Quantum computing as a future technology

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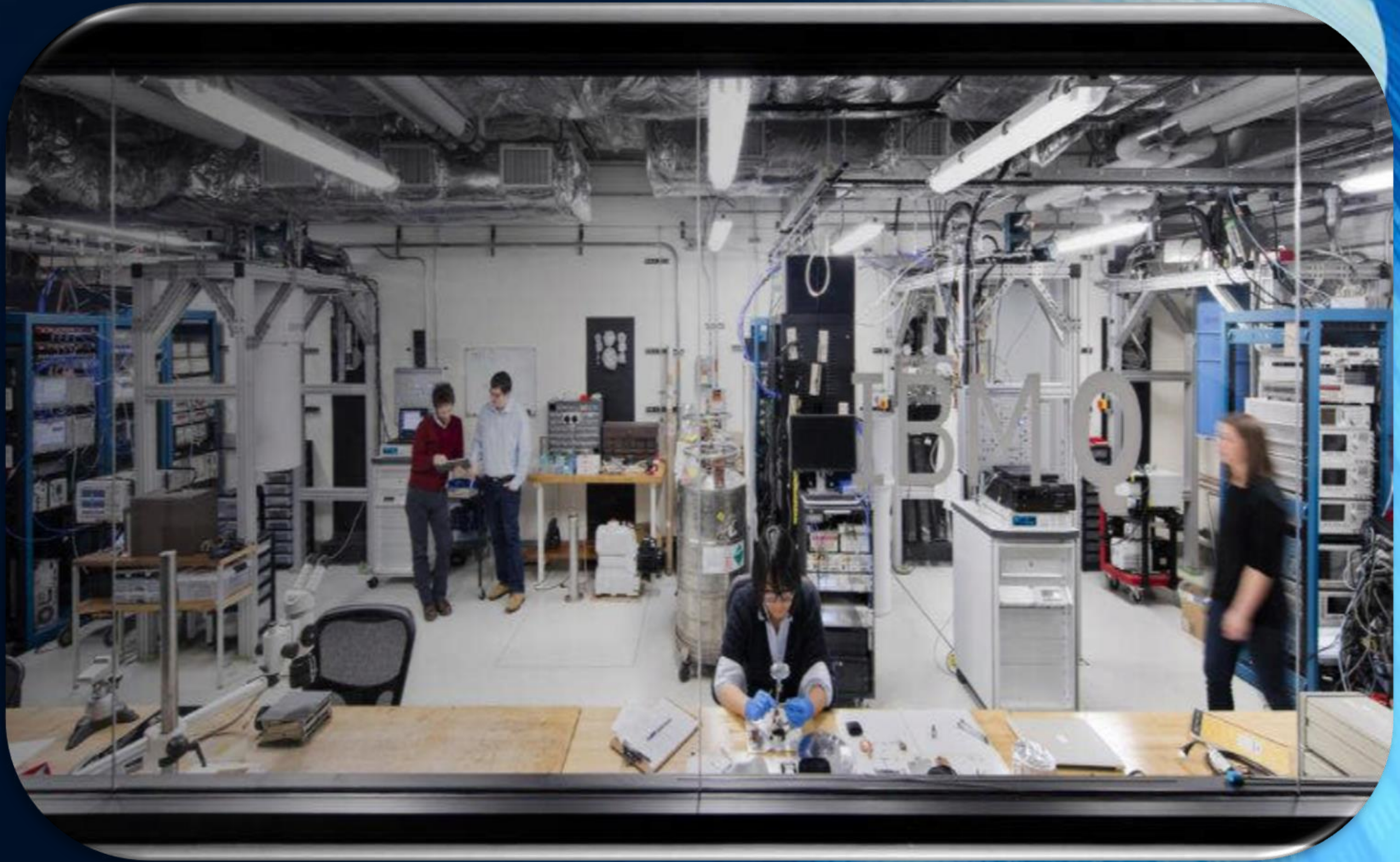
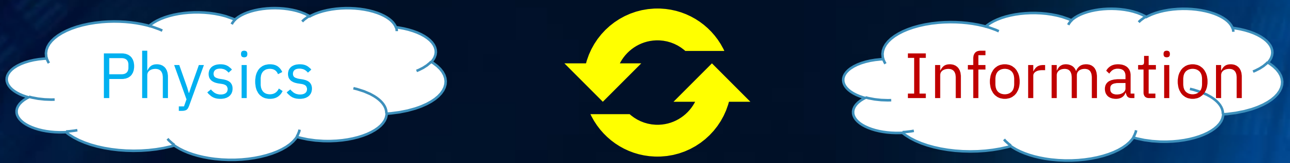


Motivation for Quantum computing

In May of 1981, IBM and MIT hosted the Physics of Computation Conference

Is there a fundamental limit to the energy efficiency of computation ?



I'm not happy with all the analyses that go with just the 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 ...

International Journal of Theoretical Physics, VoL 21, Nos. 6/7, 1982

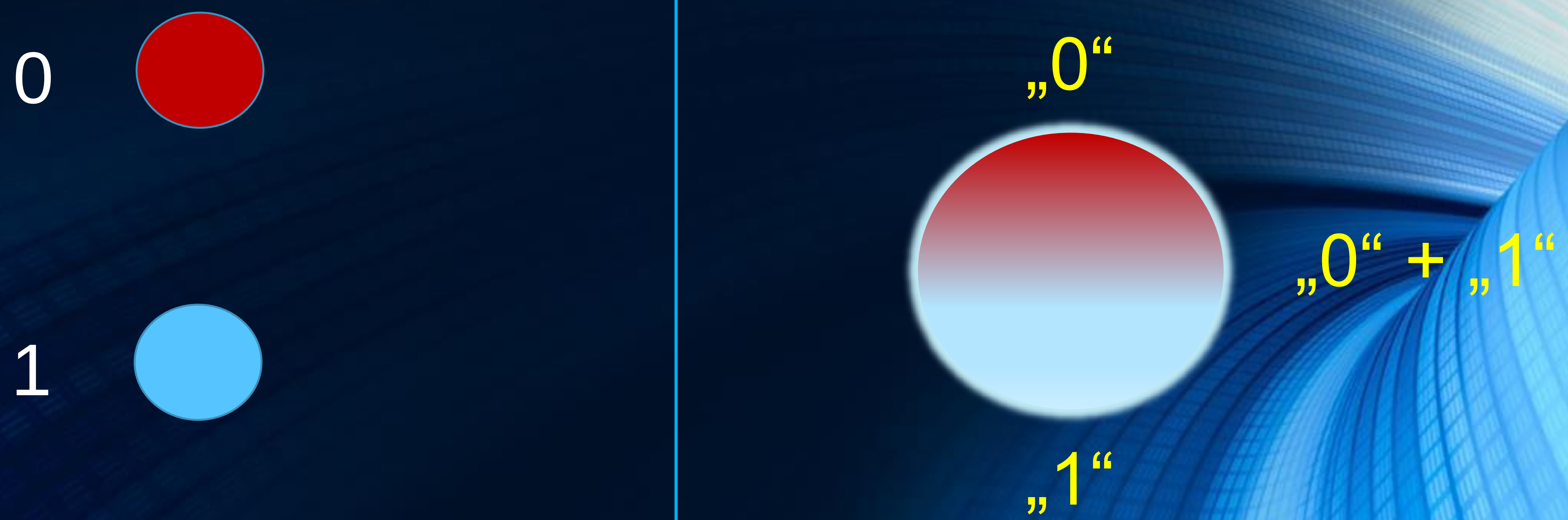
Simulating Physics with Computers

Richard P. Feynman
Department of Physics, California Institute of Technology, Pasadena, California 91107

The idea of Quantum Computer

Bit

QBit



... and then

$$H_{eff} = \sum_i (\omega_i - \delta_{i/2}) b_i^+ b_i + \frac{\delta_i}{2} b_i^+ b_i b_i^+ b_i + J_{ij}(b_i^+ b_j + b_i b_j^+)$$

“I think I can safely say that nobody understands quantum mechanics.”

— Richard Feynman

Complexity of algorithms

n - lenght of the input

Polynomial time

$$T(n) = O(P(n))$$

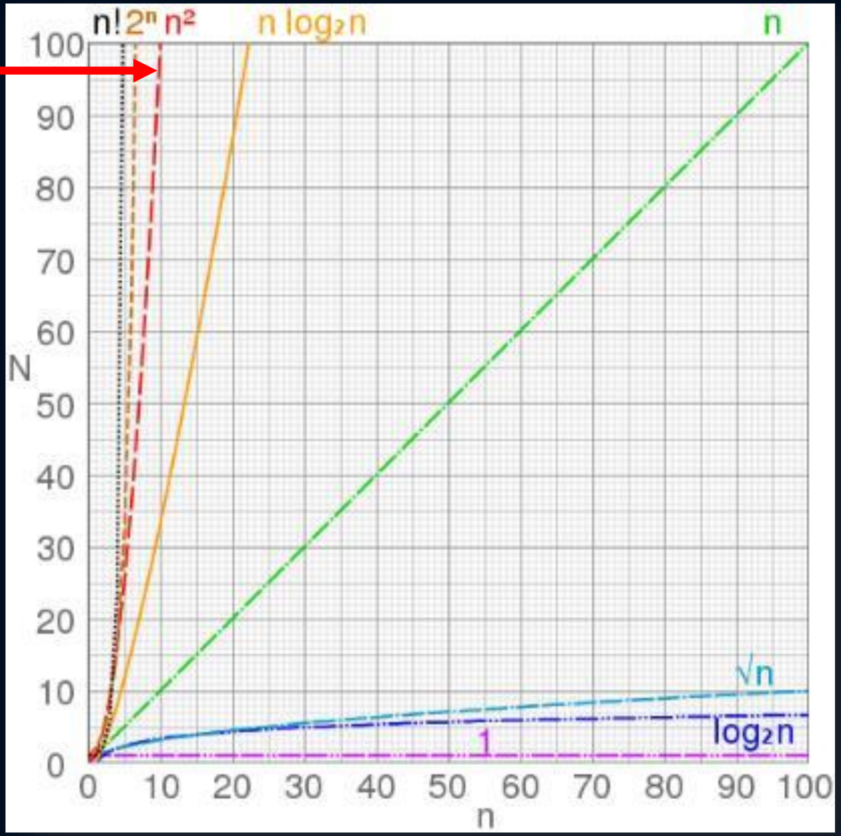
Example: $5n^3 + 3n^2$ has a complexity $O(n^3)$

Exponential time

$$T(n) = O(2^{P(n)})$$

Example: 2^n has a complexity $O(2^n)$

Efficiency limit



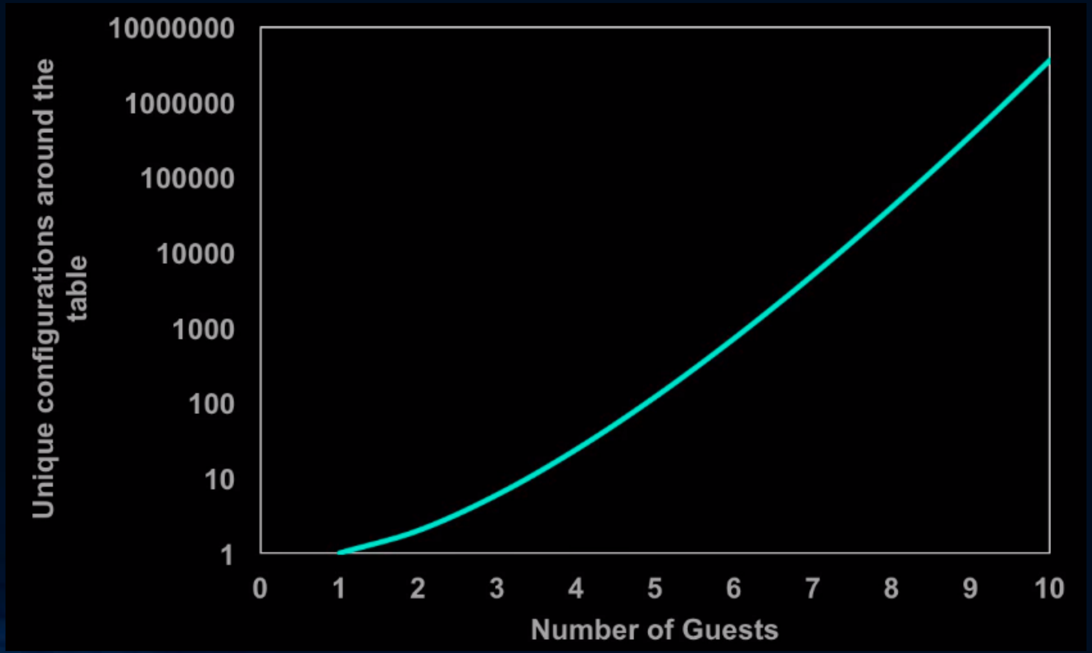
Classical computer can efficient calculate algorithms with polynomial complexity

Systems that contain up to 30-40 interconnecting objects can be calculated efficiently

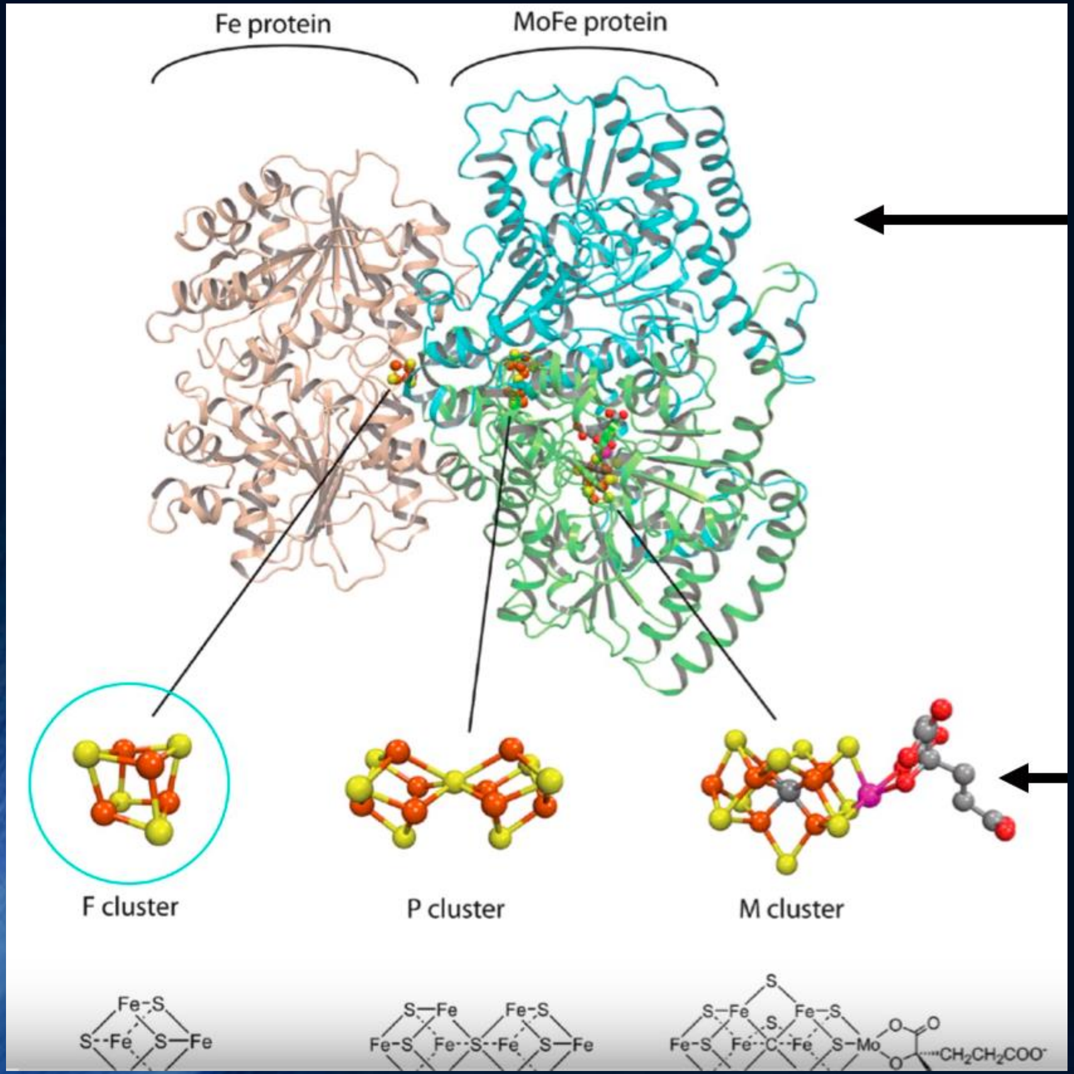
Optimization

10 people

permutations ~3,6 Mio



Chemistry



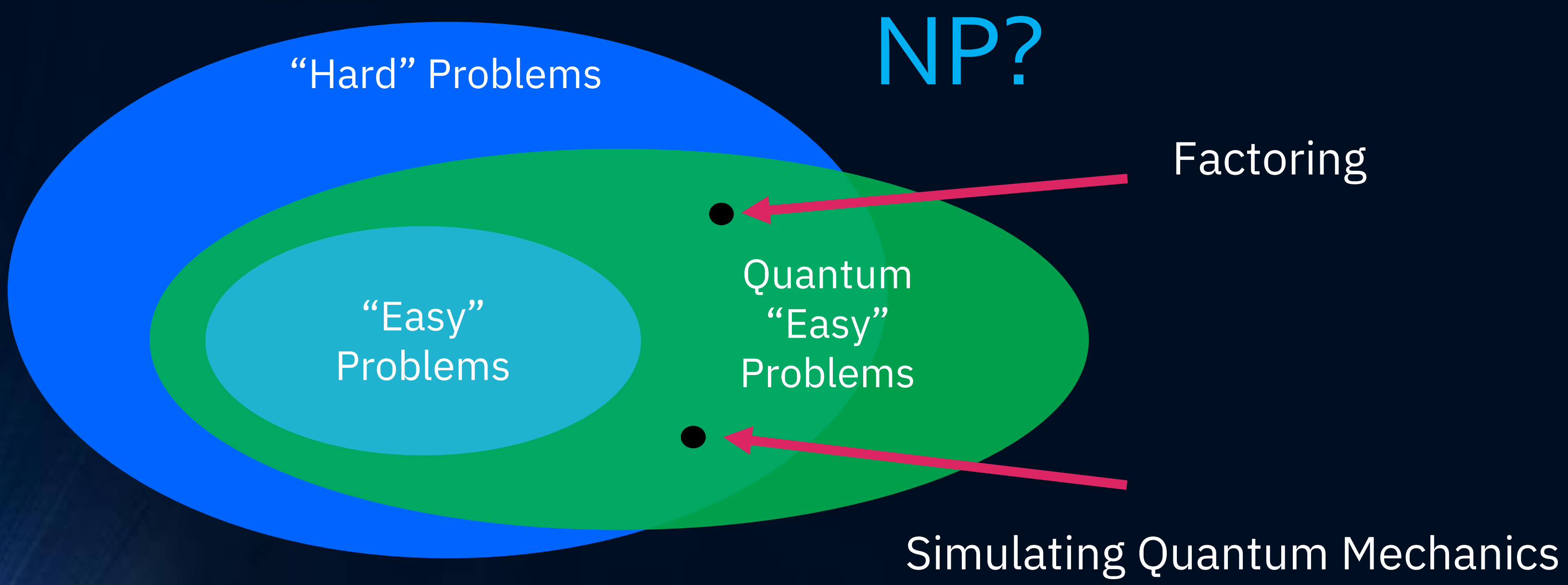
Nitrogenase enzyme involved in N_2 to NH_4 reaction

These regions are involved in different reaction stages

Iron sulfide clusters (Fe_xS_y) of different sizes.

Simulation of this cluster is on the limit of classical computer

Hard problems and quantum speedup



Quantum computing provides a new path to solve some of the hardest problems in business and science.

Cryptography as example

- RSA algorithm (private & public keys) is based on prime factorization problem
- Factorize a big number in two prime numbers

Bin lenght 1024

{101………………….11}

NP

prime

{101………11}

Bin lenght 512

prime

{101…………11}

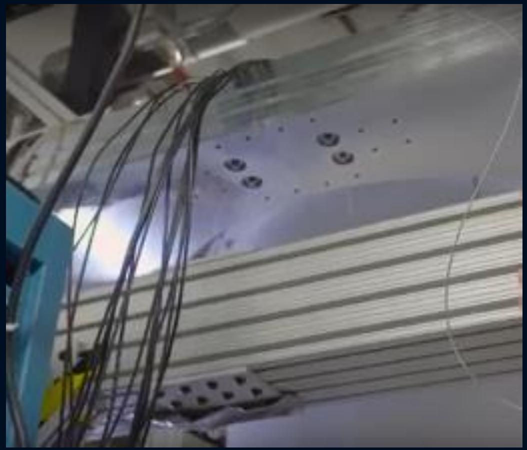
Bin lenght 512

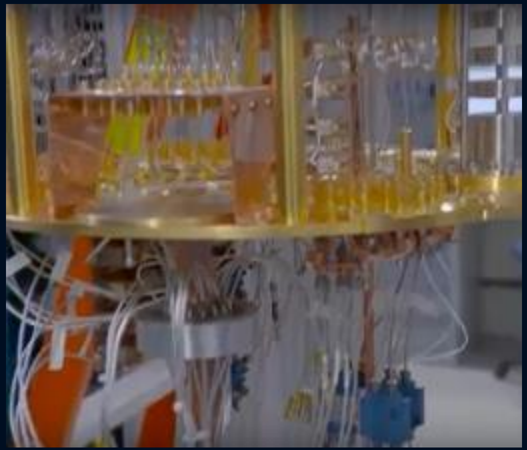
- This task requires time $T(n) = 2^n$
- It cannot be solved efficiently by classical computers
- It can be solved efficiently by quantum computer, because it somehow does anything at once.

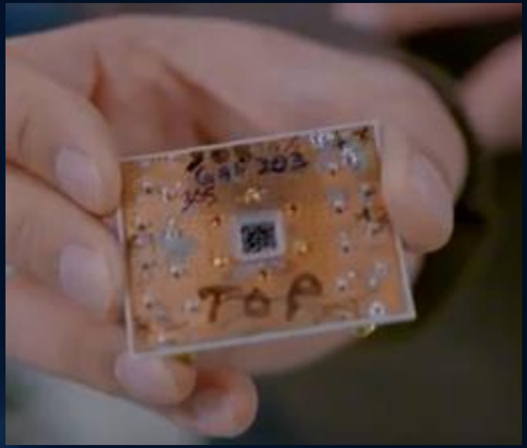
Shor`s quantum algorithm claims to solve this problem in polinomial time.

How the Quantum Computer looks like

Quantum computer IBM Quantum Experience







Fridge
Temperature:
0.015 K

IBM Quantum Experience uses a physical type of qubit called a *superconducting transmon qubit*,
which is made from superconducting materials such as niobium and aluminum, patterned on a silicon substrate.

Quantum error correction

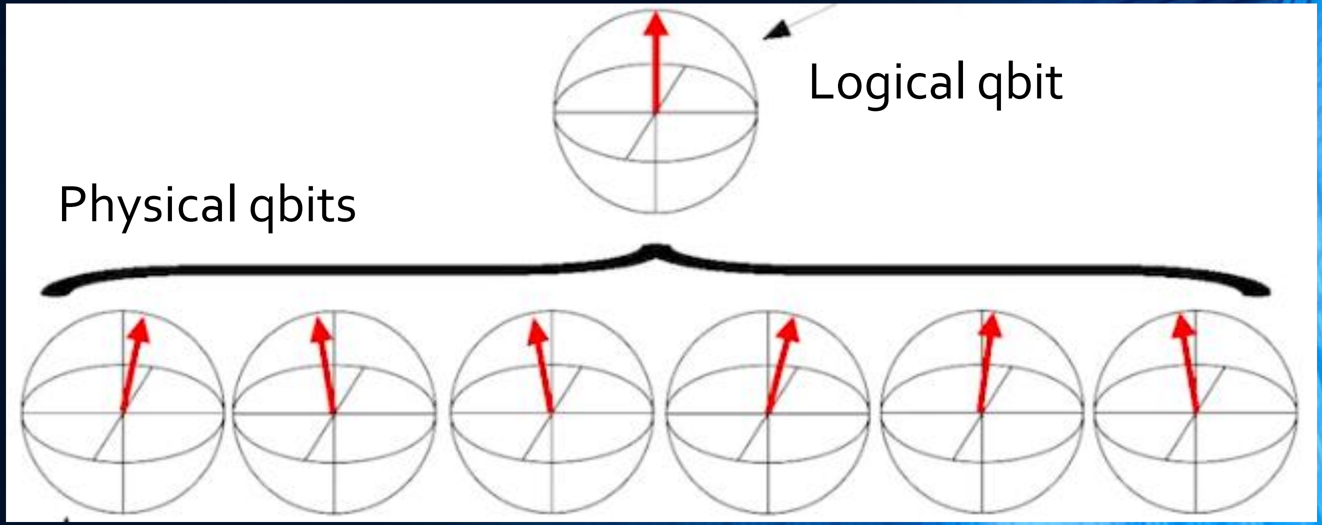
THRESHOLD (FAULT TOLERANCE) THEOREM

A Quantum Computer with a physical error rate below a certain threshold can suppress the logical error rate to arbitrarily low levels

0,1 % error rate

↓

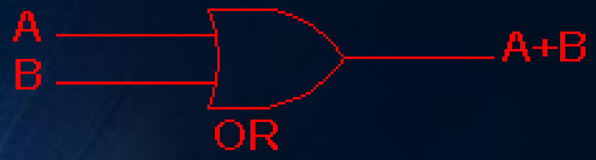
$10^3 - 10^4$ physical qbits
for 1 logical qbit



How a Qbit works

Classical bits

- Classical computation based on bits.
- Each bit can take only two states: 0 or 1 (low or high voltage level, power, whatever)
- The number of possible states of n bits: 2^n



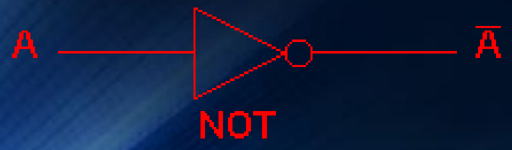
2 input OR gate		
A	B	A + B
0	0	0
0	1	1
1	0	1
1	1	1

The full logical operations are based on

OR, NOT

or

AND, NOT



Not gate	
A	Ā
0	1
1	0

The classical operations are not reversible

↓

Loss of information

Qbits

- Quantum Computation is based on Qbits
- Qbit takes a state of both $|0\rangle$ and $|1\rangle$ simultaneously

00000 11111

α β

α, β – complex numbers

After measurement of the qbit state

↓

probability of 0 or 1

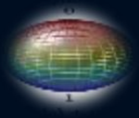
I'm half a cat,
half an elephant and a
little bit a dolphin.

Superposition vs. Parallelism

Exponential Parallelism

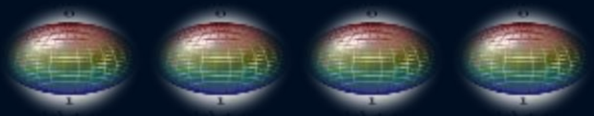
2^n potential classical computers – unrealistic

Superposition



1 qbit

2 qbits



4 qbits

2^n states in a time

Exponential Parallelism > Superposition

Qbits

- Quantum operators U must be reversible and preserve information. Therefore the operators (quantum gates) are *unitary*:

quantum operator (gate)

current quantum state vector

$$|\psi'> = U|\psi|>, \text{ where } U^\dagger U = I$$

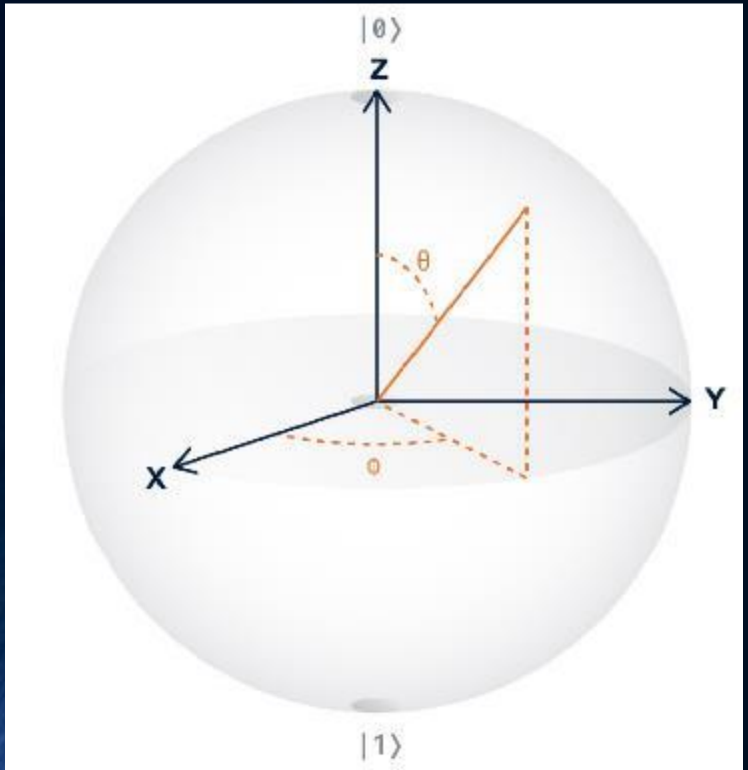
new quantum state vector

$U^\dagger$ is a complex conjugation and transpose of matrix U

I – identity matrix

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ 1 \end{pmatrix} \longleftrightarrow \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \rightarrow \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Qbit as a Bloch Sphere



$|0\rangle = \binom{1}{0}$

$|1\rangle = \binom{0}{1}$

The state of the qbit is made up of a linear combination of $|0\rangle$ and $|1\rangle$ with coefficients of proportion:

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

where α, β – complex numbers, that

$$|\alpha^2| + |\beta^2| = 1$$

The angle θ represents the superposition of $|0\rangle$ and $|1\rangle$

$$0 \leq \theta \leq \pm\pi$$

The angle ϕ represents the phase of the qbit.

$$0 \leq \phi \leq \pm\pi$$

Single qubit operations are rotations and reflections within Bloch sphere

Superposition and Entanglement

Superposition

ψ →  → P [0,1]

- Quantum theory predicts that a computer with N qubits can exist in a superposition of all 2^N of its distinct logical states $|00 \ldots 0\rangle$ through $|11 \ldots 1\rangle$ simultaneously.

- This is exponentially more than a classical superposition. Playing N musical tones at once can only produce a superposition of N states.

Entanglement

EPR experiment

- This is a quantum property only. No analogy in the macro world.
- It is a correlation between two particles.
- In an entangled state, the whole system is in a definite state, even though the parts are not.
- It cannot be used to send a message
- The ability of quantum computers to exist in entangled states is responsible for much of their extra computing power

qubits

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

orthonormal base vectors

superposition

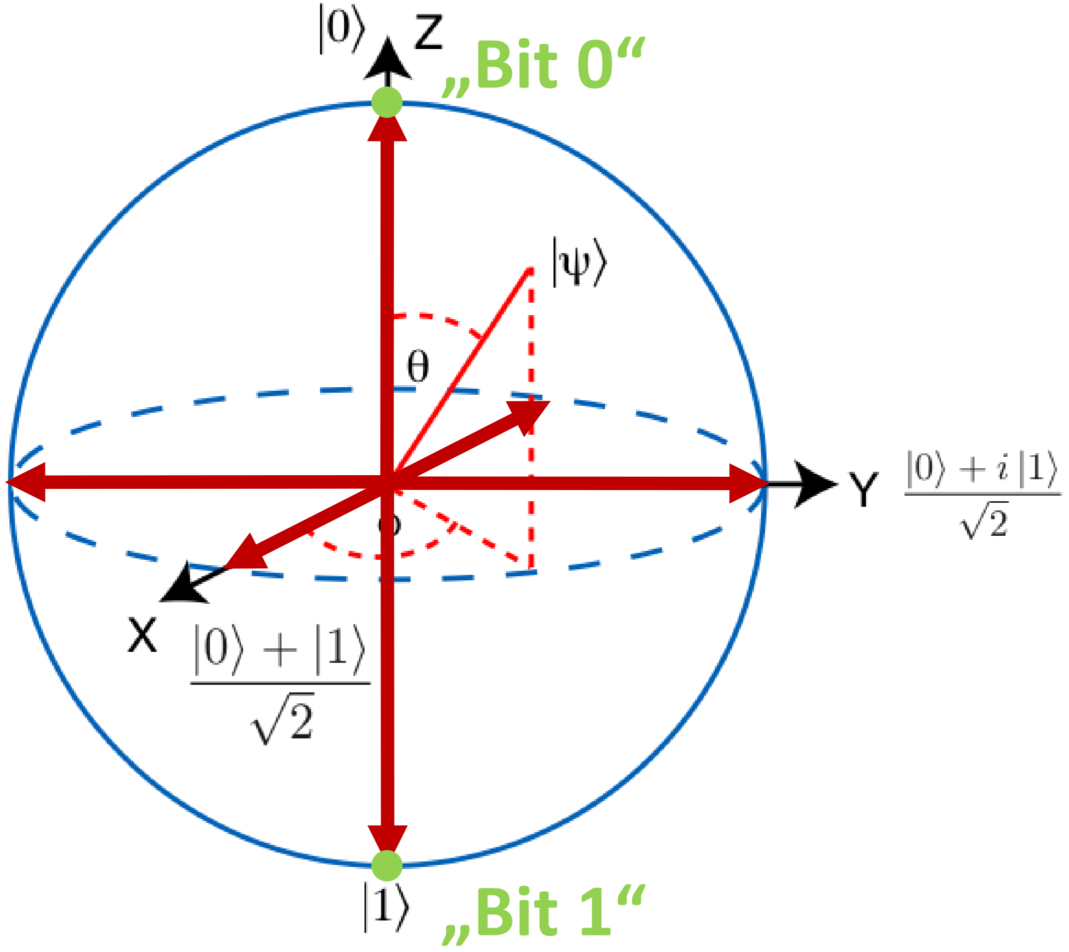
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

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

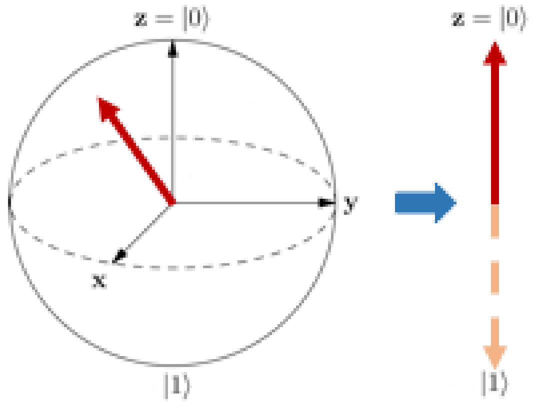


IBM Quantum Experience - quantumexperience.ng.bluemix.net/

measurement and quantum gates

measurement

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



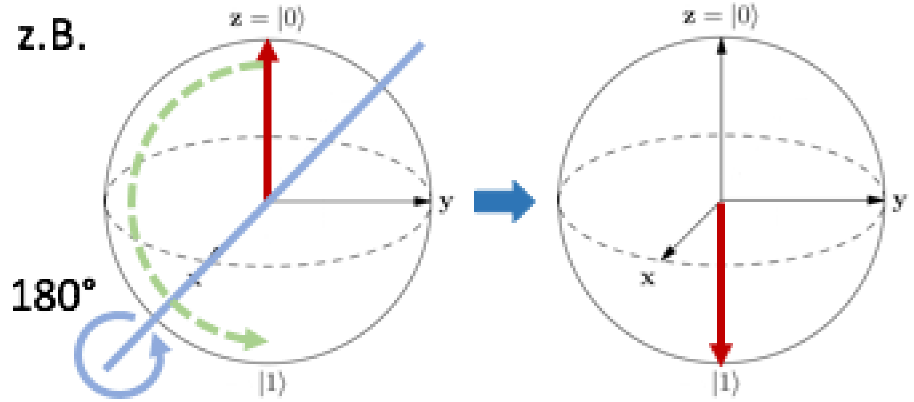
probability

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

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

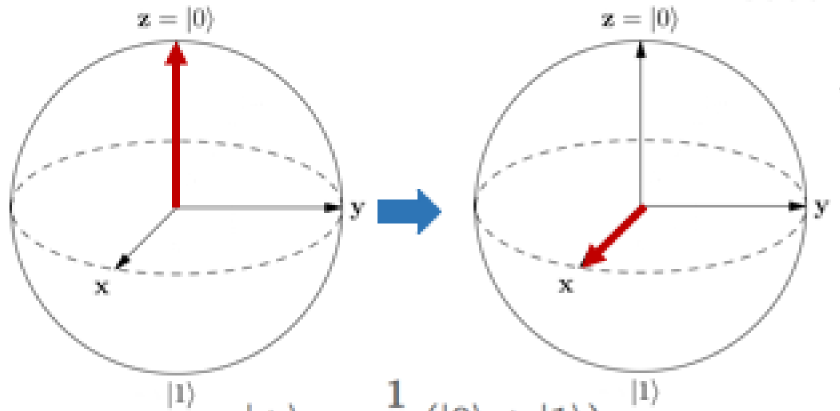
X Z Y rotations

z.B.



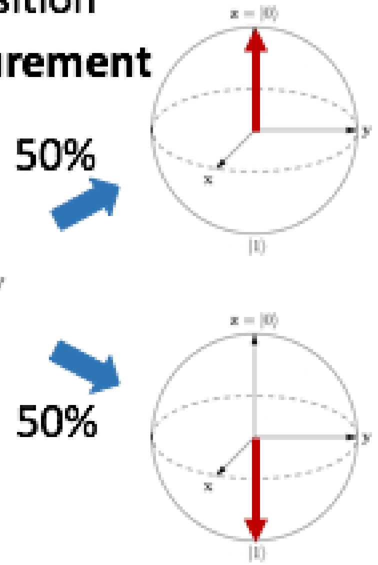
H Hadamard

creates superposition



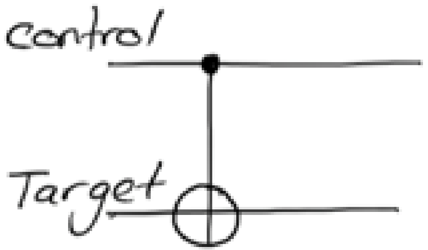
$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

measurement



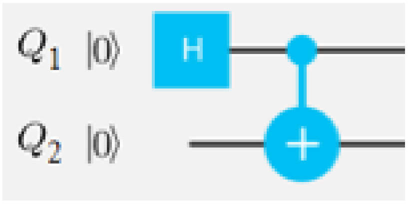
controlled-NOT

„quantum XOR“



for entanglement

e.g.



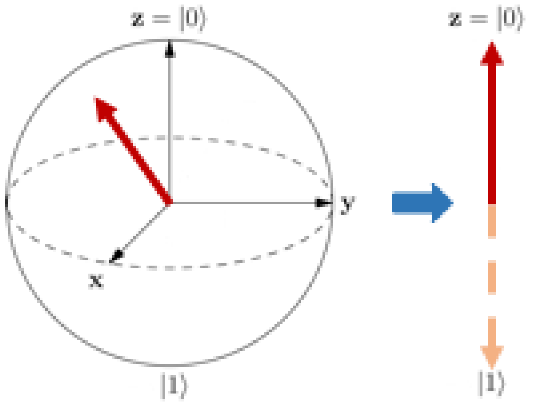
$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

→ no classical equivalent exists

measurement and quantum gates

measurement

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



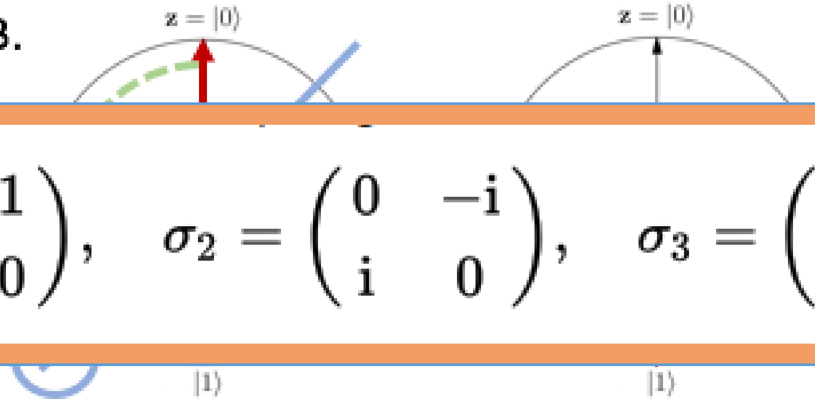
probability

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

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

X Z Y rotations

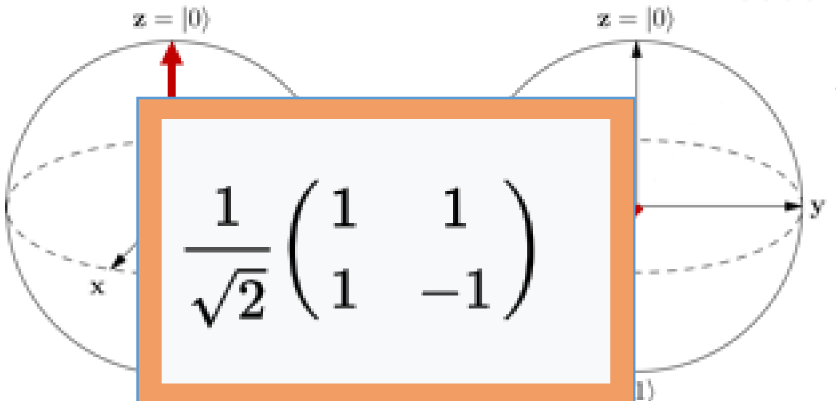
z.B.



$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

H Hadamard

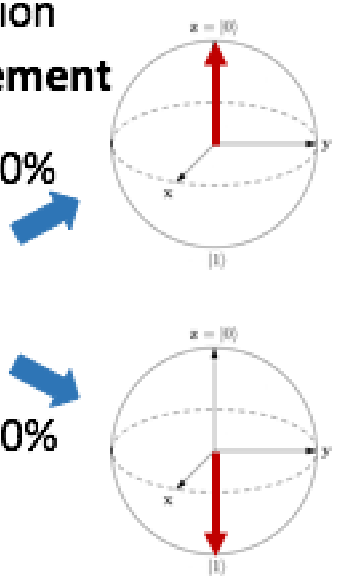
creates superposition



$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

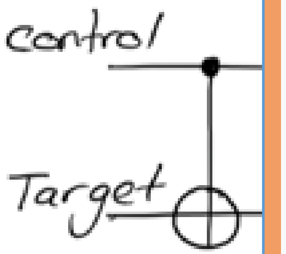
$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

measurement

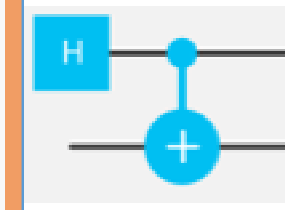


controlled-NOT

„quantum XO… …ent



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



$…00\rangle + |11\rangle)$

→ no classical equivalent exists

Quantum algorithm basics

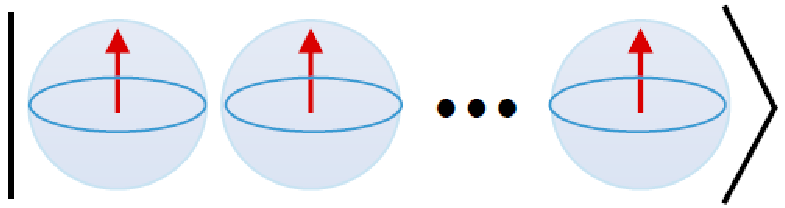
Schrödinger equation → Quantum algorithm

Time evaluation

$$i\hbar \frac{\partial}{\partial t}\psi = \hat{H}\psi$$

Hamiltonian is an operator describing the system energy

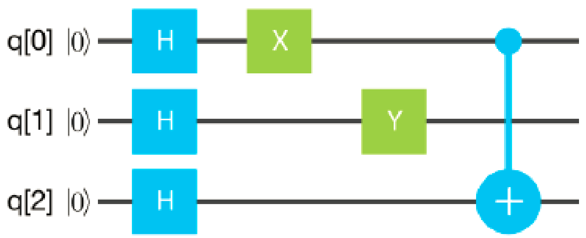
Ψ function describes the full state of the quantum system



$|0\rangle^{\otimes n} = |0\rangle$

Quantum information:
State of n qubit system,
i.e. linear combination of all 2^n states

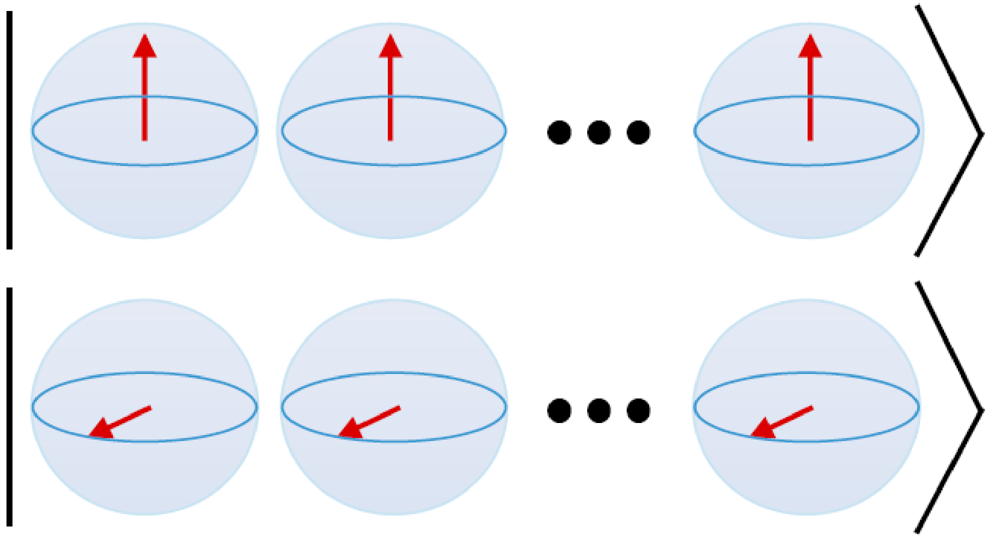
Hamilton-Operator $\hat{H}$



Series of quantum gates applied on quantum state to change the phase of the quantum state.
Energy is preserved!

Quantum algorithm basic flow

1. take/find Hamiltonian, i.e. operator for quantum algorithm
2. describe/translate Hamiltonian/operator with quantum gates
3. prepare quantum register into initial superposition state



$$|0\rangle^{\otimes n} = |0\rangle$$

$$|\psi\rangle = H^{\otimes n}|0\rangle^{\otimes n} = \frac{1}{\sqrt{2^n}}\sum_{x=0}^{2^n-1}|x\rangle$$

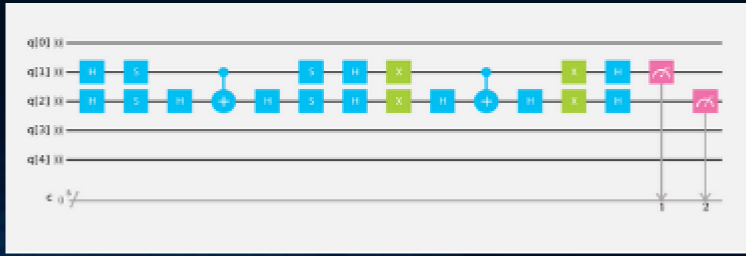
Initial zero state

H

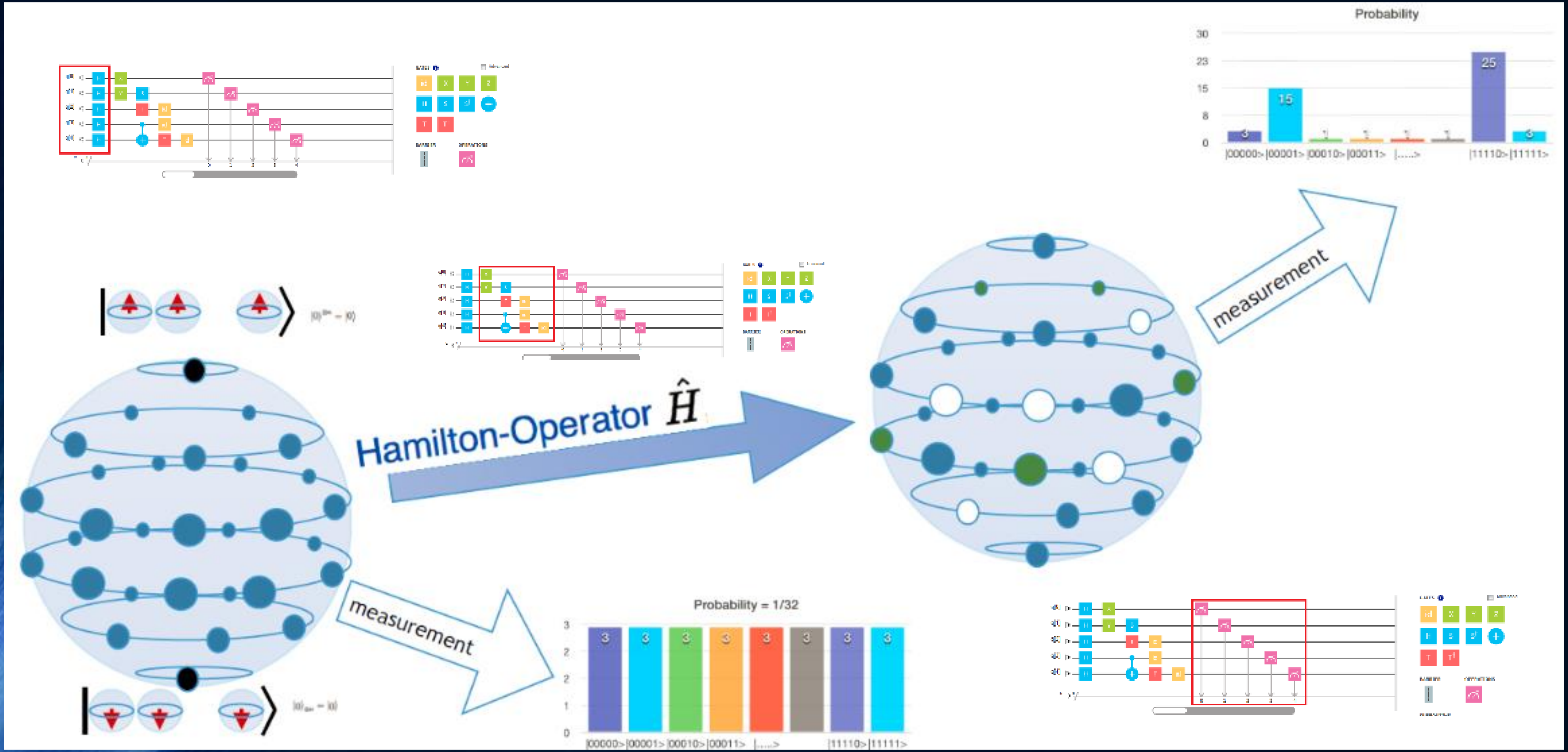
Normalization

Apply Hadamard operator to achieve superposition state for each qbit

Now the computation (algorithm) can begin

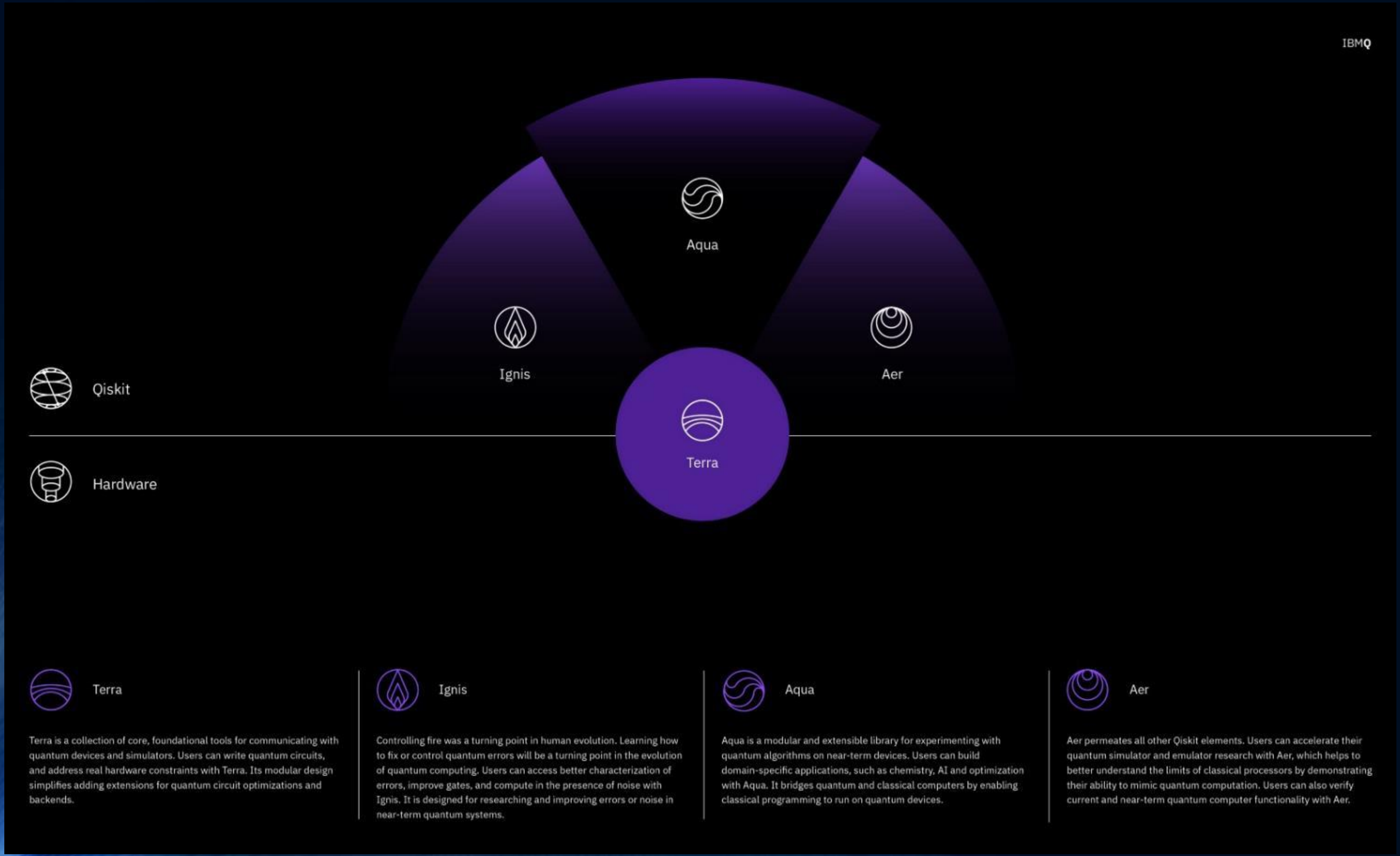


Quantum algorithm basic flow

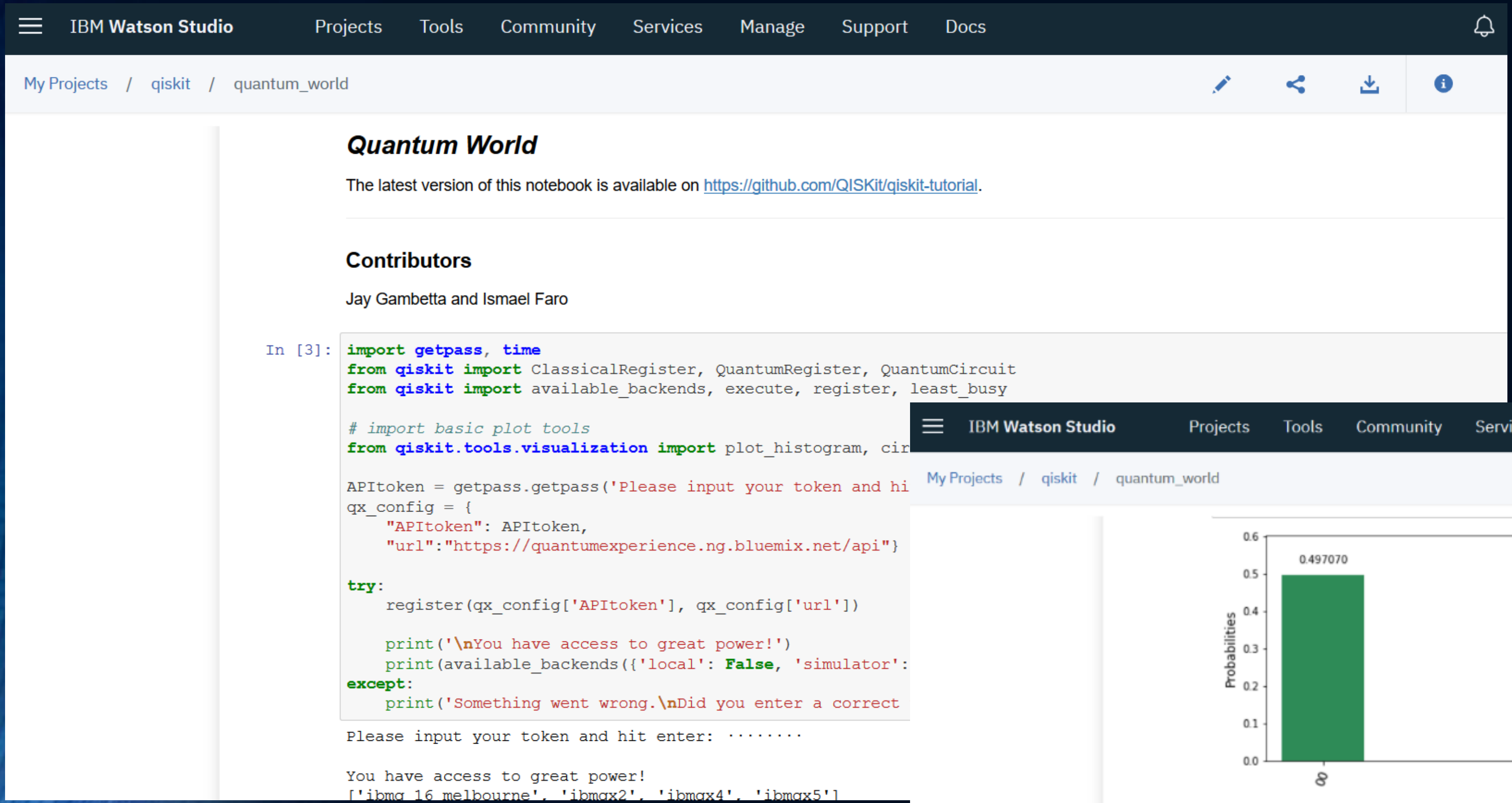


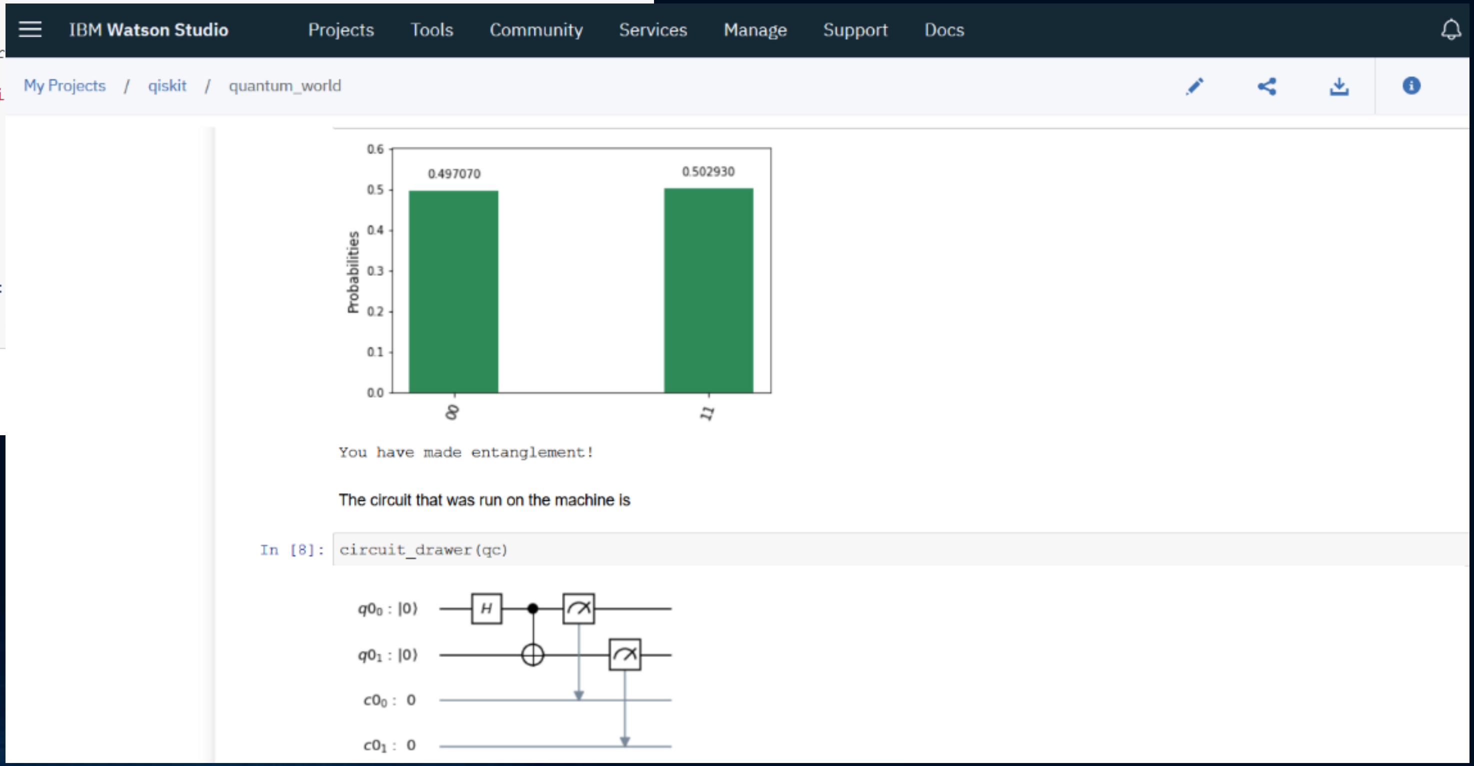
Qiskit & Aqua

Qiskit and Aqua

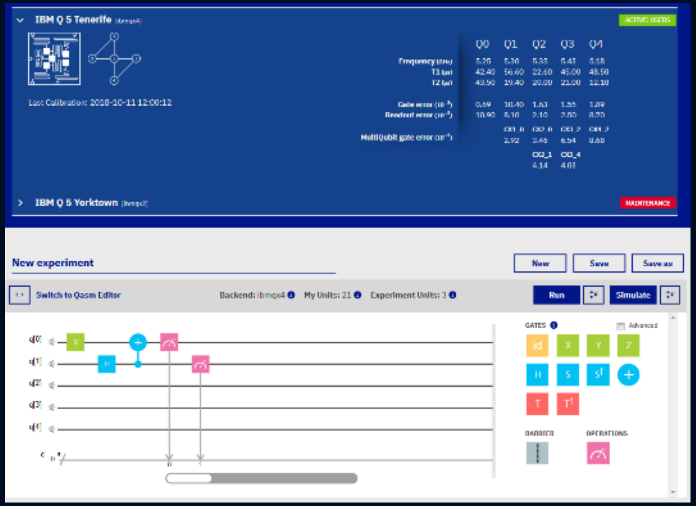


Managing Jypiter Notebooks in IBM Watson Studio

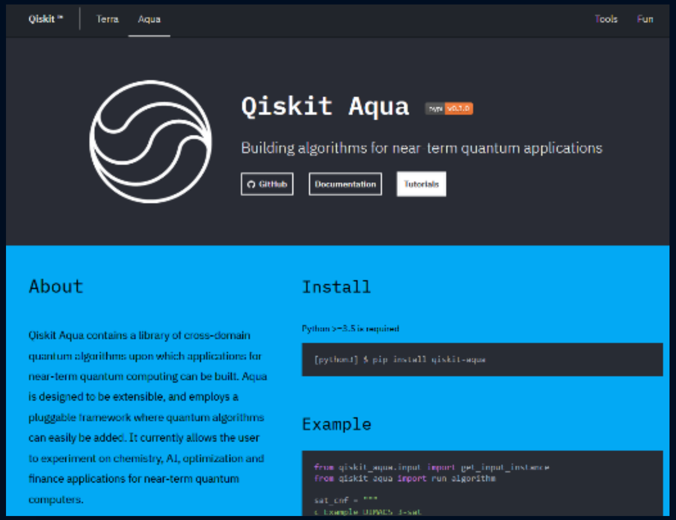




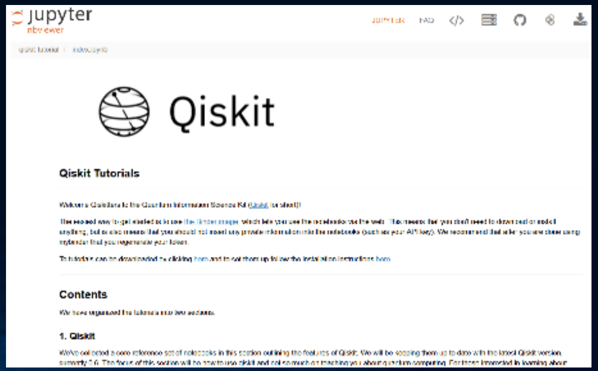
IBM Q Experience: Quantum Composer:
https://quantumexperience.ng.bluemix.net/qx/editor

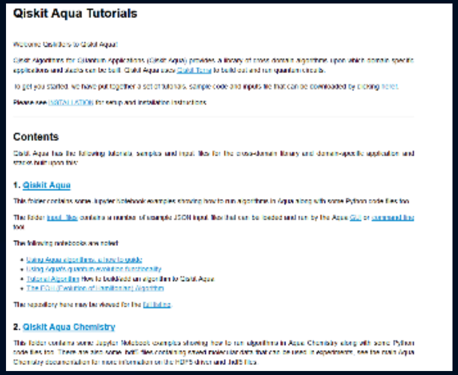


Qiskit Aqua:
https://qiskit.org/aqua



Qiskit & Aqua tutorials with Jupyter notebooks:
https://nbviewer.jupyter.org/github/Qiskit/qiskit-tutorial/blob/master/index.ipynb





Nature isn‘t classical… And if you want to make a simulation of nature, you will better make it quantum mechanical… It is a wonderful problem, because it doesn‘t look so easy.

Richard Feynman, 1982

Quantum computer will become invaluable tools of chemestry, biology, health, mathematics, and the natural environment – and they will reignite our collective scientific imagination.

Jerry Chow, 2017
IBM quantum researcher

The problem with quantum computer is that we never can say for sure, whether it is working or not.

Just an observation

Thank you

Questions

?

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