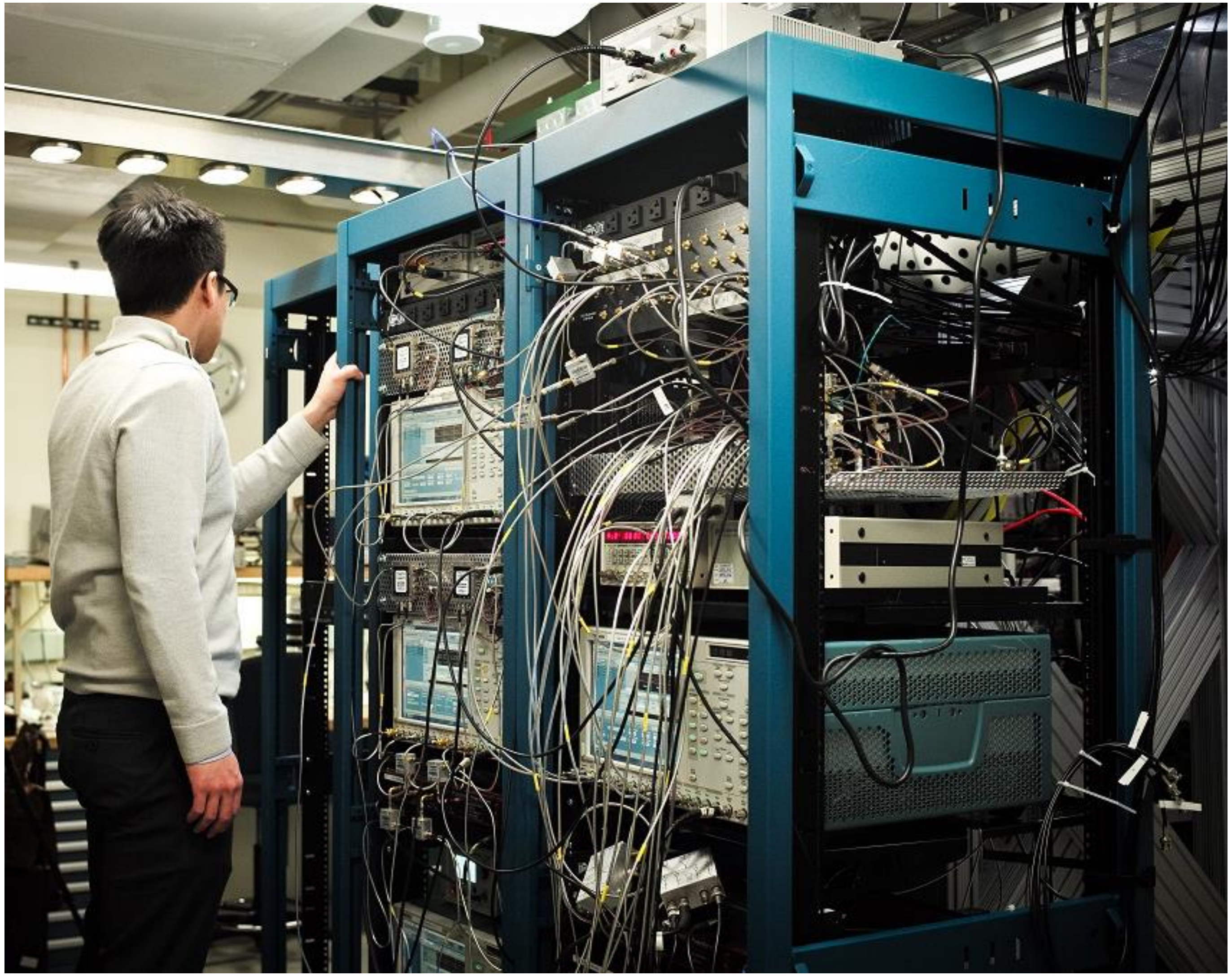
"Building logical qubits in a superconducting quantum computing system", J. Gambetta et al., npj Quantum Information 3, 2 (2017)

Lab Environment

IBM Q

rf electronic equipment

dilution refrigerators

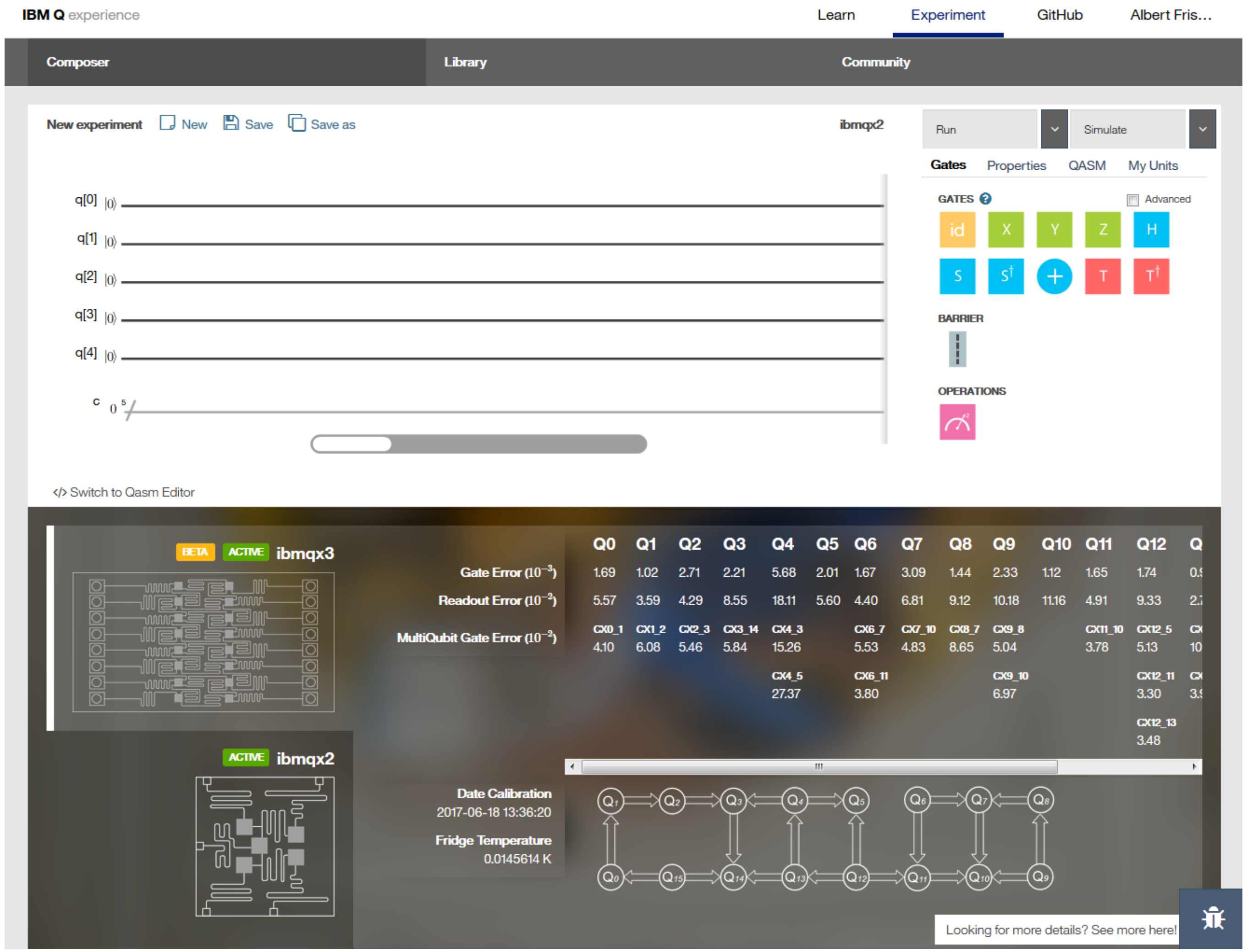


quantum programming

IBM Quantum Experience

IBM Q

www.ibm.com/quantumexperience



The worlds first

cloud quantum computer

Over 40,000 users

All 7 continents

>150 colleges and Universities

Over 300,000 experiments

Live Demo

IBM **Q**

Help

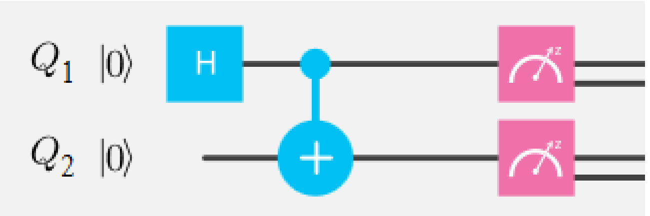
×

- **Id** — The identity gate performs an idle operation on the qubit for a time equal to the single-qubit gate duration.
- **X** — The Pauli X gate is a π-rotation around the X axis and has the property that $X \to X$, $Z \to -Z$. Also referred to as a bit-flip.
- **Z** — The Pauli Z gate is a π-rotation around the Z axis and has the property that $X \to -X$, $Z \to Z$. Also referred to as a phase-flip.
- **Y** — The Pauli Y gate is a π-rotation around the Y axis and has the property that $X \to -X$, $Z \to -Z$. This is both a bit-flip and a phase-flip, and satisfies $Y = XZ$.
- **H** — The Hadamard gate has the property that it maps $X \to Z$, and $Z \to X$. This gate is required to make superpositions.
- **S** — The Phase gate that is $\sqrt{Z}$ and has the property that it maps $X \to Y$ and $Z \to Z$. This gate extends H to make complex superpositions.
- **$S^\dagger$** — The Phase gate that is the transposed conjugate of S and has the property that it maps $X \to -Y$, and $Z \to Z$.
- **+** — Controlled-NOT gate: a two-qubit gate that flips the target qubit (i.e. applies Pauli X) if the control is in state 1. This gate is required to generate entanglement.
- **T** — The Phase gate that is $\sqrt{S}$, which is a $\pi/4$ rotation around the Z axis. This gate is required for universal control.
- **$T^\dagger$** — The Phase gate that is the transposed conjugate of T.
- Measurement in the computational (standard) basis (Z).
- Bloch measurement: Tomography of the individual qubits.

Show Tips

QISKit - OPENQASM

IBM Q



quantum score file

OPENQASM 2.0

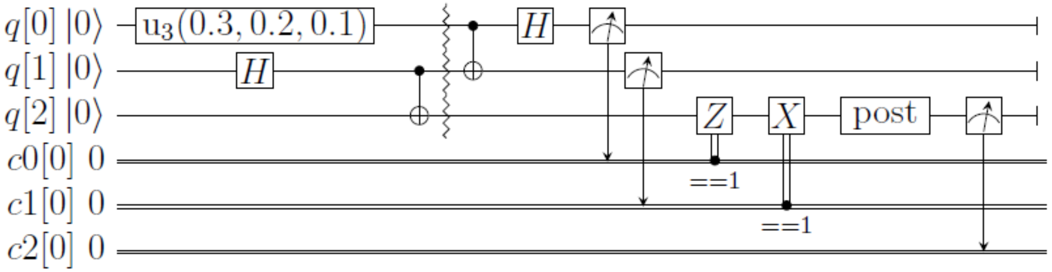
```
include "qelib1.inc";
qreg q[5];
creg c[5];

h q[0];
cx q[0],q[1];
measure q[1] -> c[1];
measure q[0] -> c[0];
```

https://developer.ibm.com/open/openprojects/qiskit/

e.g. quantum teleportation

```
// quantum teleportation example
IBMQASM 2.0;
include "qelib1.inc";
qreg q[3];
creg c0[1];
creg c1[1];
creg c2[1];
// optional post-rotation for state tomography
gate post q { }
u3(0.3,0.2,0.1) q[0];
h q[1];
cx q[1],q[2];
barrier q;
cx q[0],q[1];
h q[0];
```

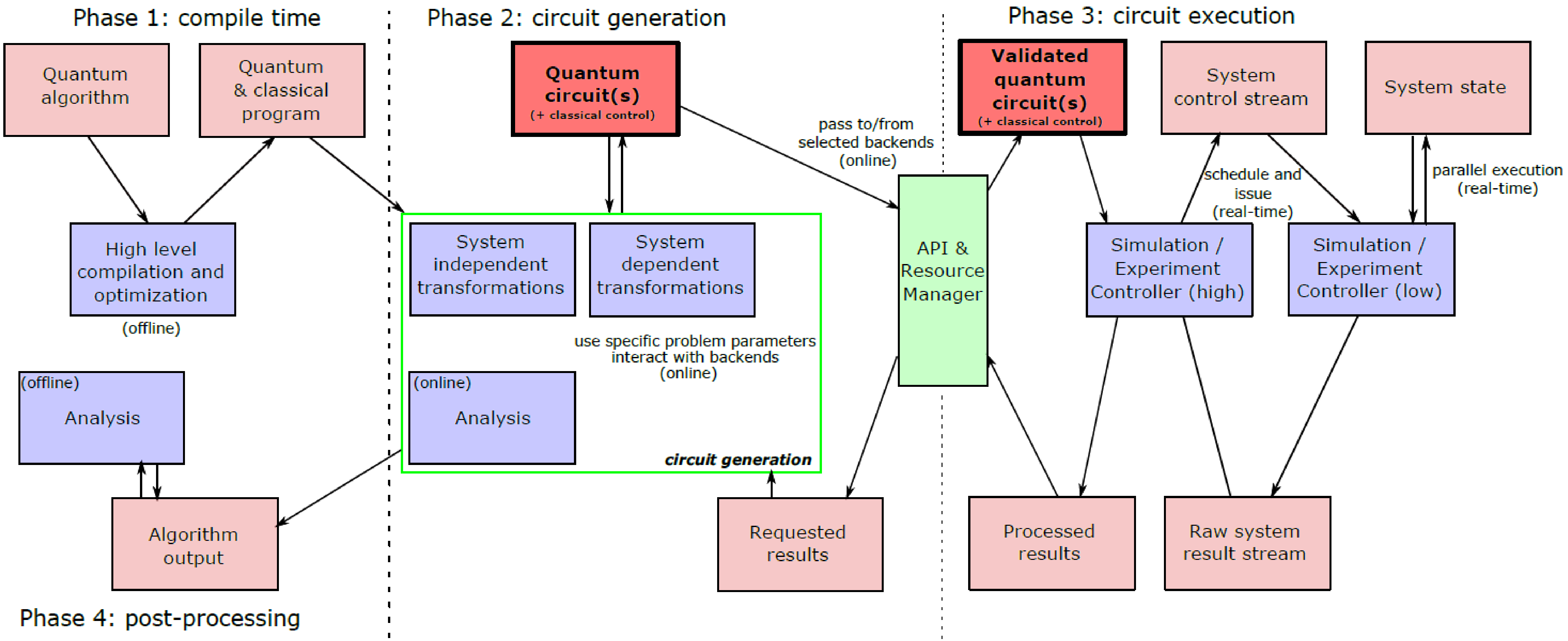


IBM Q

demo

QISKit - Executing Quantum Algorithms

IBM Q



QISKit – Python API and SDK

IBM Q

execute OPENQASM code from Python, e.g. Jupyter Notebook

Getting Started

Now it's time to begin doing real work with Python and the Quantum Experience. First, we import the Python interface for web API:

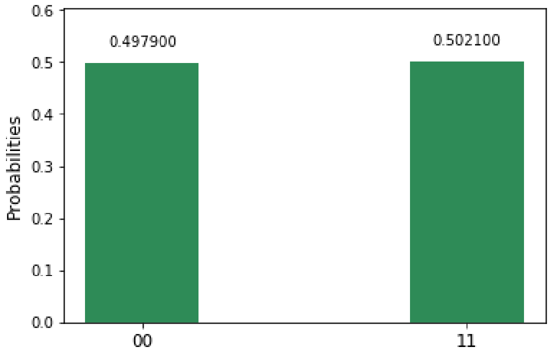
In [1]:
```
import sys
if sys.version_info < (3,0):
    raise Exception("Please use Python version 3 or greater.")
from IBMQuantumExperience import IBMQuantumExperience
```

In [2]:
```
import Qconfig
api = IBMQuantumExperience.IBMQuantumExperience(Qconfig.APItoken, Qconfig.config)
```

In [5]:
```
out = api.run_job(qasms = [{'qasm' : make_bell}],device = 'sim',shots = 1024, max_credits=3)
print(out['status'])
```

In [7]:
```
get_data = lambda results, i: results['qasms'][i]['result']['data']['counts']
```

In [8]:
```
data=get_data(results,0)
```



https://developer.ibm.com/open/openprojects/qiskit/

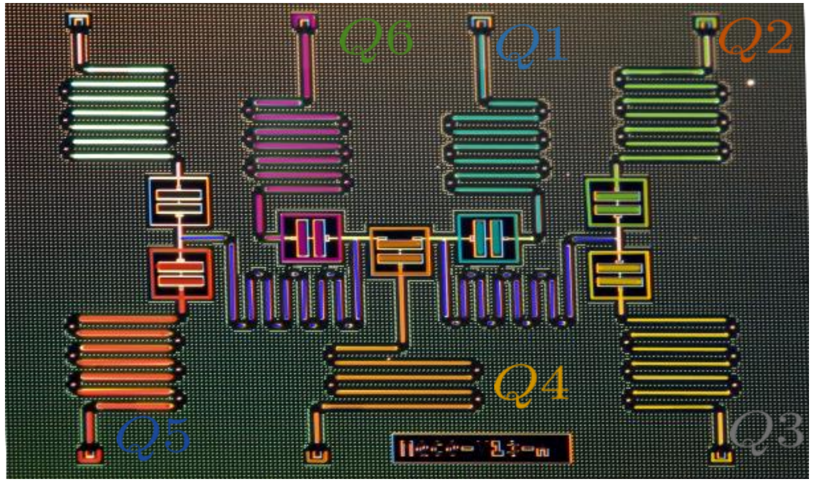
https://github.com/QISKit/

optimization

Hybrid Quantum-Classical Approach

IBM Q

A simple hybrid quantum-classical algorithm can be used to solve problems by minimizing the energy of the qubit system.



$$E(\theta)$$

$$\theta$$

Prepare a trial state $|\psi(\theta)\rangle$ and compute its energy $E(\theta)$

Use classical optimizer to choose a new value of θ to try

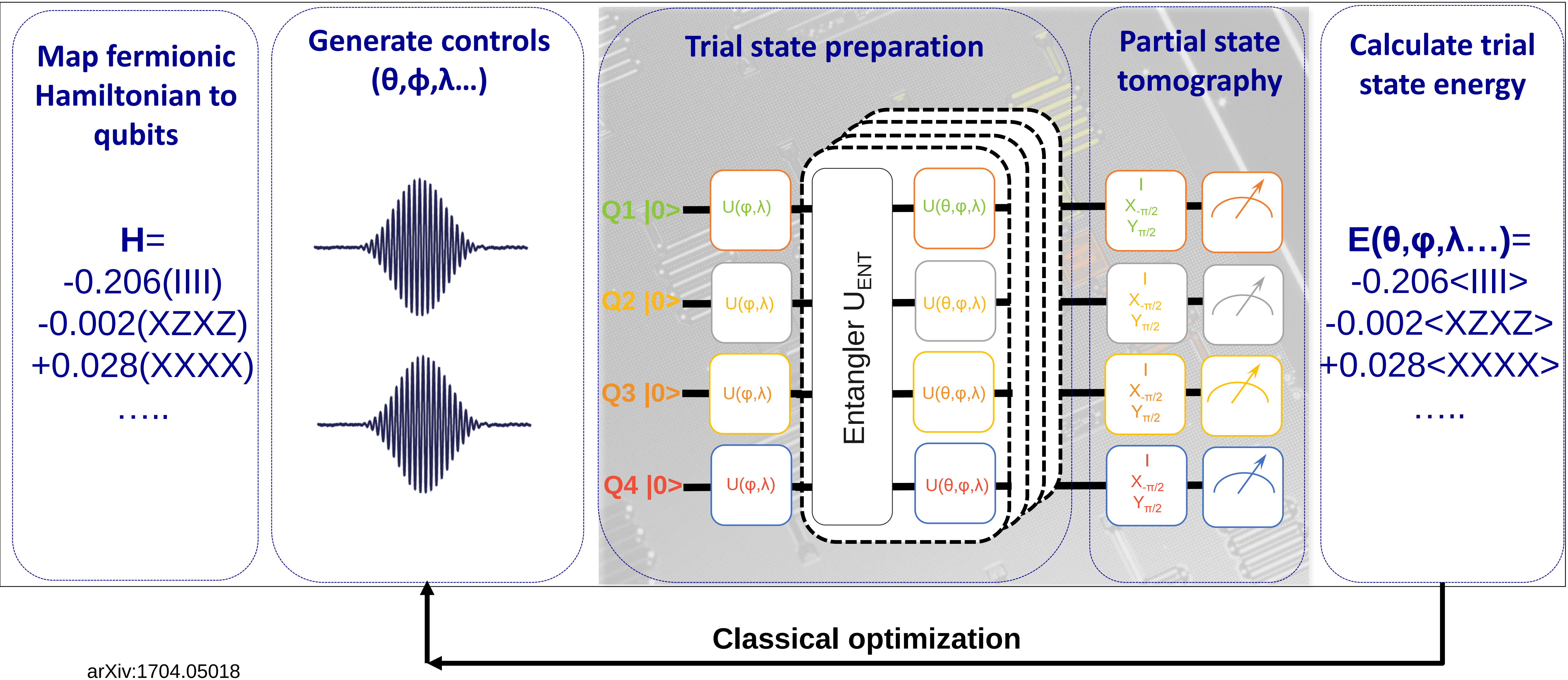
Advantages:

Use short circuits which fit into our coherence time

Improve on best classical estimates by using non-classical trial states

Quantum Chemistry Experiment

IBM Q



arXiv:1704.05018

Weighted Max-Cut

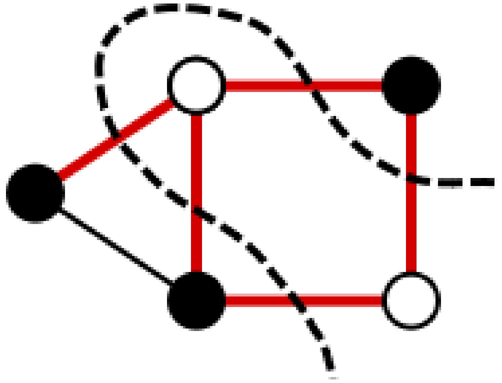
IBM Q

where to cut a graph while maximizing the number of edges between two subsets?

NP-complete problem
applications in clustering, network science, and statistical physics
N nodes, weights of edges w_{ij}, weights of nodes w_i

1. cost function

$$C(\mathbf{x}) = \sum_{i,j} w_{ij} x_i (1 - x_j) + \sum_i w_i x_i$$



maxcut problem - wikipedia

2. rewrite using Pauli matrices N qubits necessary

$$x_i \to (1 - Z_i)/2$$

$$C(\mathbf{Z}) = \sum_{i<j} \frac{w_{ij}}{2}(1 - Z_i)(1 + Z_j) + \sum_i w_i (1 - Z_i)/2 =$$

$$= -\frac{1}{2}\left(\sum_{i<j} w_{ij} Z_i Z_j + \sum_i w_i Z_i\right) + \text{const}$$

3. solve Ising Hamiltonian

$$H = \sum_i w_i Z_i + \sum_{i<j} w_{ij} Z_i Z_j$$

Travelling Salesman Problem

IBM **Q**

what is the shortest route to visit each city once and return to the origin city?

NP-complete problem, important applications in finance and marketing
N nodes, distances as weights w_{ij}
(N-1)! possible routes
N^2 variables $x_{i,p}$, i … nodes, p … order in list

TSP - wikipedia

1. cost function

$$C(\mathbf{x}) = \underbrace{\sum_{i,j=1}^{N-1} w_{ij} \sum_{p=1}^{N-1} x_{i,p} x_{j,p+1}}_{\text{total distance}} + \underbrace{\sum_{j=1}^{N-1} w_{0j} x_{j,1} + \sum_{i=1}^{N-1} w_{i0} x_{i,N-1}}_{\text{return to original city}} + \underbrace{A \sum_{p=1}^{N-1} \left(1 - \sum_{i=1}^{N-1} x_{i,p}\right)^2}_{\text{every city only once}} + \underbrace{A \sum_{i=1}^{N-1} \left(1 - \sum_{p=1}^{N-1} x_{i,p}\right)^2}_{\text{each time one node}}$$

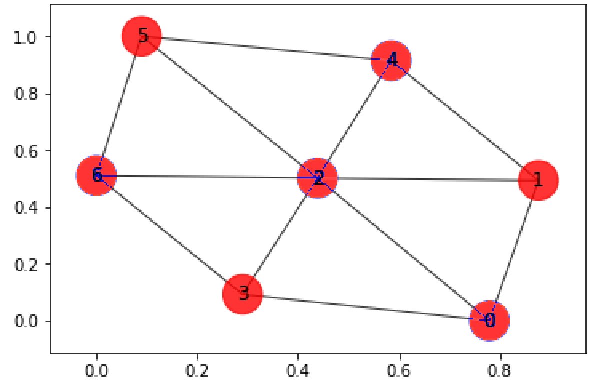
2. rewrite using Pauli matrices $(N-1)^2$ qubits necessary

3. solve Ising Hamiltonian

Quantum Approximate Optimization Algorithm

IBM Q

```
[[ 0.  1.  1.  1.  0.  0.  0.]
 [ 1.  0.  1.  0.  1.  0.  0.]
 [ 1.  1.  0.  1.  1.  1.  1.]
 [ 1.  0.  1.  0.  0.  0.  1.]
 [ 0.  1.  1.  0.  0.  1.  0.]
 [ 0.  0.  1.  0.  1.  0.  1.]
 [ 0.  0.  1.  1.  0.  1.  0.]]
```



same weight on all edges

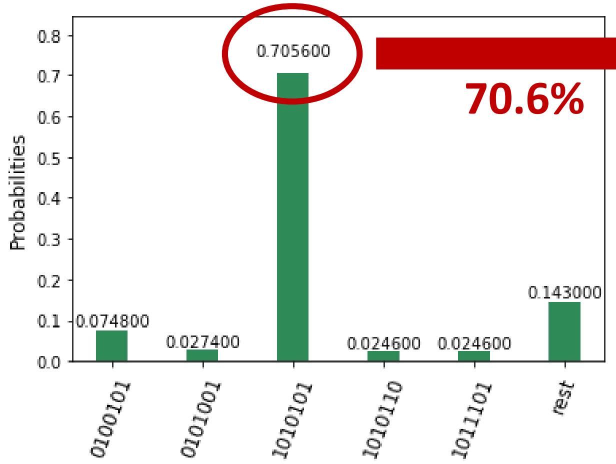
1. **choose w_{ij} and w_i from Ising Hamiltonian**
2. **choose depth m of quantum circuit**
3. **choose set of control values θ and create trial quantum state $|\psi(\theta)\rangle$**

$$|\psi(\theta)\rangle = \left[U_{\text{single}}(\theta)U_{\text{entangler}}\right]^m |+\rangle \qquad U_{\text{single}}(\theta) = \prod_{i=1}^{n} Y(\theta_i)$$

4. **evaluate Ising Hamiltonian on trial function by sampling outcome of quantum circuit**

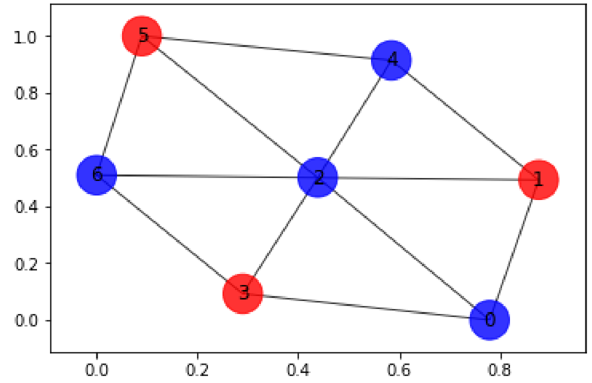
$$C(\boldsymbol{\theta}) = \langle\psi(\boldsymbol{\theta})\,|H|\,\psi(\boldsymbol{\theta})\rangle = \sum_i w_i \langle\psi(\boldsymbol{\theta})\,|Z_i|\,\psi(\boldsymbol{\theta})\rangle + \sum_{i<j} w_{ij} \langle\psi(\boldsymbol{\theta})\,|Z_i Z_j|\,\psi(\boldsymbol{\theta})\rangle$$

5. **use a classical optimizer to choose a new set of θ**
6. **repeat steps 4. and 5. until $C(\theta)$ reaches minimum, close to exact solution θ^* sufficient**
7. **use the last θ to generate the distribution $|\langle z_i|\psi(\theta)\rangle|^2$ $\forall i$ and obtain the answer**



70.6%

one solution is 1010101



E. Farhi, J. Goldstone, S. Gutmann e-print arXiv 1411.4028 (2014)

Example for Trial State Preparation

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$$|\psi(\theta)\rangle = \left[U_{\text{single}}(\theta)U_{\text{entangler}}\right]^m |+\rangle$$

prepare superposition $|+\rangle$ using Hadamard gates

$|+\rangle$

apply $U_{\text{single}}(\theta)U_{\text{entangler}}$ m = 3 times

$U_{\text{entangler}}$

apply $U_{\text{single}}(\theta)U_{\text{entangler}}$ m = 3 times

⋮

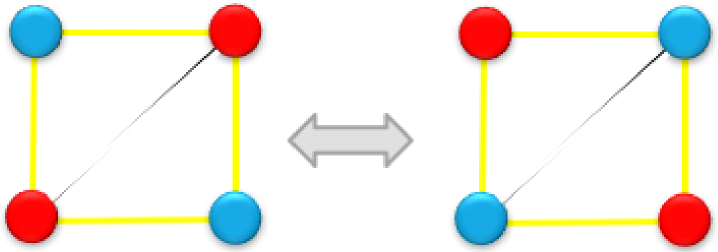
```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[4];
creg c[4];
h q[0];
h q[1];
h q[2];
h q[3];
barrier q[0],q[1],q[2],q[3];
cz q[0],q[1];
cz q[1],q[2];
cz q[2],q[3];
ry(0.774302821967637) q[0];
ry(1.213878478460519) q[1];
ry(0.081014534505463) q[2];
ry(0.639908340049906) q[3];
barrier q[0],q[1],q[2],q[3];
cz q[0],q[1];
cz q[1],q[2];
cz q[2],q[3];
ry(0.594261337237044) q[0];
ry(0.418228030778053) q[1];
ry(-2.294033956355921) q[2];
ry(-1.389598877196701) q[3];
barrier q[0],q[1],q[2],q[3];
cz q[0],q[1];
cz q[1],q[2];
cz q[2],q[3];
ry(2.066783534064343) q[0];
ry(-1.138230423916167) q[1];
ry(0.415789403306592) q[2];
ry(-0.213067545667126) q[3];
barrier q[0],q[1],q[2],q[3];
```

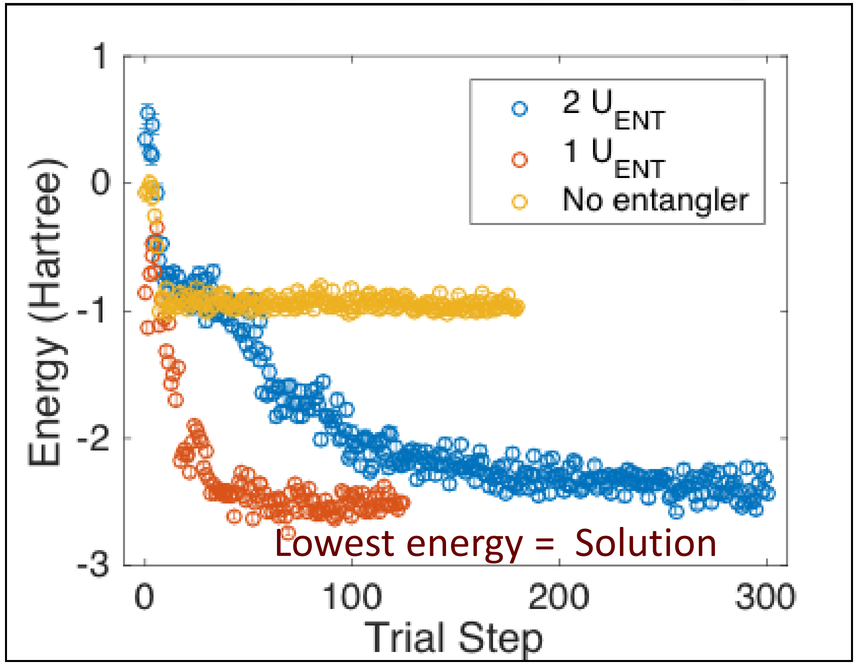
results

MaxCut Optimization - Result Summary

IBM Q

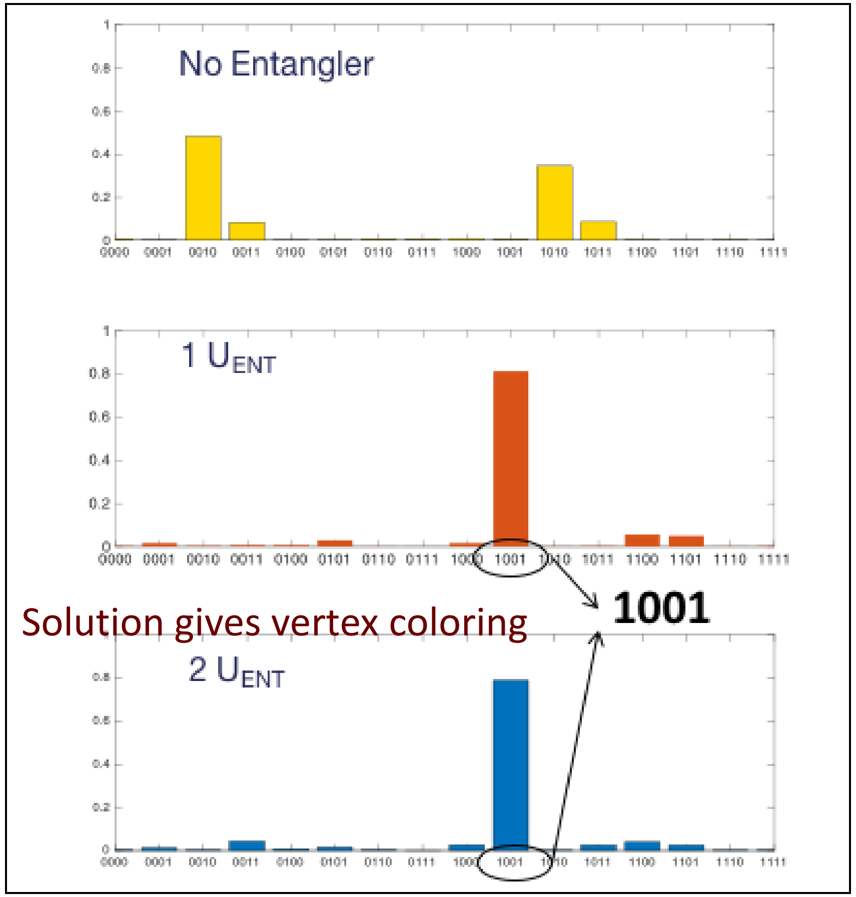
The MaxCut problem: Given a finite graph, color the vertices blue and red such that the number of edges between a blue vertex and a red vertex is as large as possible.





Map problem to qubits:
Express problem as energy
of Qubits- like Utility function

Solve with heuristic algorithm



Traveling Salesman Problem - Result Summary

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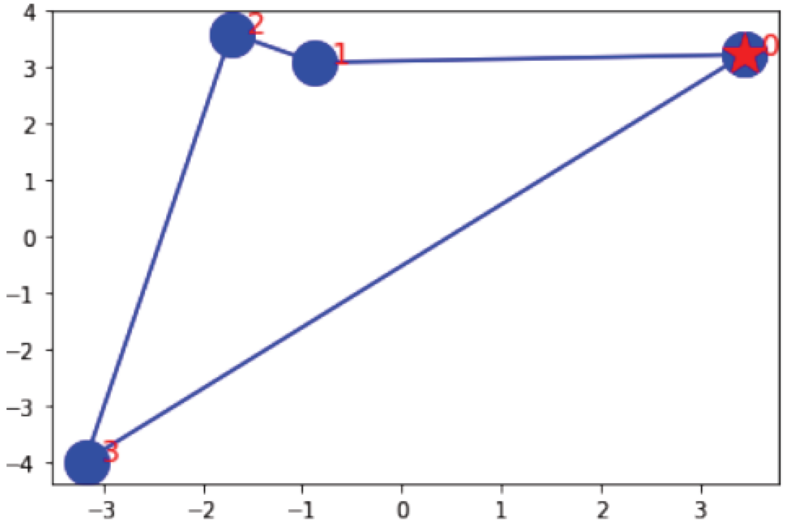
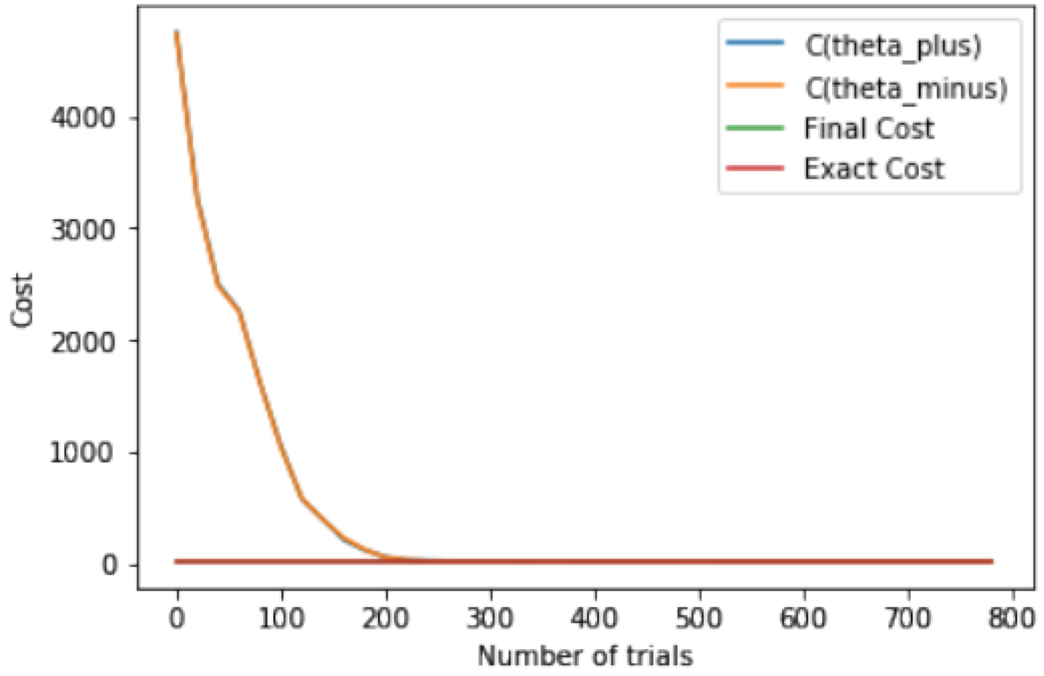
Recall from the introduction that the cost function of the TSP mapped to binary variables is of the form:

$$C(\mathbf{x}) = \sum_{i,j=1}^{N-1} w_{ij} \sum_{p=1}^{N-1} x_{i,p} x_{j,p+1} + \sum_{j=1}^{N-1} w_{0j} x_{j,1} + \sum_{i=1}^{N-1} w_{i0} x_{i,N-1} + A \sum_{p=1}^{N-1} \left(1 - \sum_{i=1}^{N-1} x_{i,p}\right)^2 + A \sum_{i=1}^{N-1} \left(1 - \sum_{p=1}^{N-1} x_{i,p}\right)^2$$



Research:
Understand how Quantum resource scales with problem size, how solution accuracy varies with Quantum Volume and error mitigation



Quantum Simulator – Result Summary

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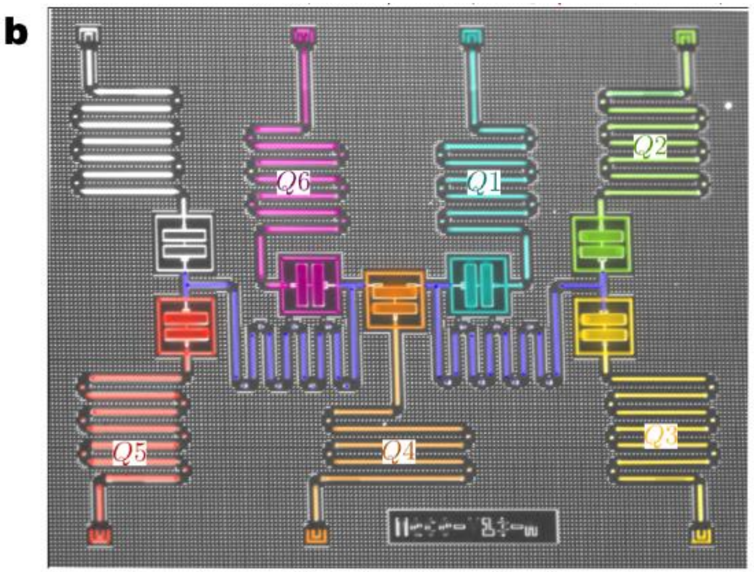
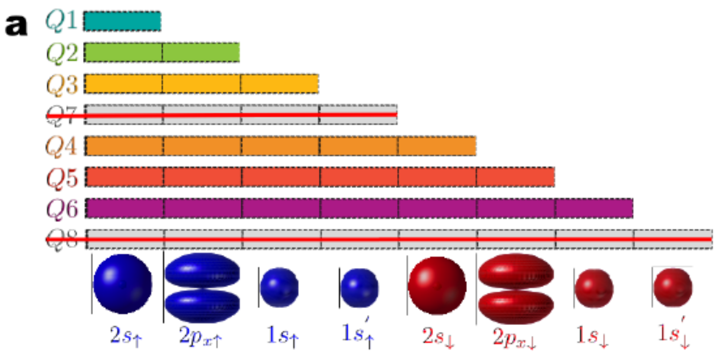
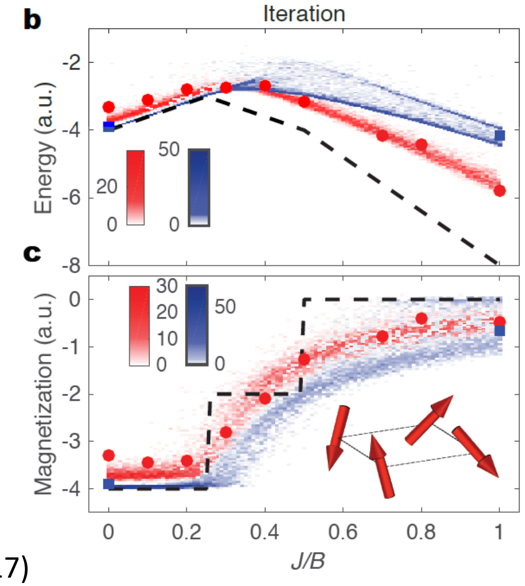
IBM 7-qubit processor used to „encode“ electron orbitals

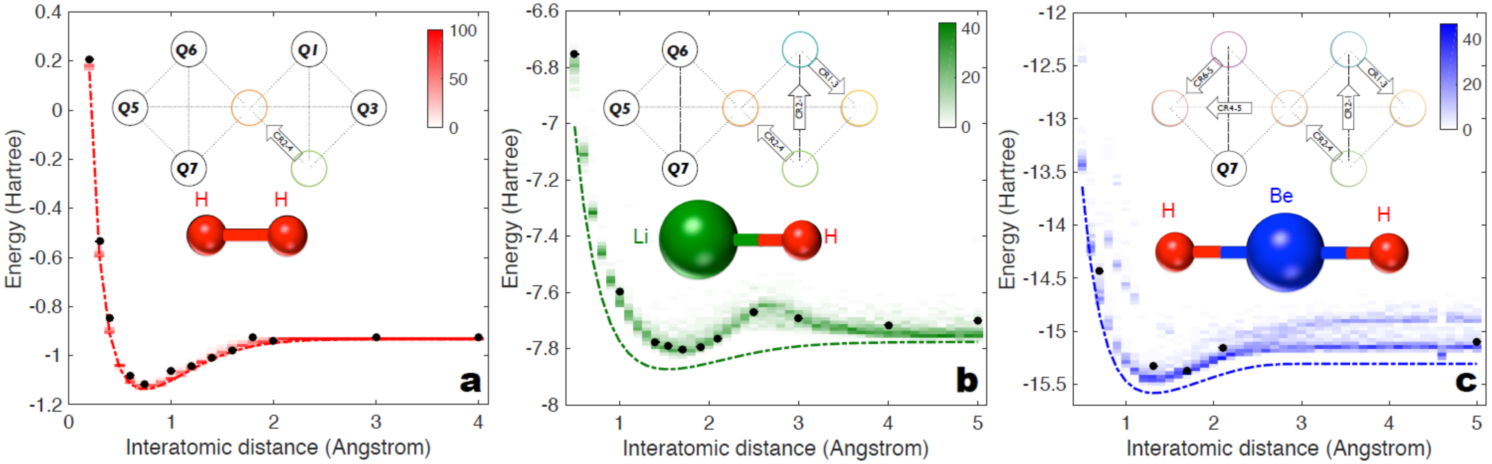




magnetism



chemistry



“Hardware-efficient Quantum Optimizer for Small Molecules and Quantum Magnets”, A. Kandala et al., Nature 549, 242–246 (2017)

Quantum Chemistry - H_2 Molecule (2 qubits)

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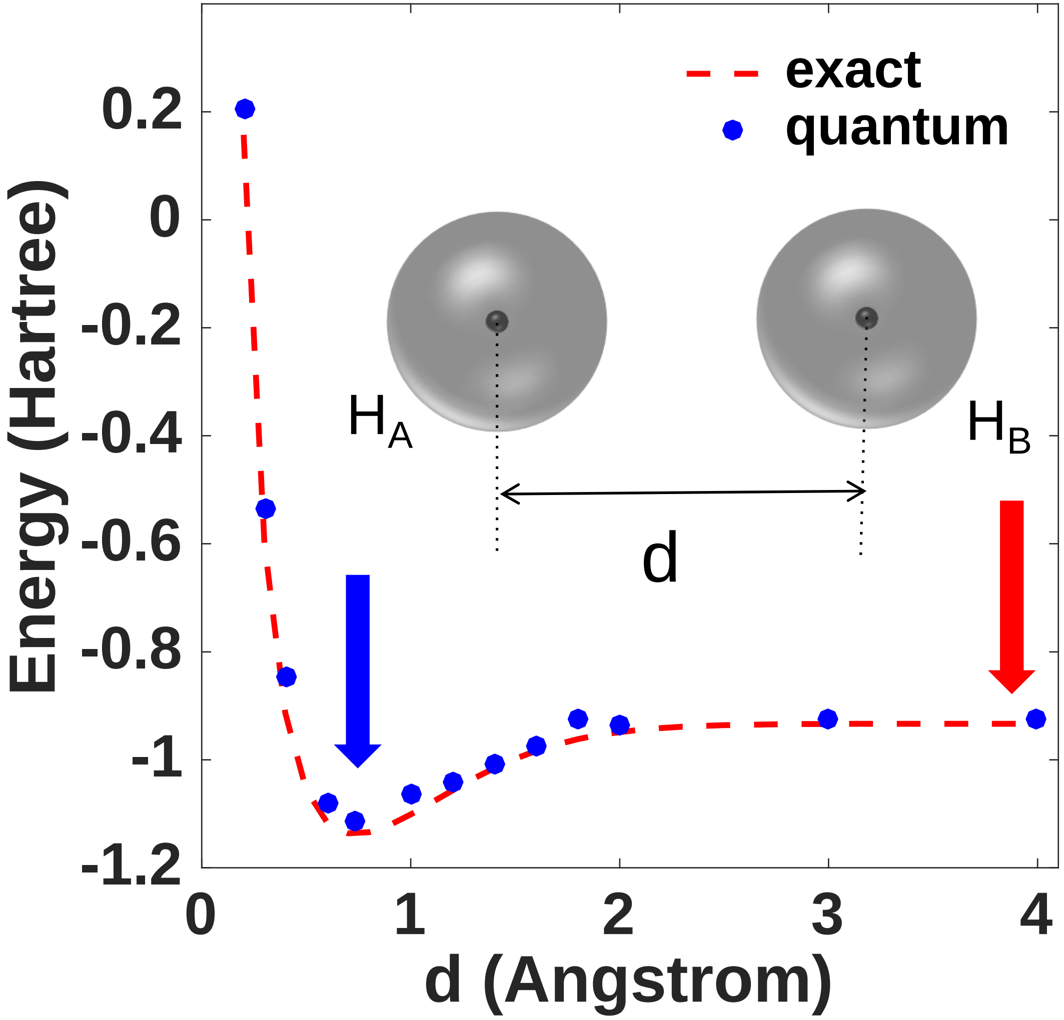
	Equilibrium (d=0.735 Å)	Dissociation (d=4 Å)
Exact	-1.858	-1.0655
1 U_{ENT}	-1.8365	-1.0595
2 U_{ENT}	-1.8229	-1.0586



"Hardware-efficient Quantum Optimizer for Small Molecules and Quantum Magnets", A. Kandala et al., Nature 549, 242–246 (2017)

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