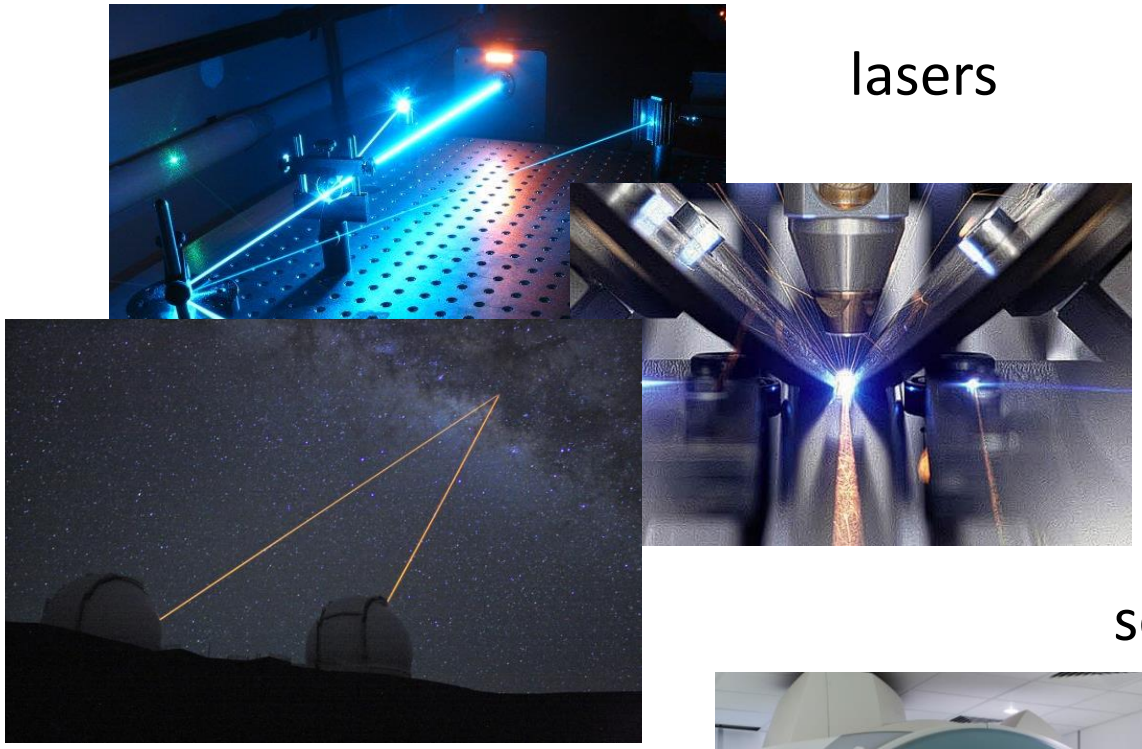
Quantum Computing

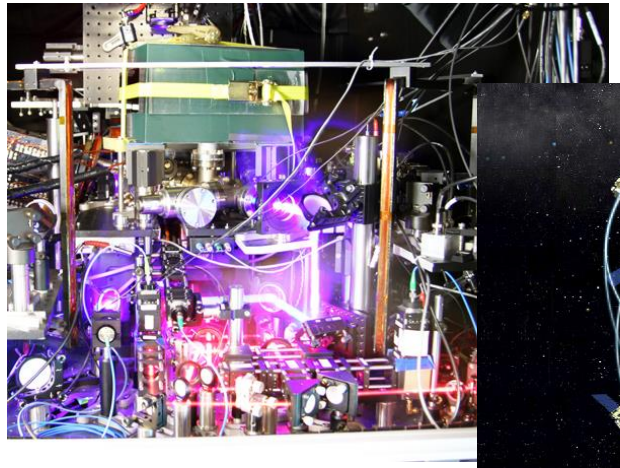
IBM Systems for Cognitive Solutions – Ehningen – 12th of July 2017
Albert Frisch, PhD - albert.frisch@de.ibm.com

1st wave of Quantum Revolution

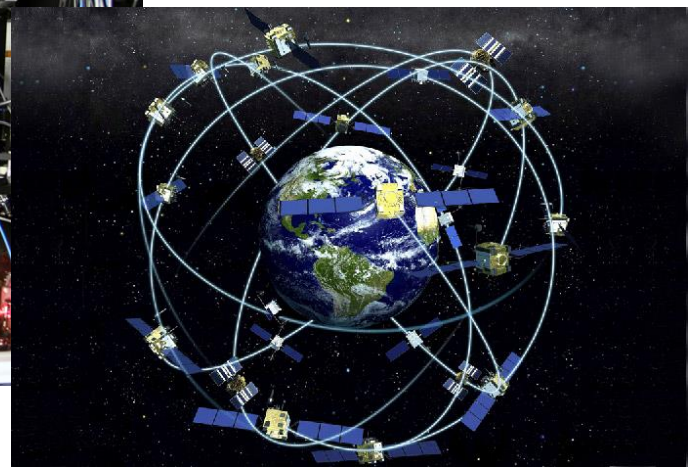
lasers



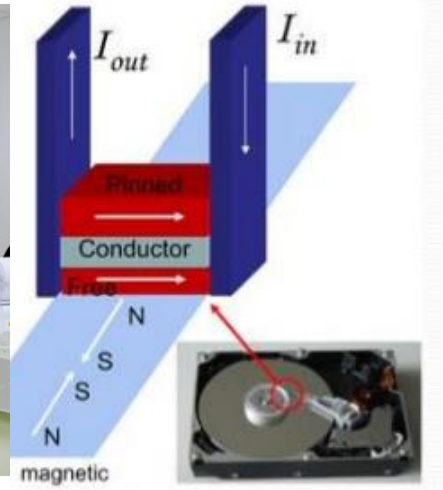
atomic clocks



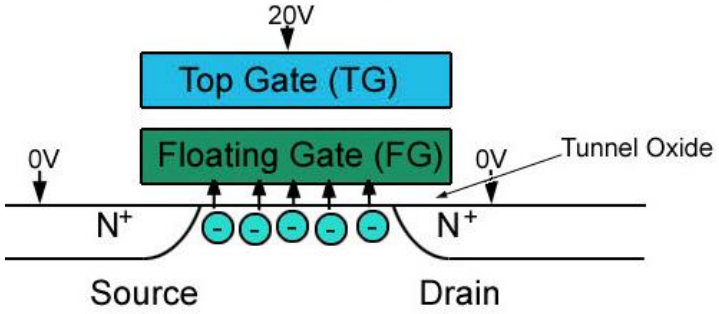
GPS



sensors



flash memory



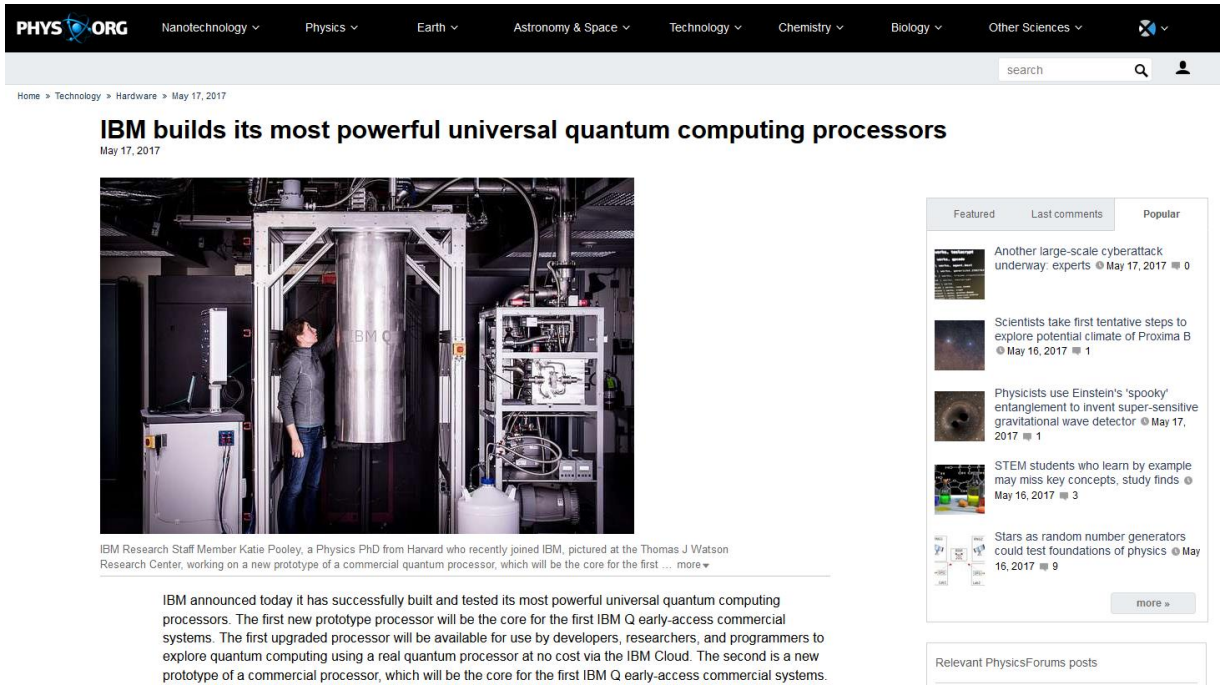
IBM Q

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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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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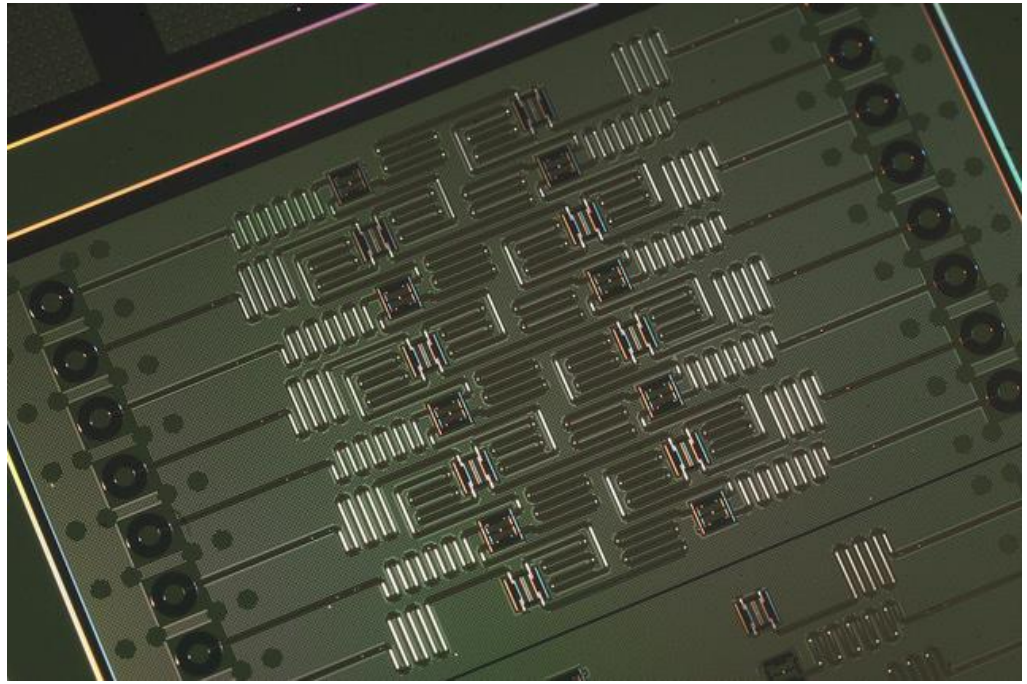
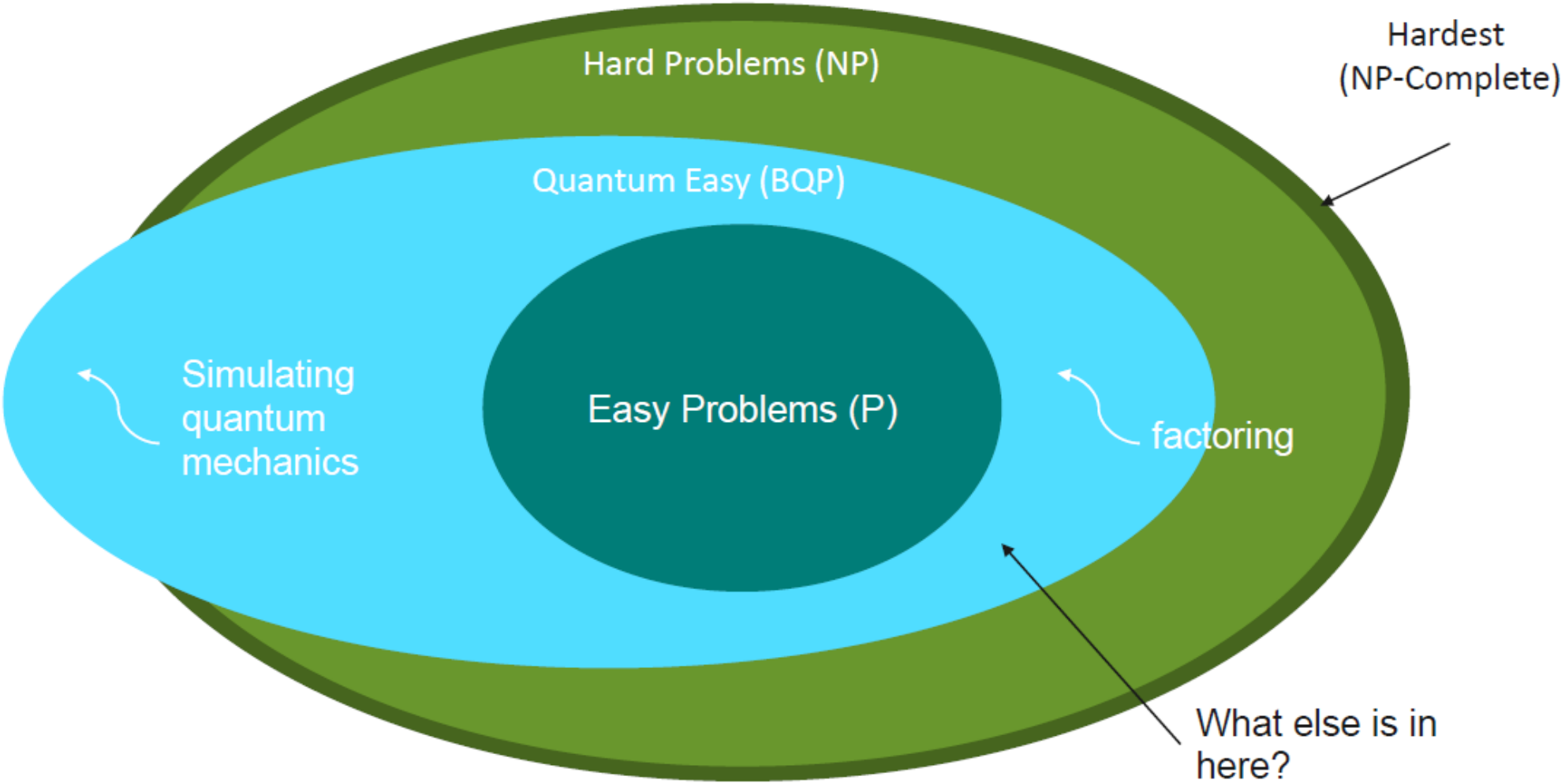
IBM 16-qubit processor



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**

motivation



Lev S. Bishop - https://developer.ibm.com/open/events/dw-open-tech-talk-qiskit-and-quantum-computing/

computing revolution

Medicine & Materials

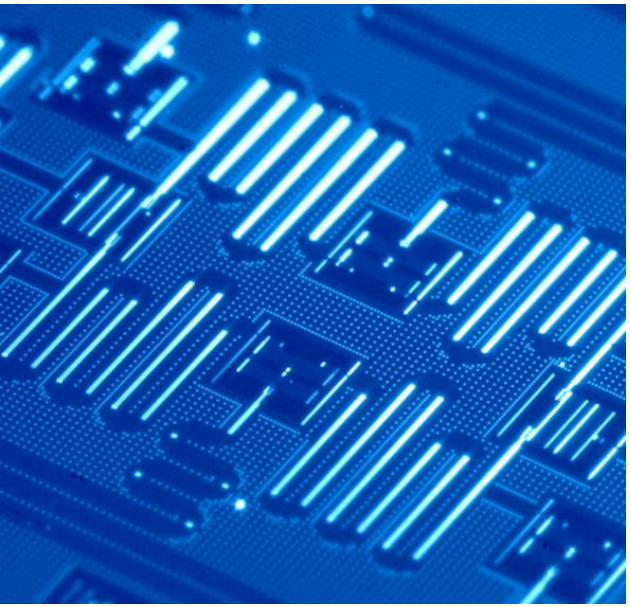
Untangling the complexity of molecular and chemical interactions leading to the discovery of new medicines and materials.

Supply Chain & Logistics

Finding the optimal path for ultra-efficient logistics and global supply chains, such as optimizing fleet operations for deliveries during the holiday season.

Financial Services

Finding new ways to model financial data and isolating key global risk factors to make better investments.



Artificial Intelligence

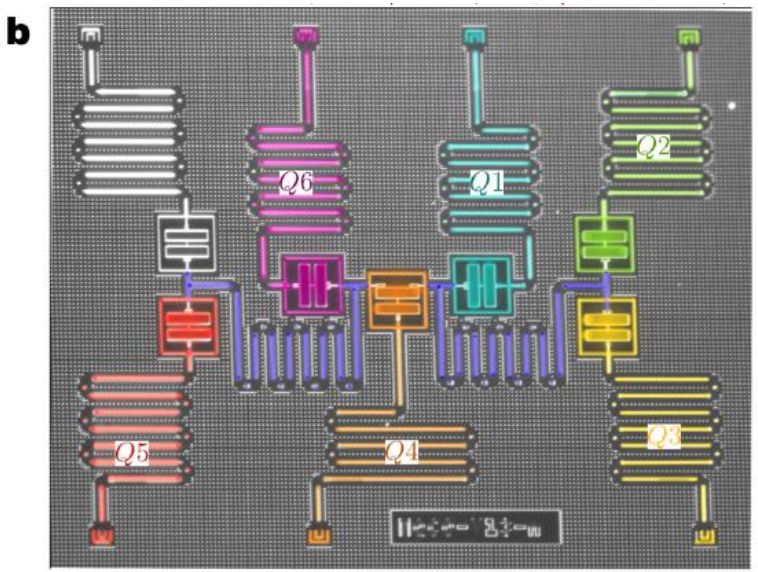
Making facets of artificial intelligence such as machine learning much more powerful when data sets are very large, such as in searching images or video.

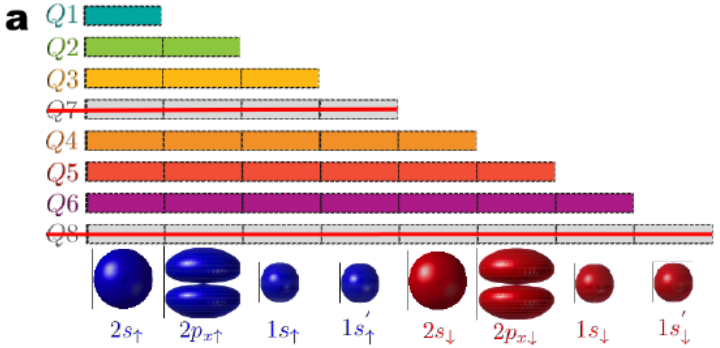
Cloud Security

Making cloud computing more secure by using the laws of quantum physics to keep private data safe no matter where it is stored or processed.

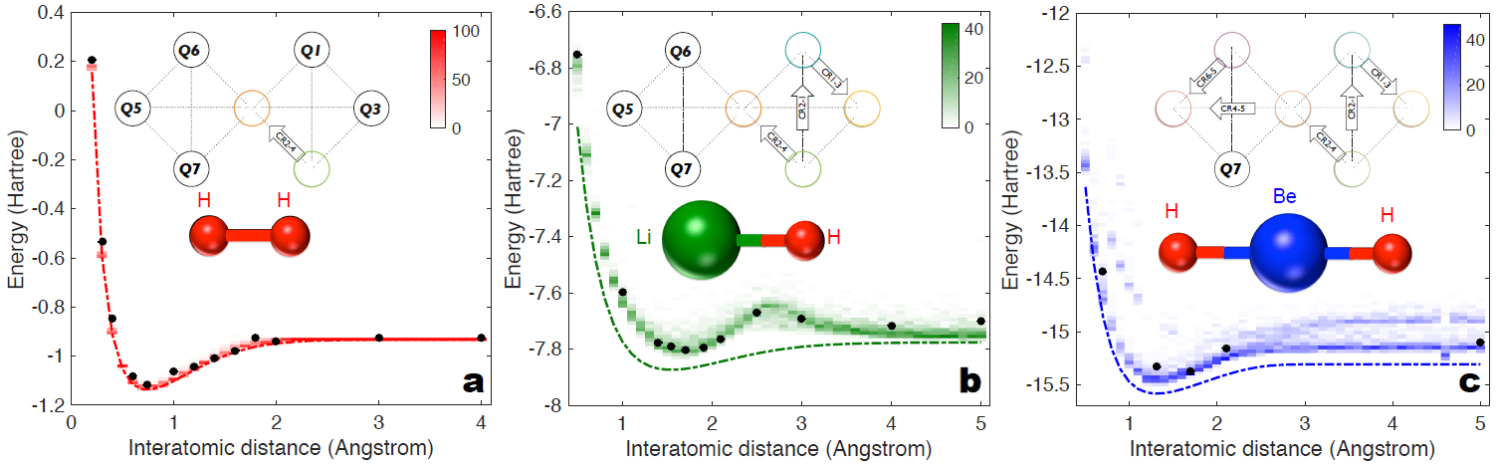
quantum simulator

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

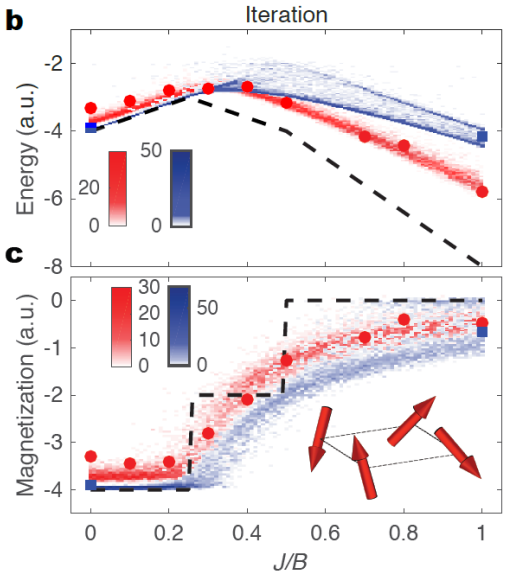




chemistry



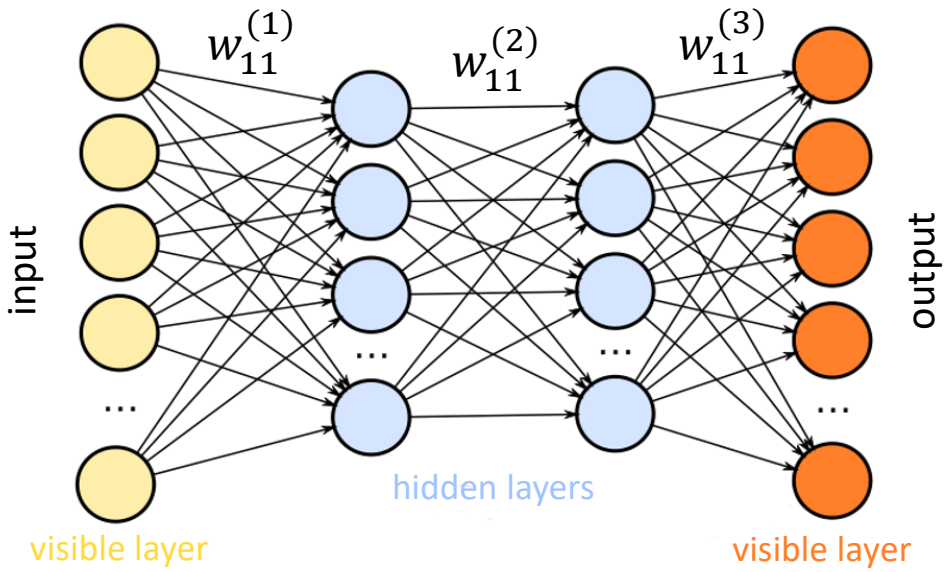
magnetism



“Hardware-efficient Quantum Optimizer for Small Molecules and Quantum Magnets”, A. Kandala et al., arxiv 1704.05018 (2017)

quantum-enhanced machine learning

e.g. deep learning neural network



Ising model at thermal equilibrium

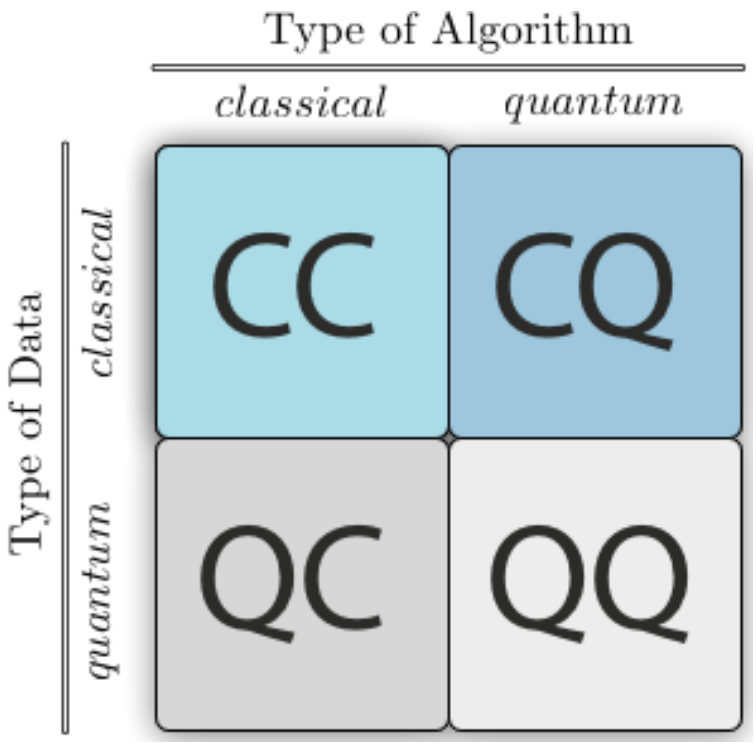
$$E(\mathbf{v},\mathbf{h}) = -\sum_i a_i v_i - \sum_j b_j h_j - \sum_{i,j} w_{ij} v_i h_j$$

→ minimize energy for optimal learning

solving systems of linear equations
classical: $O(N)$, quantum: $O(\log(N))$

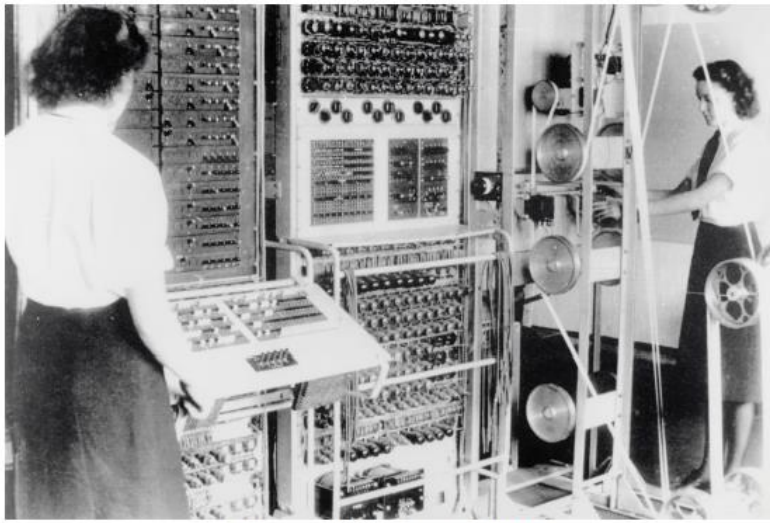
"Advances in quantum machine learning", J. C. Adcock et al., arxiv 1512.02900 (2015)

data processing for
quantum neural networks

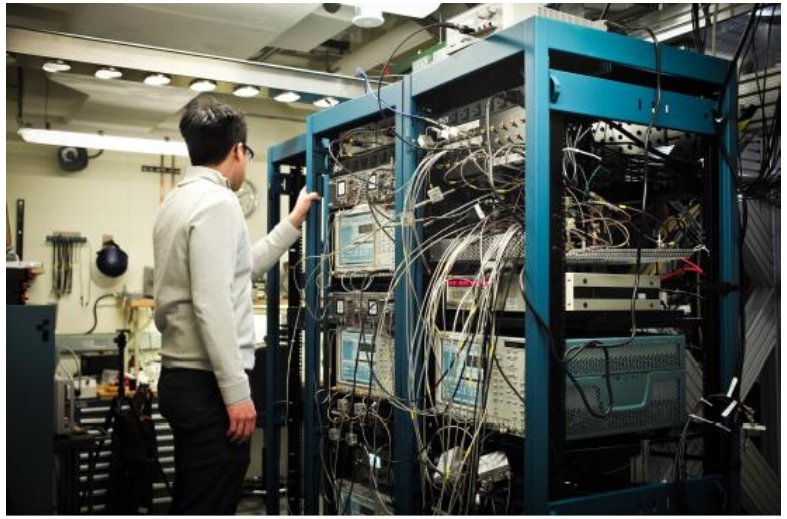


source: wikipedia

The Quantum World



Classical Computer, 1940s



Quantum Computer, 2010s

classical computer

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

n bits $\rightarrow 2^n$ possible states, one at a time

quantum computer

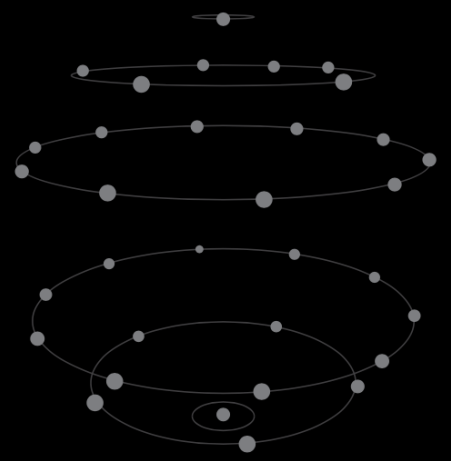
uses **qubits** to take advantage of quantum speedup

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

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

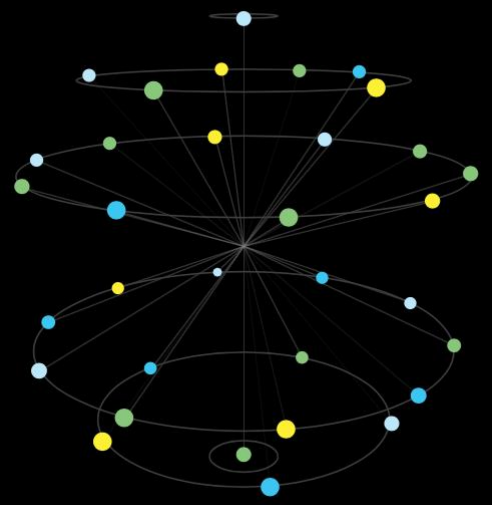
e.g. $|\psi\rangle = \mathrm{a}|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + \cdots$

a quantum algorithm



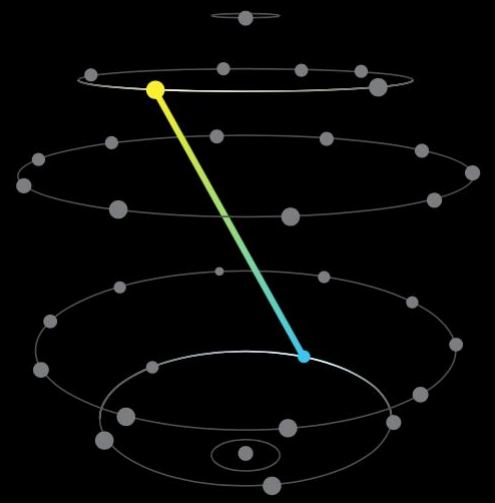
The spread

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

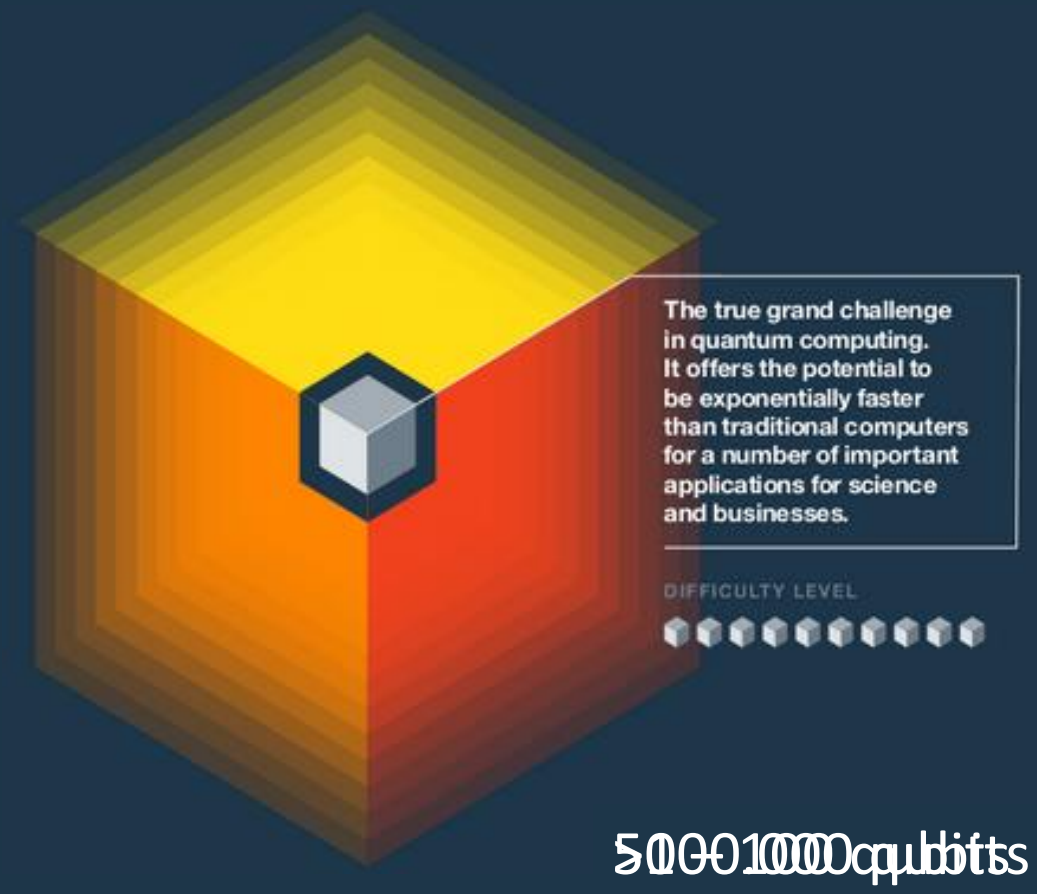


The magic

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

three steps of development

3. Universal Quantum Computer



applications

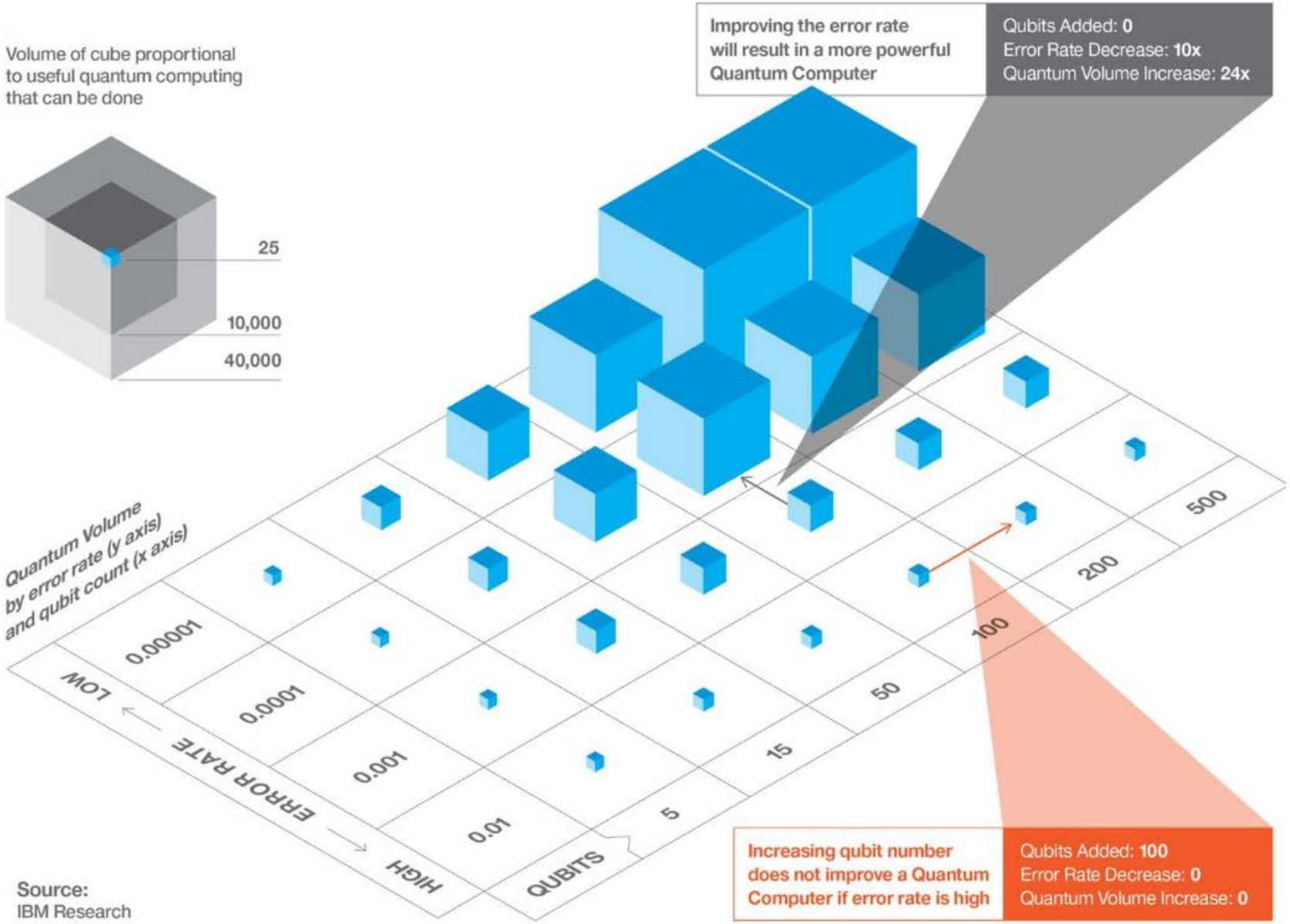
cryptography
searching
machine learning

optimization
quantum chemistry
material sciences
quantum dynamics

generality
complete

computational power
very high

Quantum Volume



qubits

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

superposition

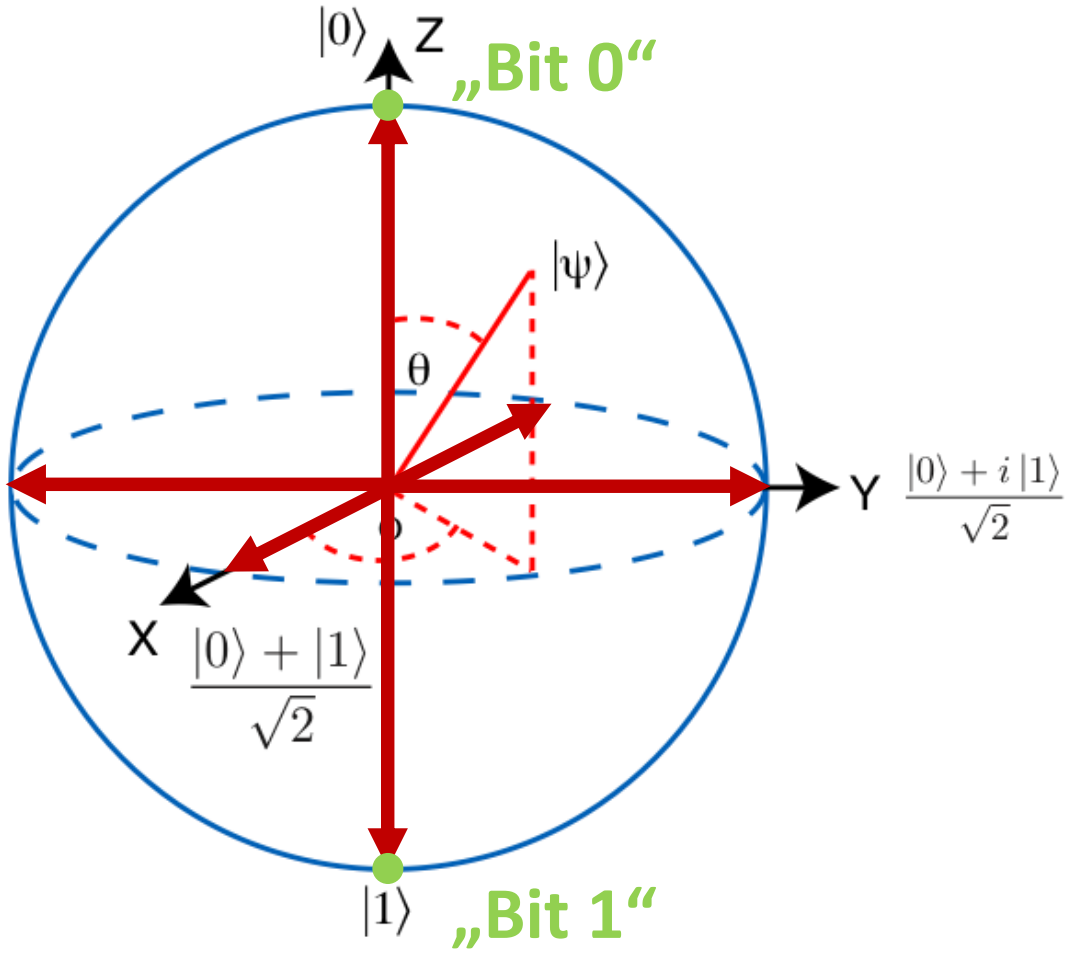
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

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

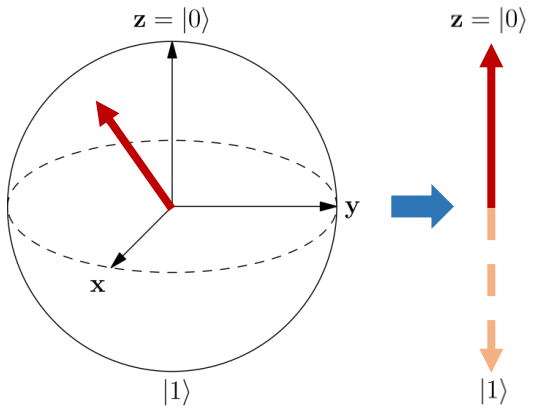


IBM Quantum Experience - quantumexperience.ng.bluemix.net/

measurement and quantum gates

measurement

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



probability

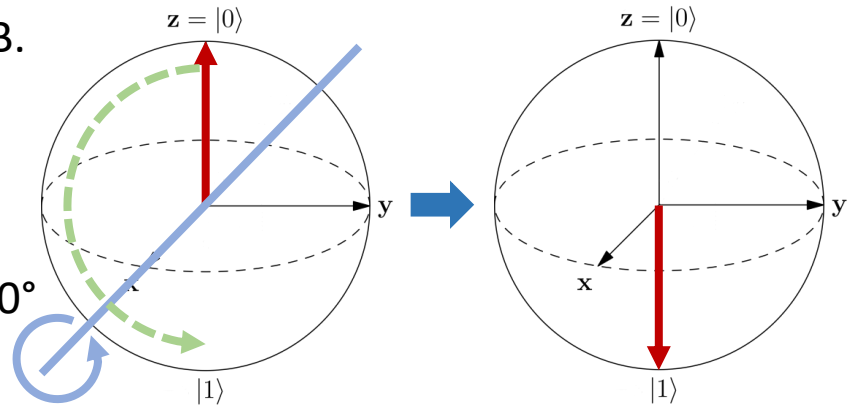
either $|0\rangle$ $\quad |\alpha|^2$

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

rotations

z.B.

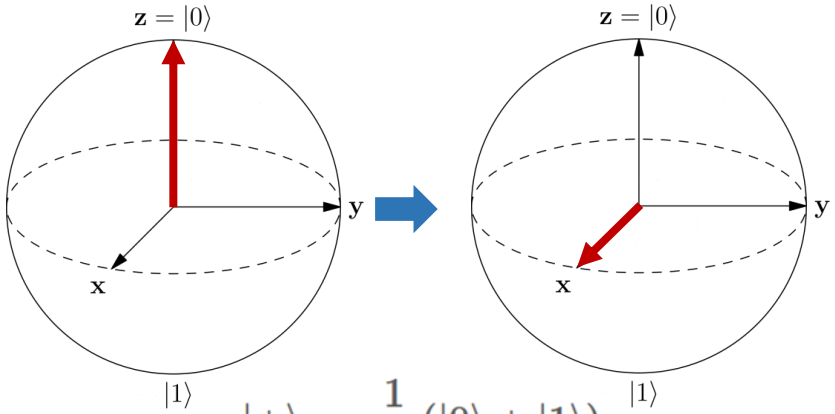
180°



Hadamard

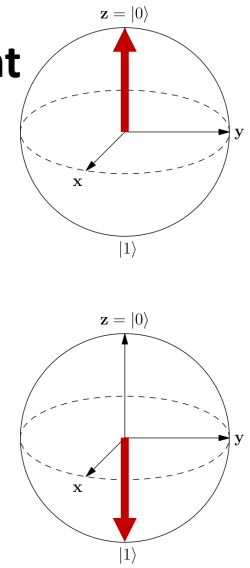
creates superposition

measurement



50%

50%



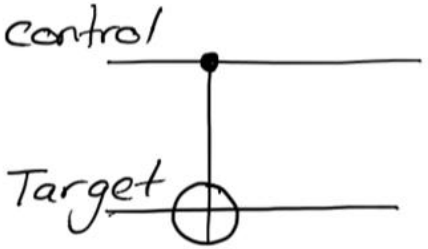
$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

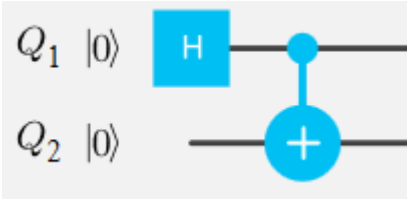
controlled-NOT

„quantum XOR“

for entanglement

e.g.

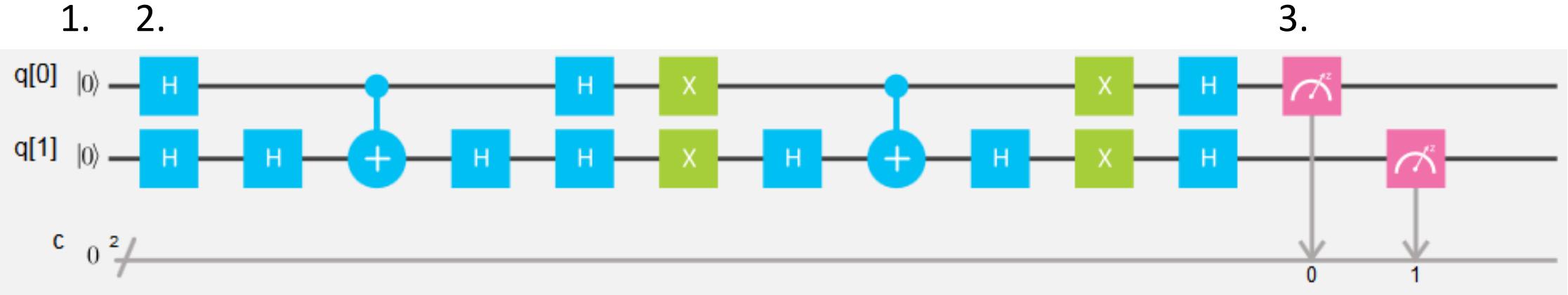




$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

→ **no classical equivalent exists**

quantum algorithm



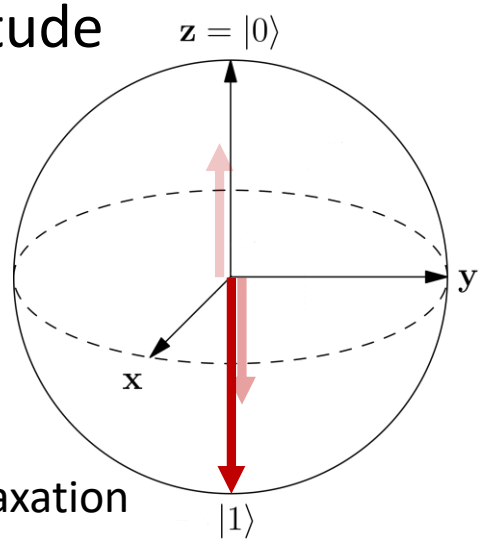
1. **initialization** of all qubits in $|0\rangle$
2. sequence of **operations** on single or multiple qubits
3. **measurement** (read-out) concludes algorithm

multiple repetitions for **statistical claims** necessary

decoherence

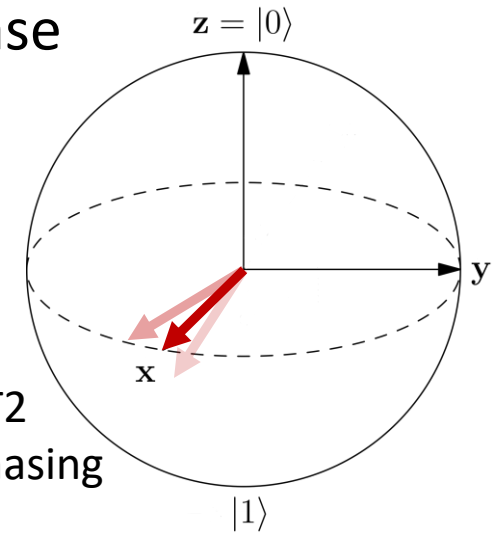
loss of quantum information

amplitude

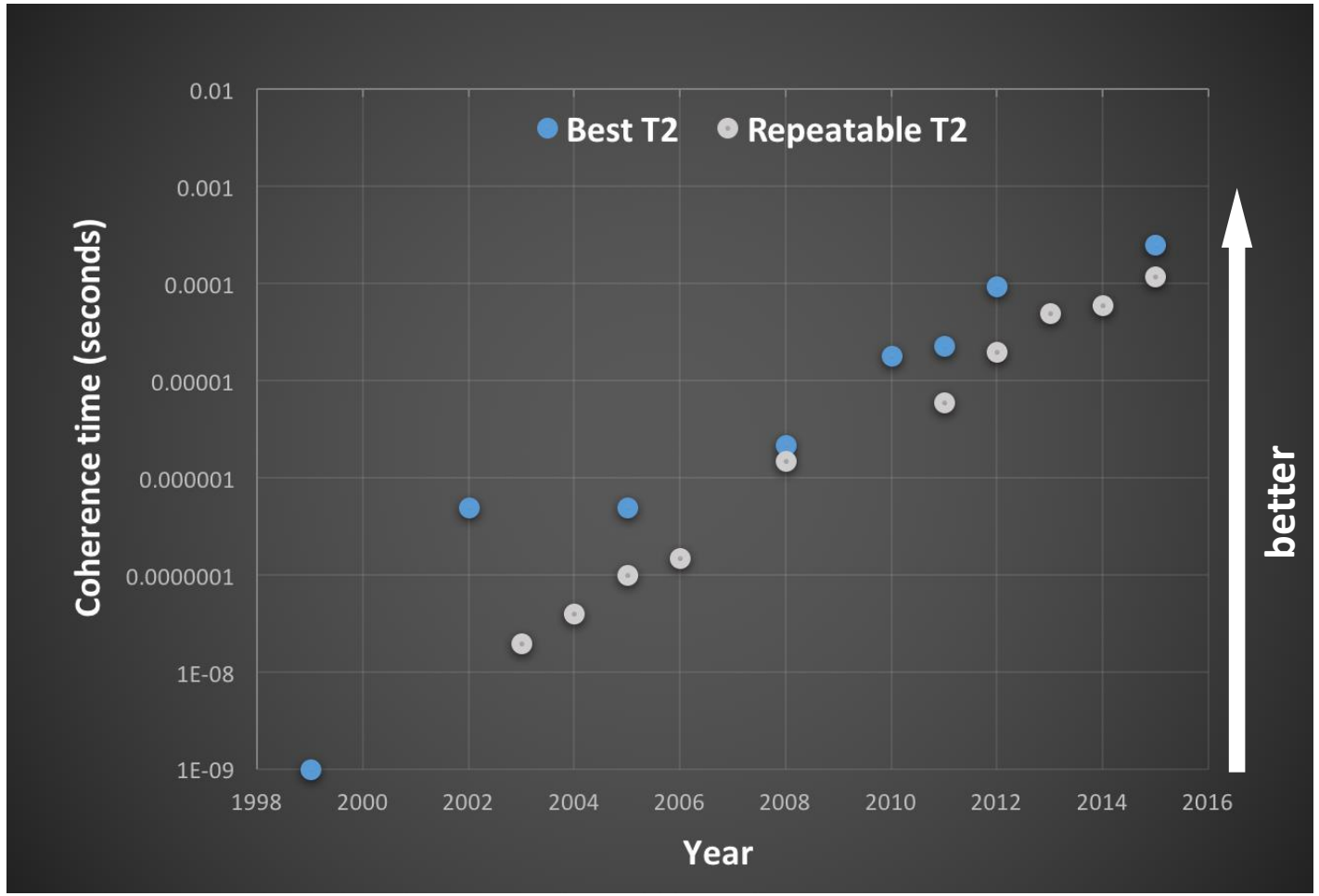


T1
energy relaxation

phase



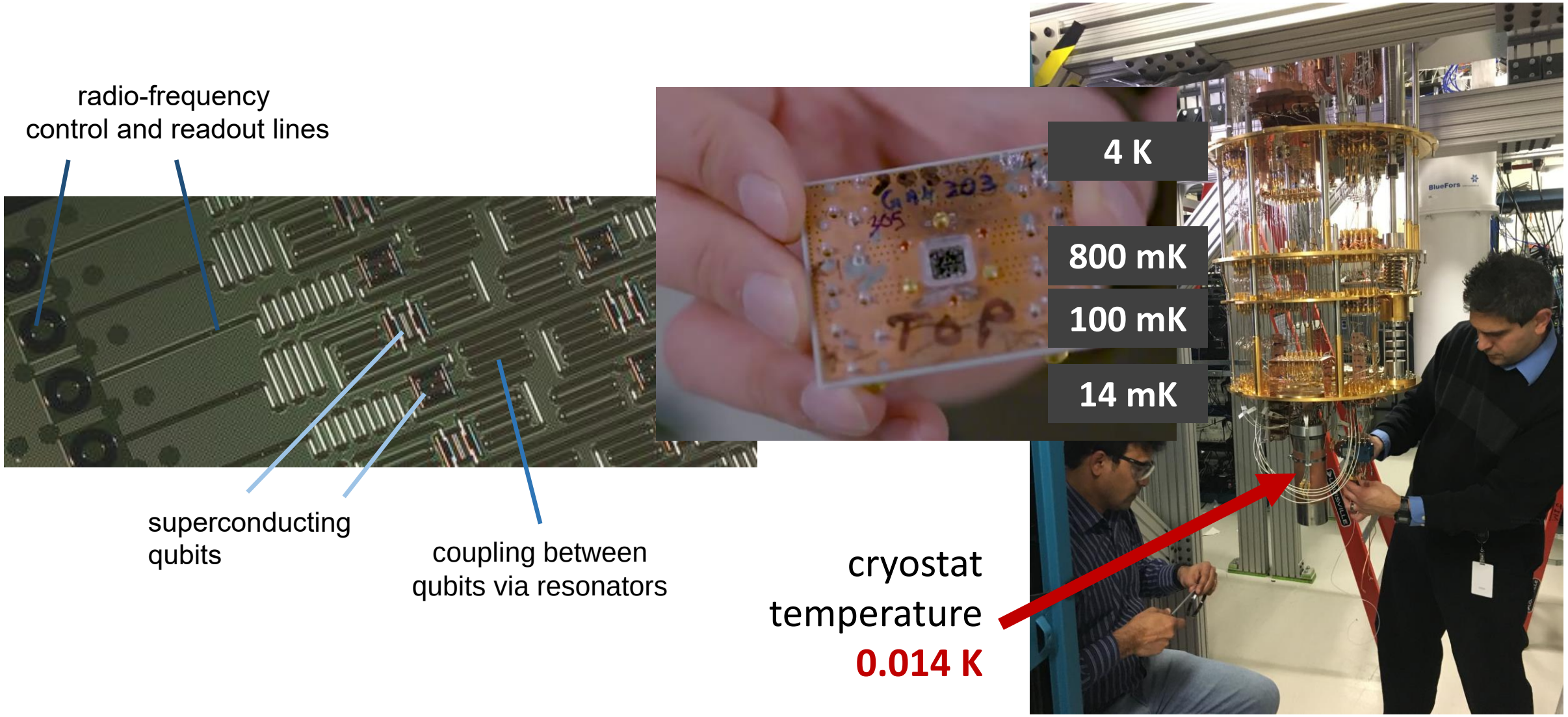
T2
dephasing



longer coherence times mean lower error rates
which allows more time to compute

IBM Quantum Experience – http://quantumexperience.ng.bluemix.net/

IBM quantum computer

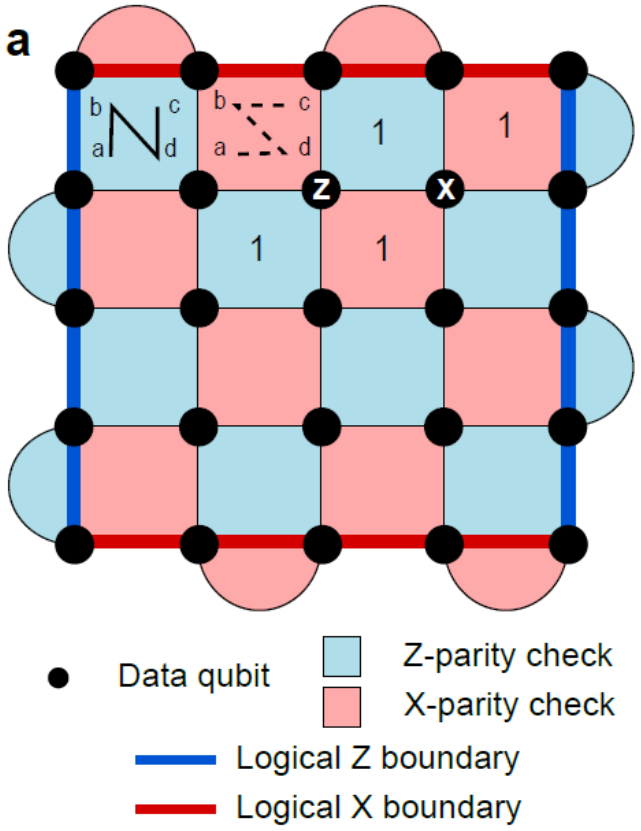


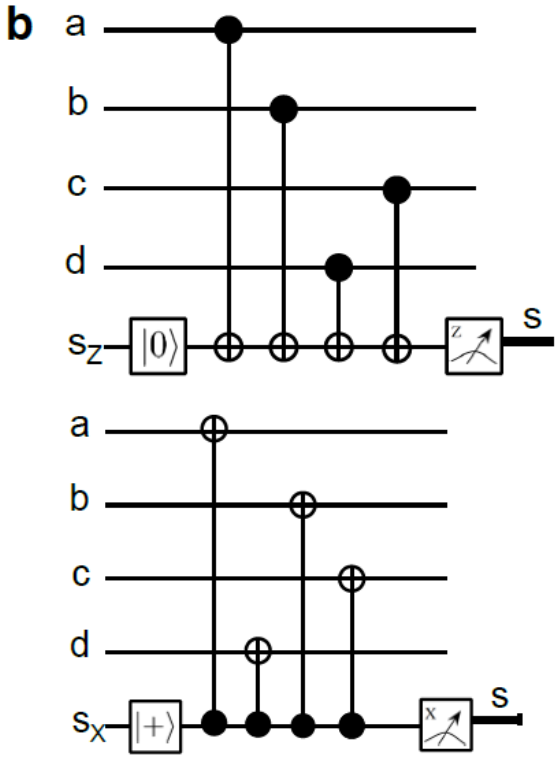
"Demonstration of a quantum error detection code using a square lattice of four superconducting qubits", A.D. Córcoles et al., **Nat. Comm.**, 6:6979 (2015)

a scalable quantum chip architecture

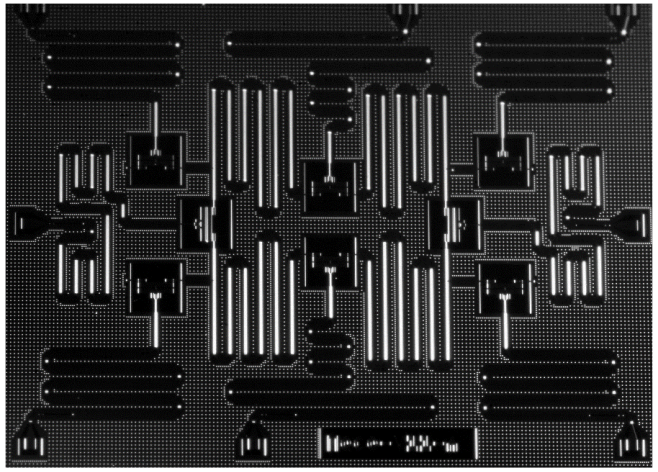
fault-tolerant quantum computing via the surface code
topological quantum computing

logical qubits formed by delocalized states of data qubits

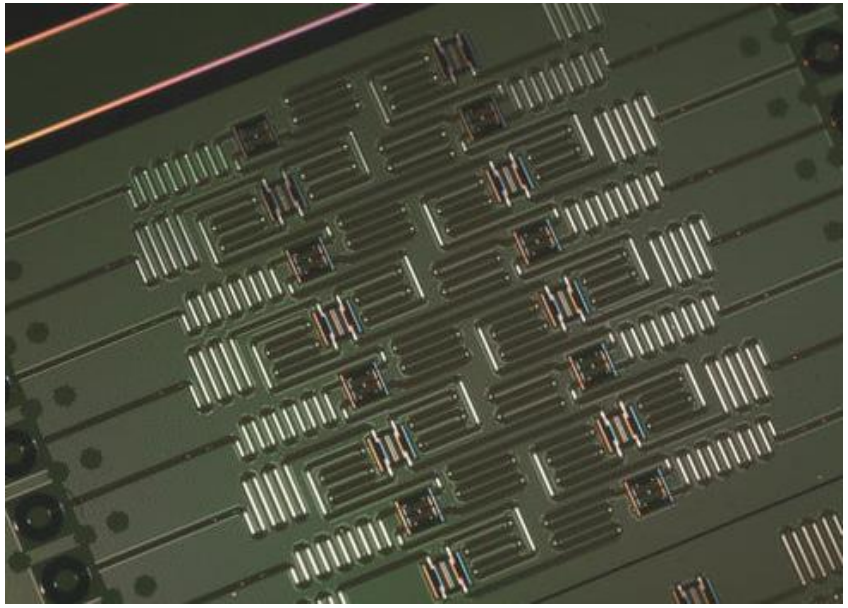




error correction on data qubits



8 Qubits / 4 Buses / 8 Readouts

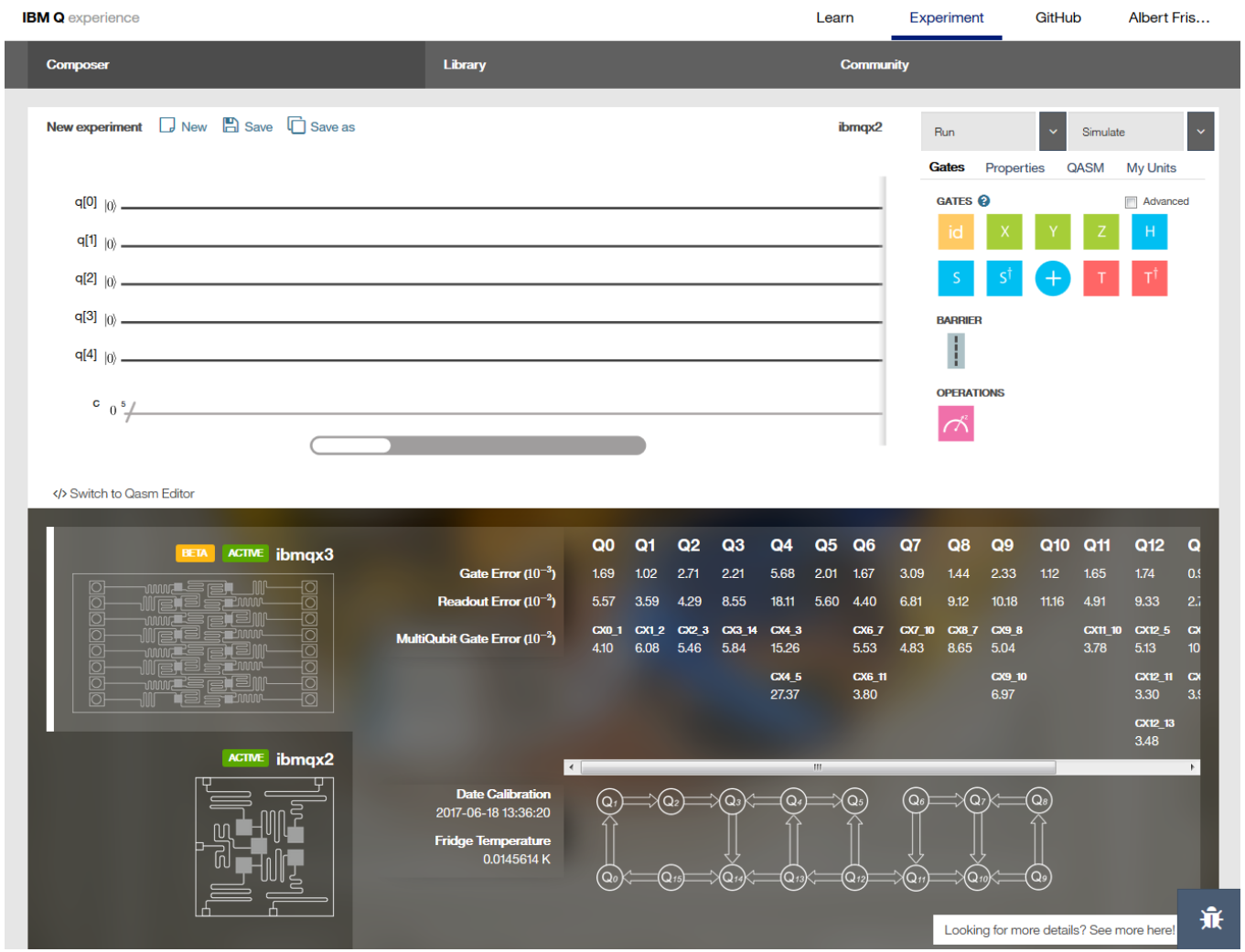


16 Qubits / 22 Buses / 16 Readouts

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

IBM Quantum Experience

www.ibm.com/quantumexperience



quantum computer as an IBM cloud service

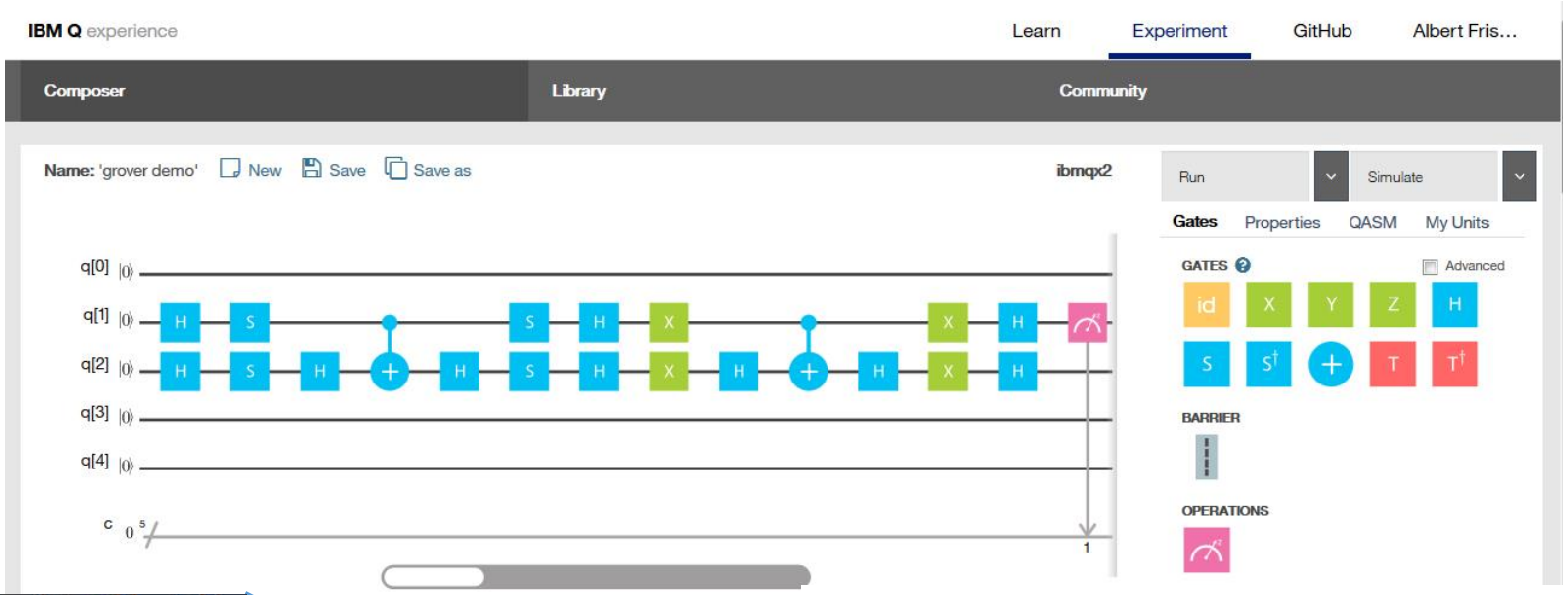
Over 40,000 users

All 7 continents

>150 colleges and Universities

Over 300,000 experiments

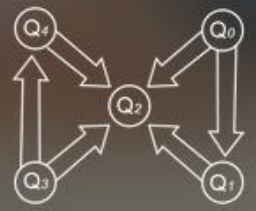
live demo 2-qubit Grover algorithm

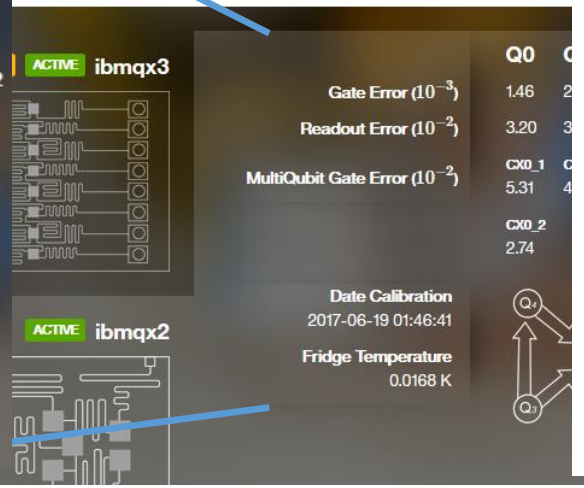


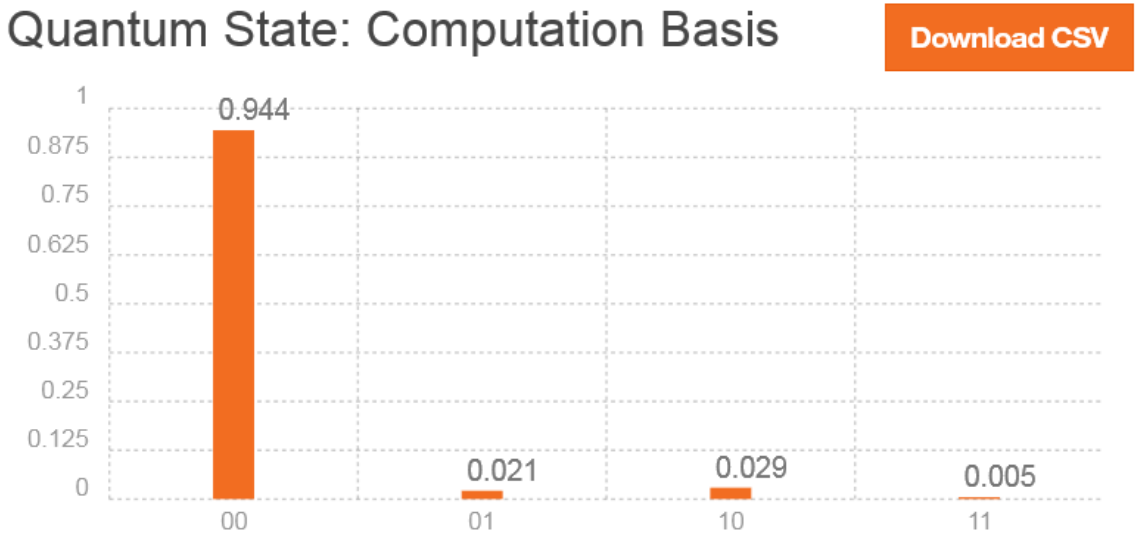
	Q0	Q1	Q2	Q3	Q4
Gate Error (10^{-3})	1.46	2.58	1.97	1.80	1.12
Readout Error (10^{-2})	3.20	3.40	1.10	3.80	3.60
MultiQubit Gate Error (10^{-2})	CX0_1 5.31	CX1_2 4.28		CX3_2 3.71	CX4_2 3.02
	CX0_2 2.74			CX3_4 2.99	

Date Calibration
2017-06-19 01:46:41

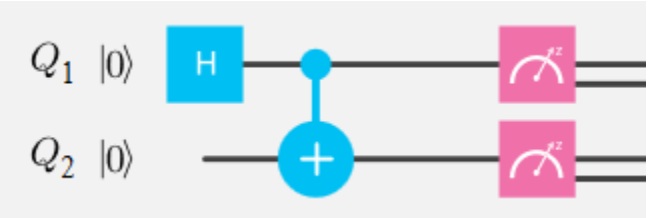
Fridge Temperature
0.0168 K







QISKit - OPENQASM



quantum score file

OPEMQASM 2.0

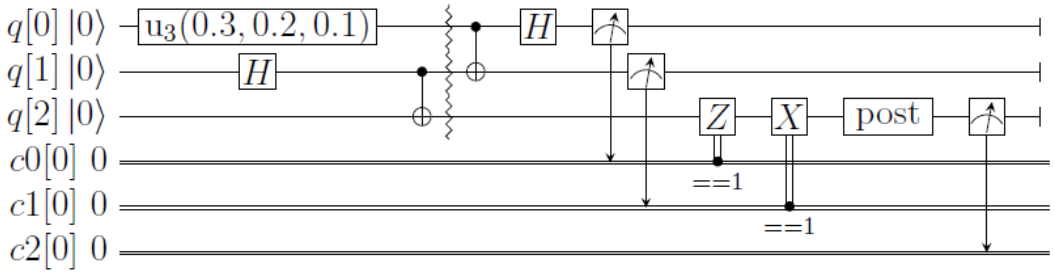
```
include "qelib1.inc";
qreg q[5];
creg c[5];

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];
```



QISKit – Python API and SDK

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:

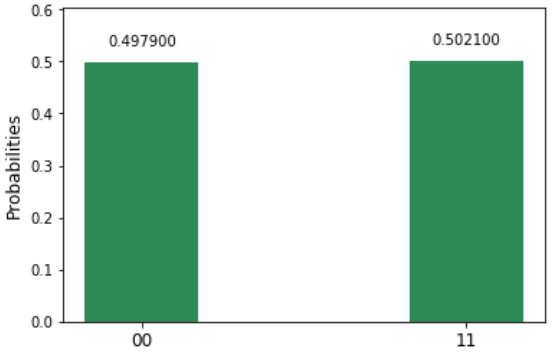
In [1]:
```
import sys
if sys.version_info < (3,0):
    raise Exception("Please use Python version 3 or greater.")
from IBMQuantumExperience import IBMQuantumExperience
```

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/

backup

DiVincenzo's criteria

set of criteria necessary for quantum computation:

1. ✓ A scalable physical system with well characterised qubits.
2. ✓ The ability to initialise the state of the qubits to a simple fiducial state.
3. ✓ Long relevant coherence times.
4. ✓ A "universal" set of quantum gates.
5. ✓ A qubit-specific measurement capability.

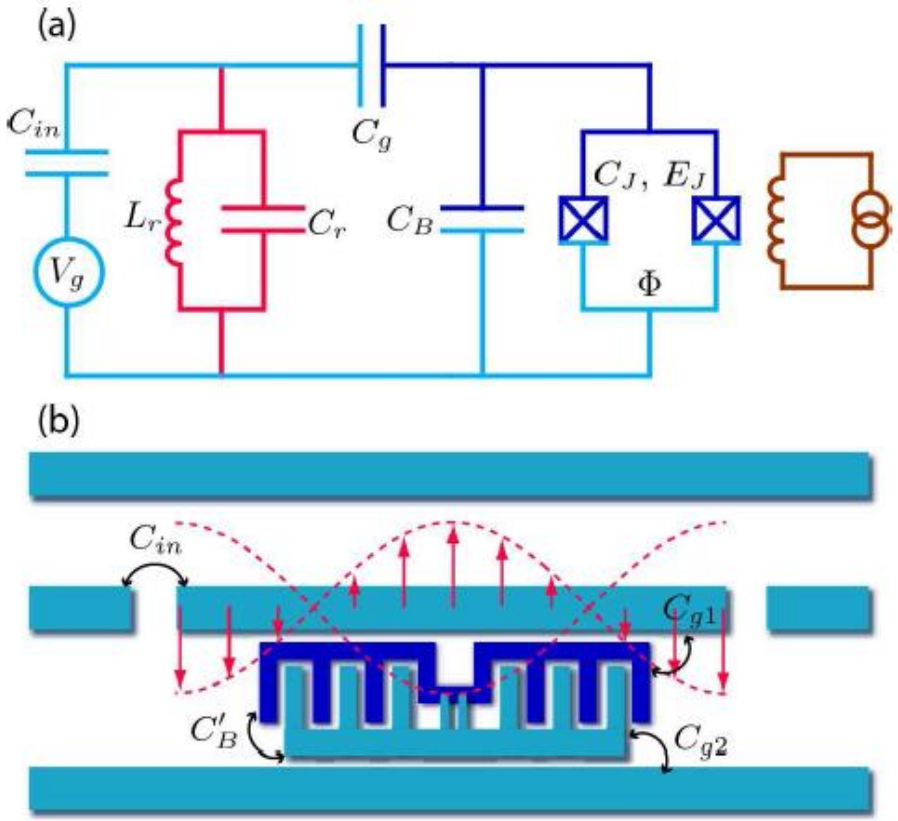
additional criteria for quantum communication:

for QKD

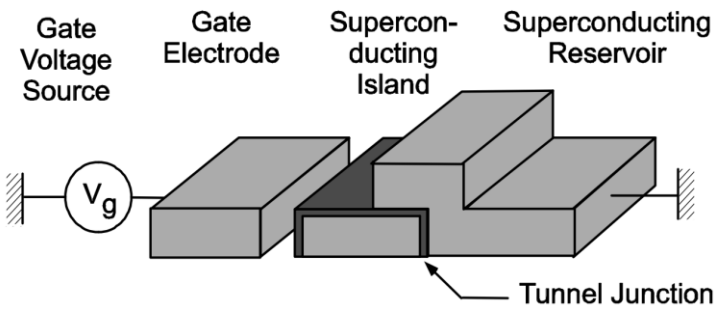
6. ✓ The ability to interconvert stationary and flying qubits.
7. ✓ The ability to transmit flying qubits between specified locations.

transmon qubit

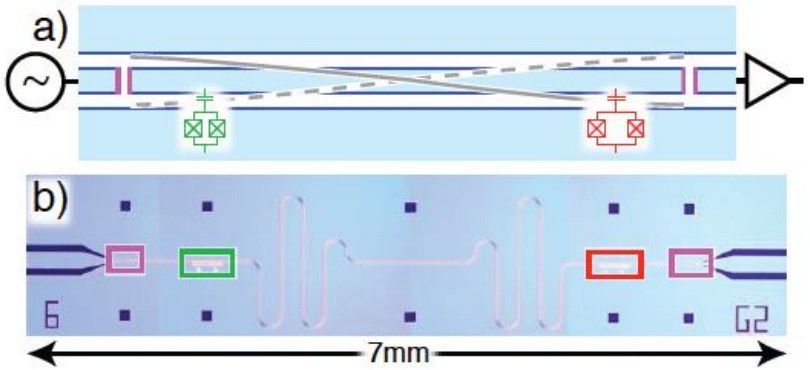
a „transmission-line shunted plasma oscillation qubit“ [1]



Josephson junction

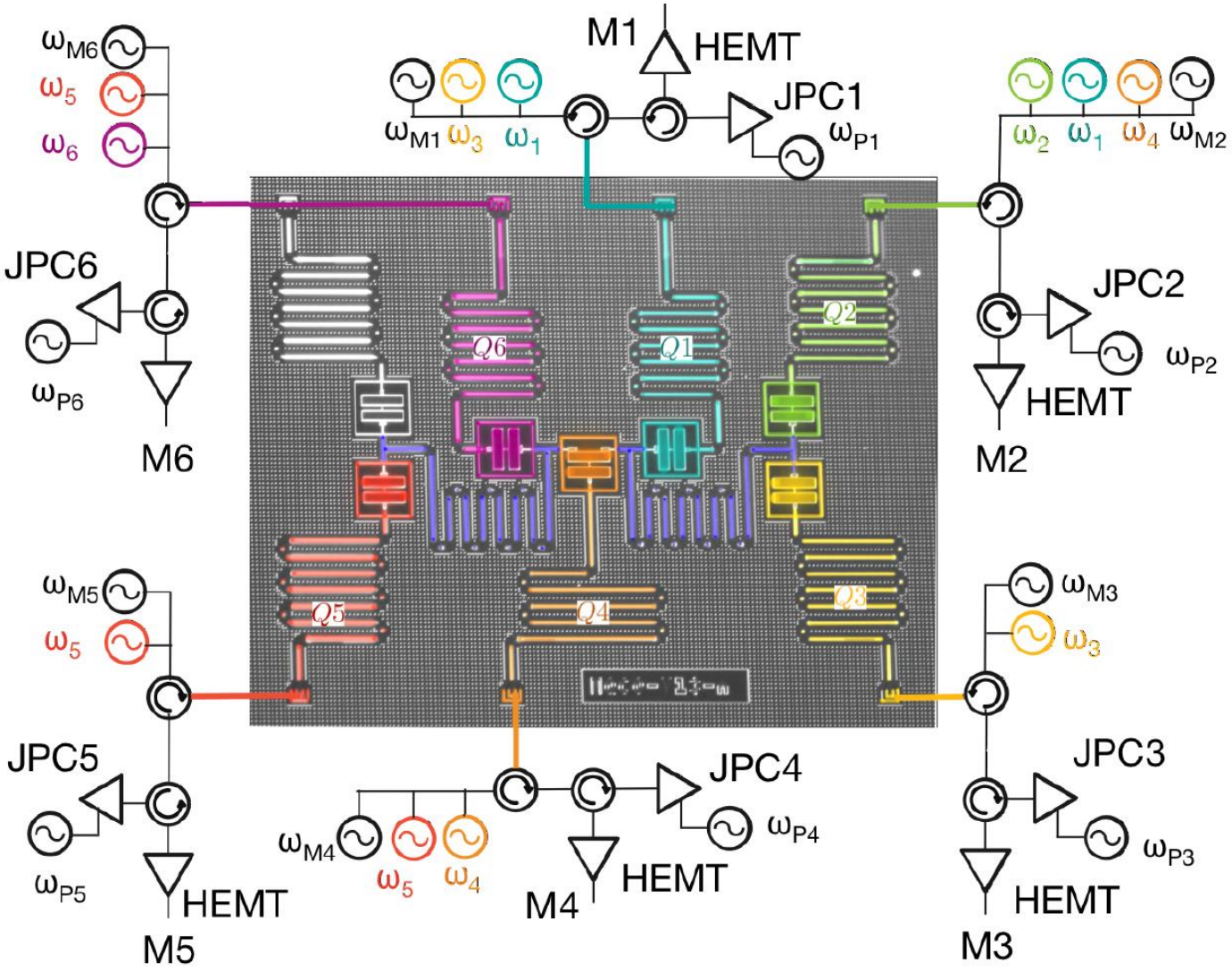


coupling qubits via cavity bus [2]



[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)

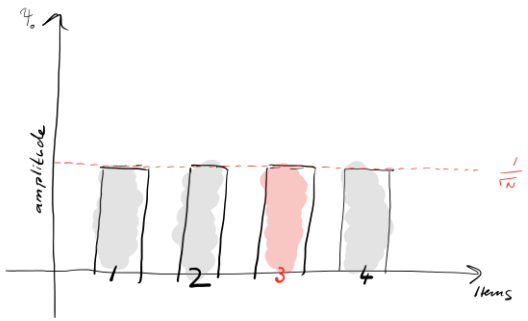
microwave control and read-out



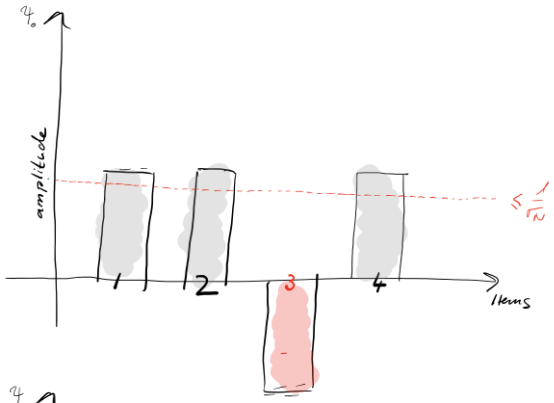
"Hardware-efficient Quantum Optimizer for Small Molecules and Quantum Magnets", A. Kandala et al., arxiv 1704.05018 (2017)

Grover search algorithm

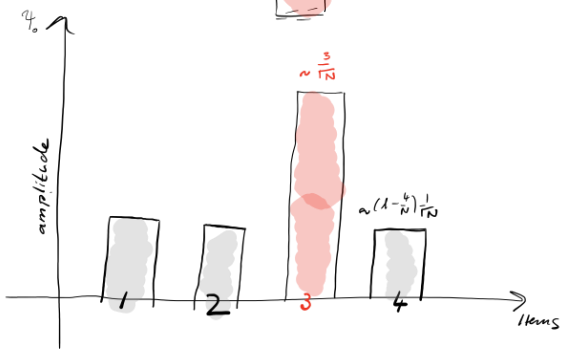
1.



2.



3.

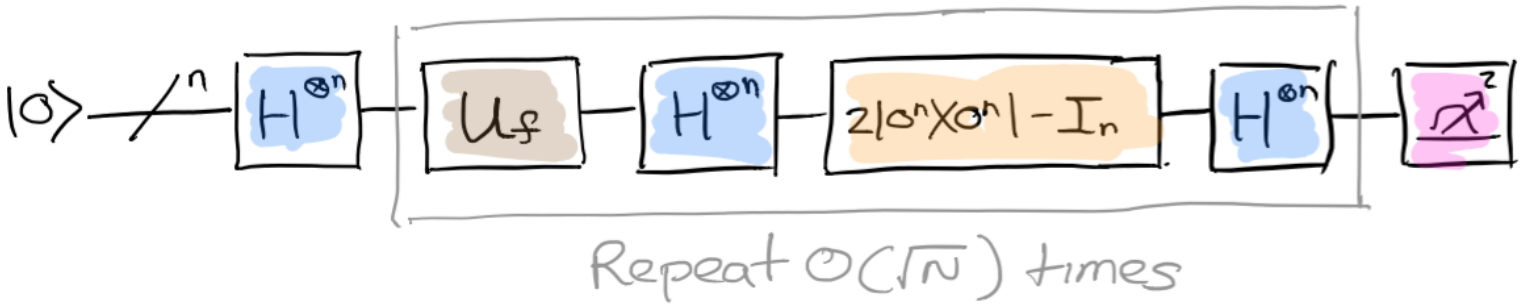


- finds element always in time $O\left(\sqrt{N}\right)$ with probability $1 - O\left(\frac{1}{N}\right)$

  classical algorithm $O(N)$

- optimal search algorithm

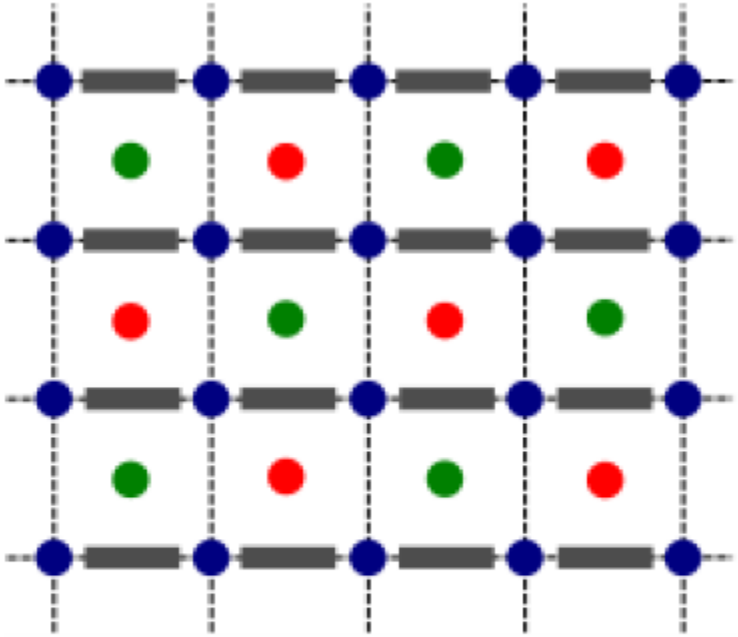
- amplitude amplification



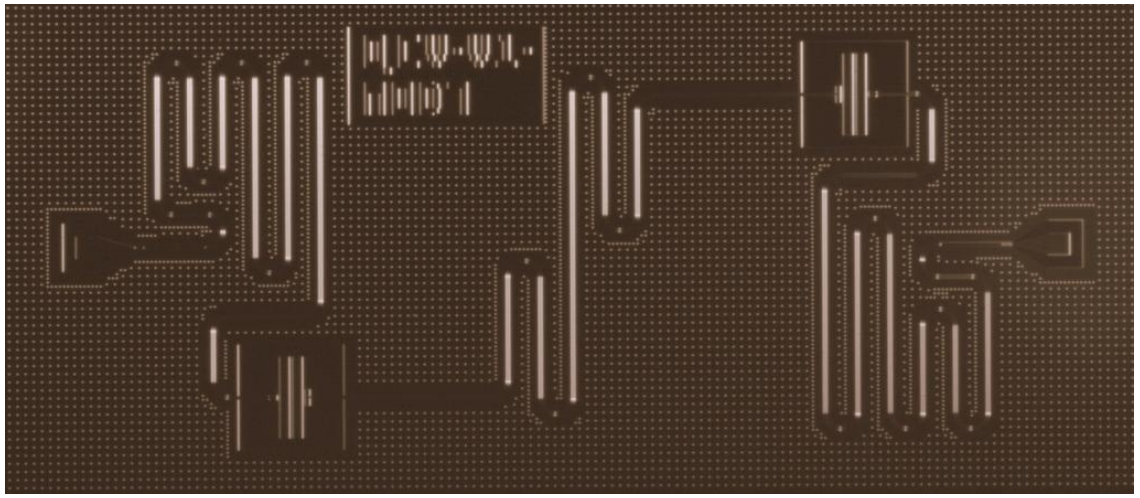
„A fast quantum mechanical algorithm for database search“, L. Grover, **arXiv:quant-ph** 9605043 (1996)

qubit architecture

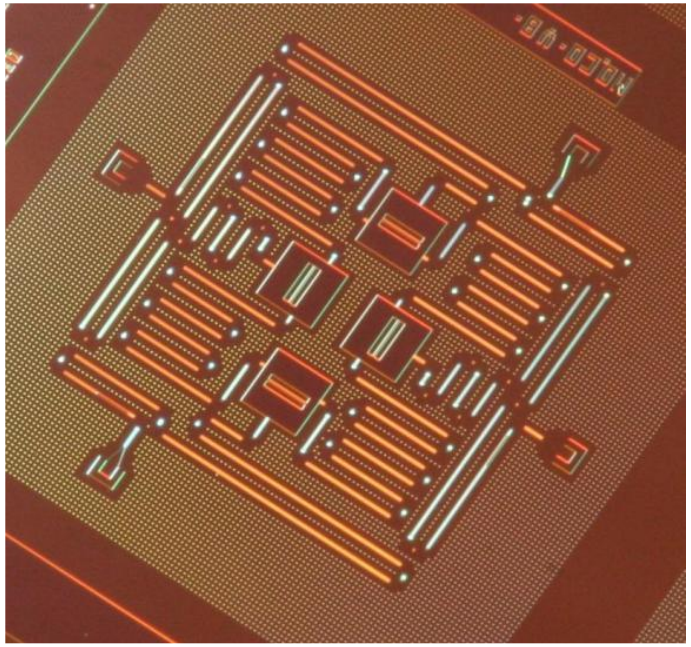
Implementation of quantum network



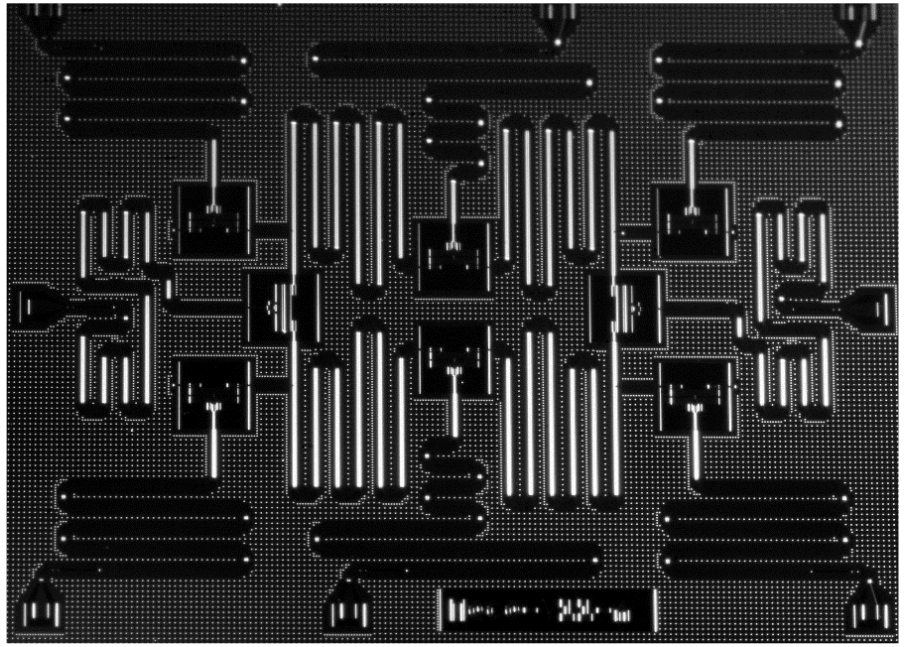
Resonator
Code qubit
X ancilla qubit
Z ancilla qubit



2Qubits/1Bus/2Readouts



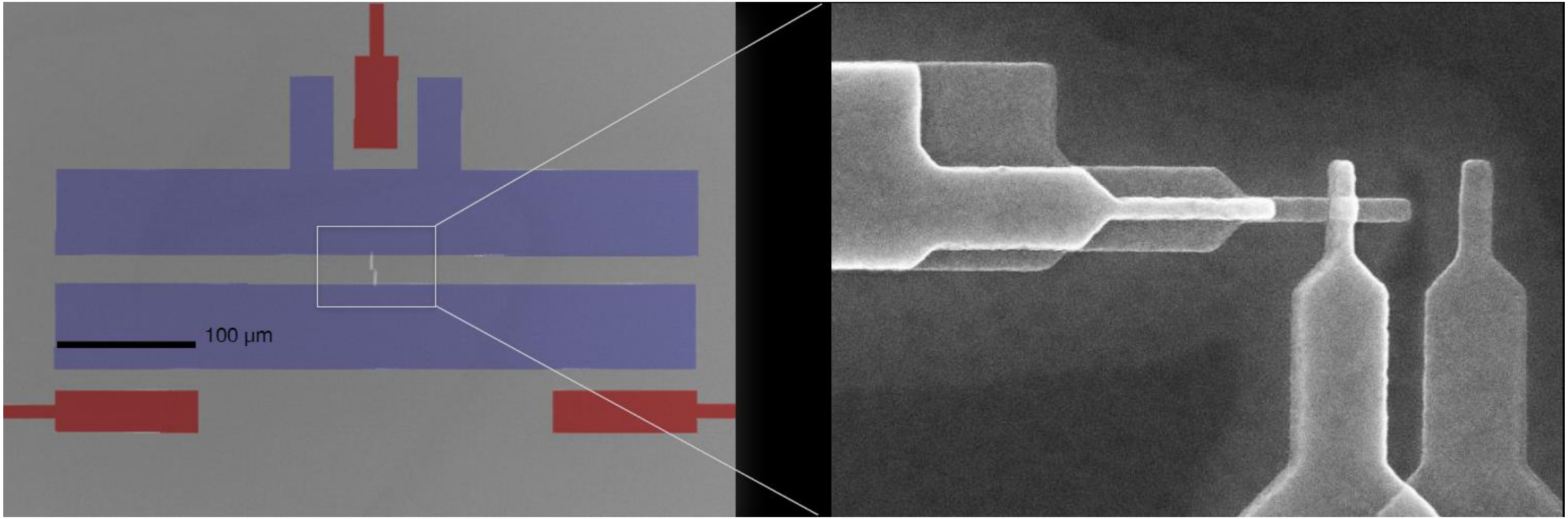
4Qubits/4Bus/4Readouts



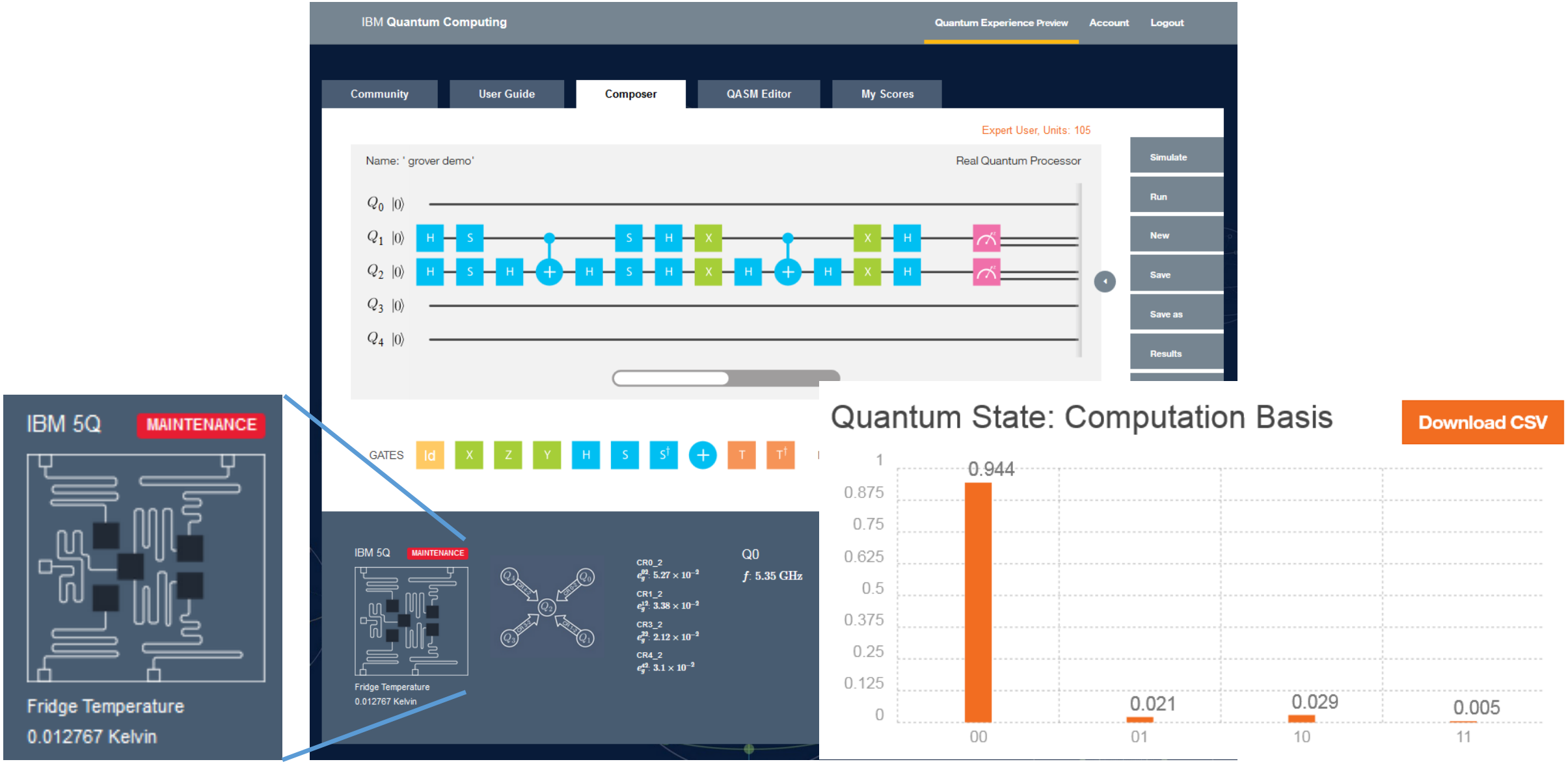
8Qubits/4Bus/8Readouts

https://developer.ibm.com/open/events/dw-open-tech-talk-qiskit-and-quantum-computing/

transmon - Josephson junction



live demo 2-qubit Grover algorithm



Live Demo

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 - running quantum algorithms