

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 ?

Physics



Information

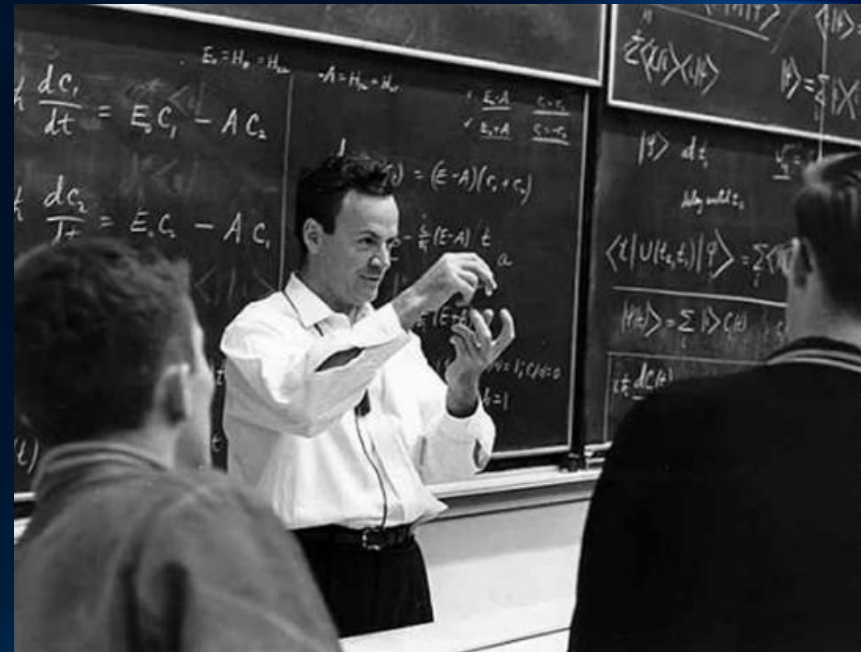
I'm not happy with all the analyses
that go with just the classical theory,
because nature isn't classical,
dammit, and if you want to make a
simulation of nature, you'd better
make it quantum mechanical ...

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

Simulating Physics with Computers

Richard P. Feynman

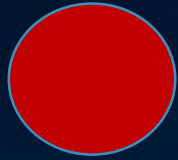
Department of Physics, California Institute of
Technology, Pasadena, California 91107



The idea of Quantum Computer

Bit

0

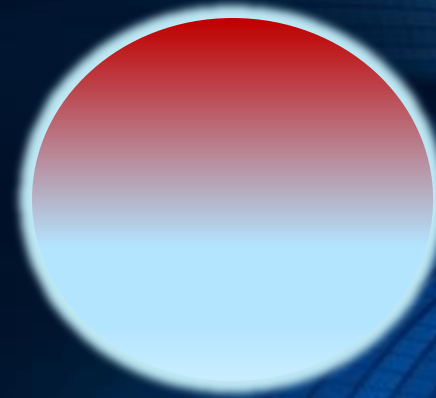


1



QBit

„0“



„0“ + „1“

„1“

... and then

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

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

— Richard Feynman

Complexity of algorithms

n - length of the input

Polynomial time

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

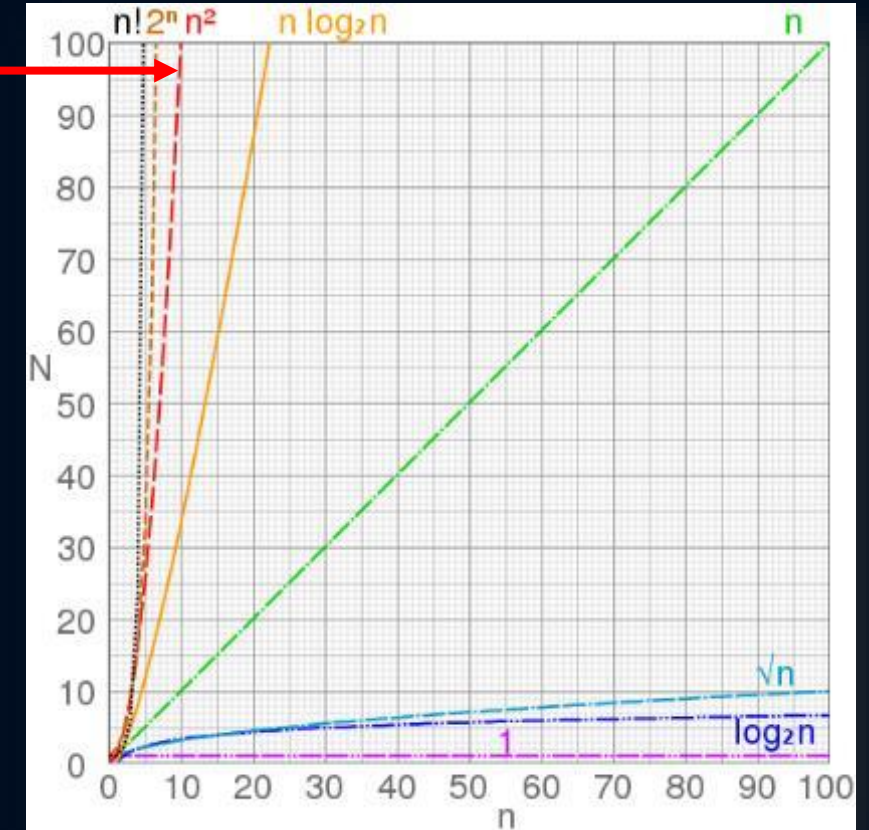
Example: $5n^3 + 3n^2$ has a complexity $O(n^3)$

Exponential time

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

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

Efficiency limit



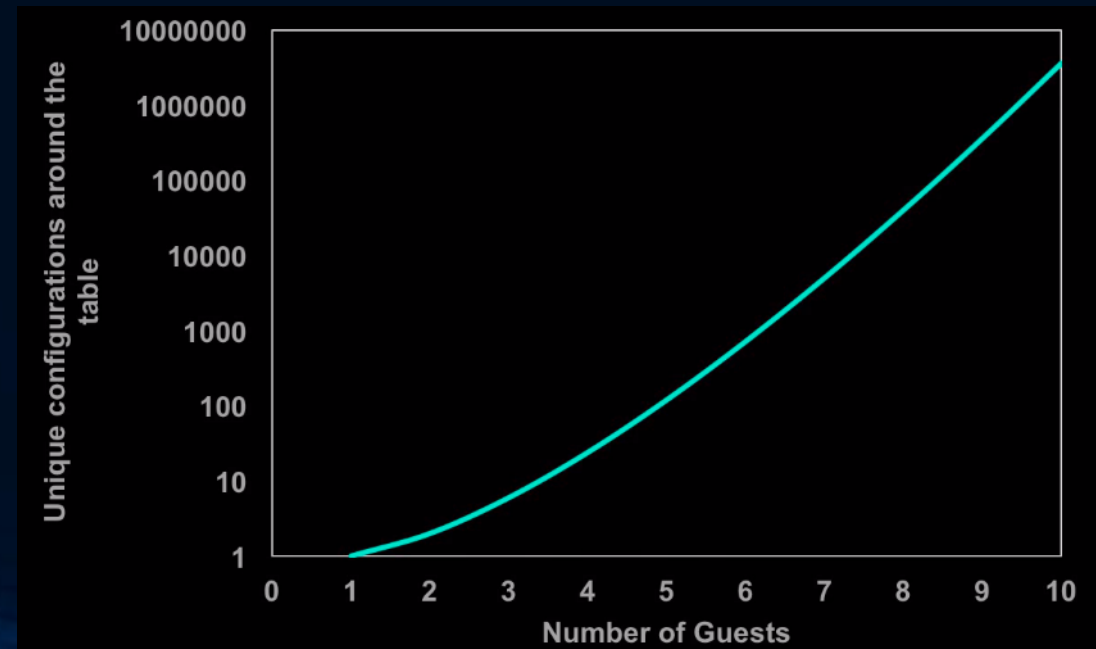
Classical computer can efficiently calculate algorithms with polynomial complexity

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

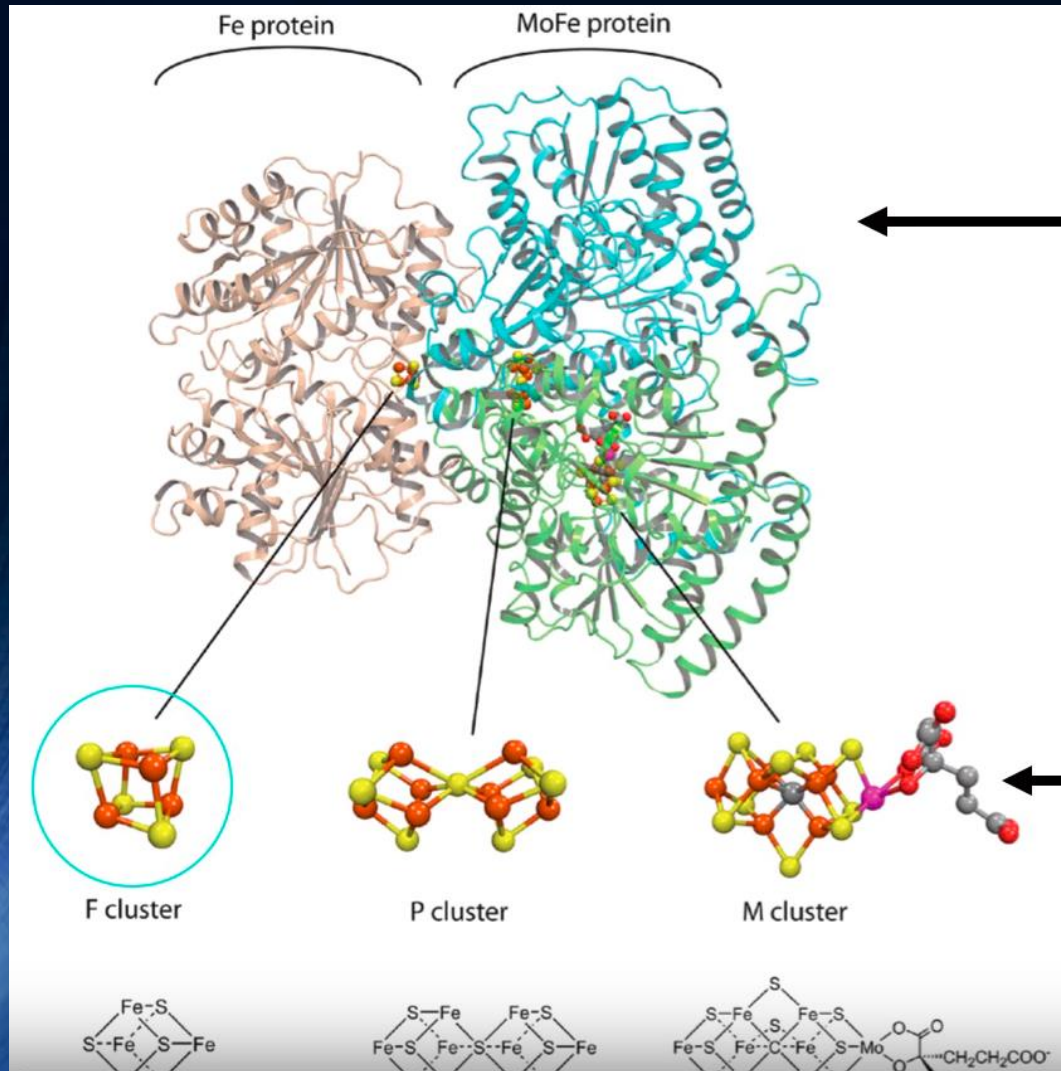
Optimization



10 people
permutations ~3,6 Mio



Chemistry



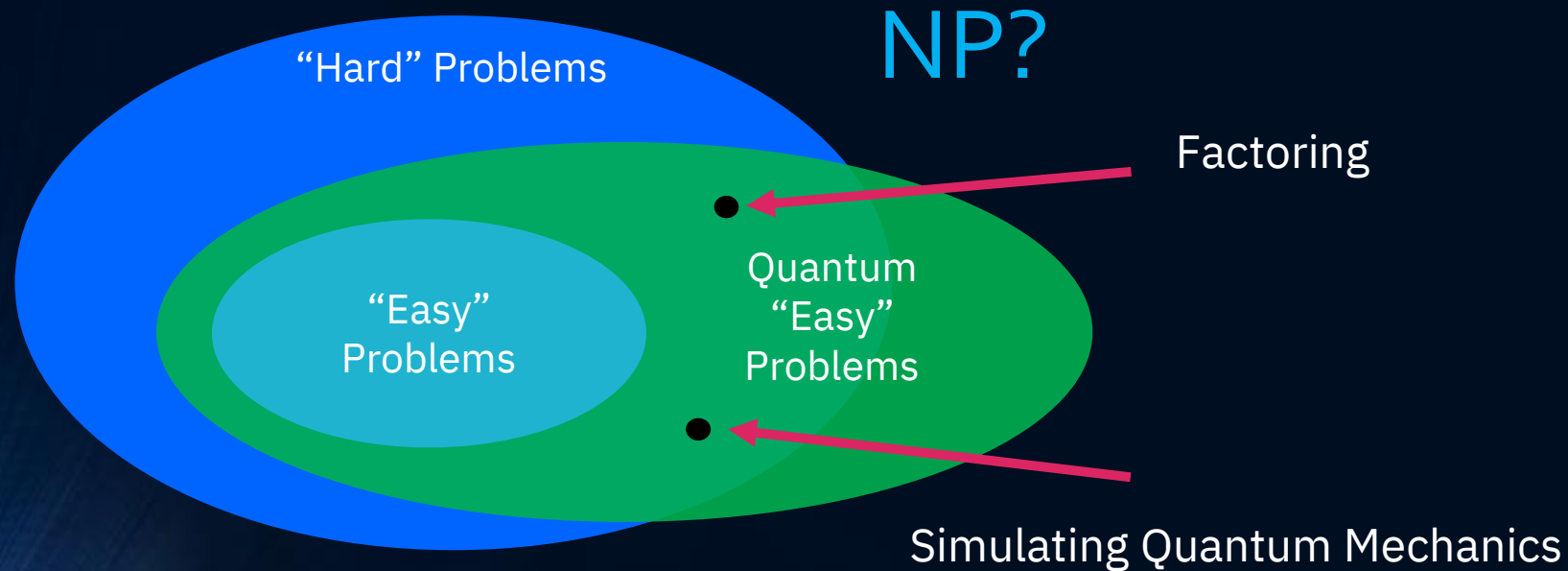
Nitrogenase enzyme
involved in N_2 to NH_4 reaction

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

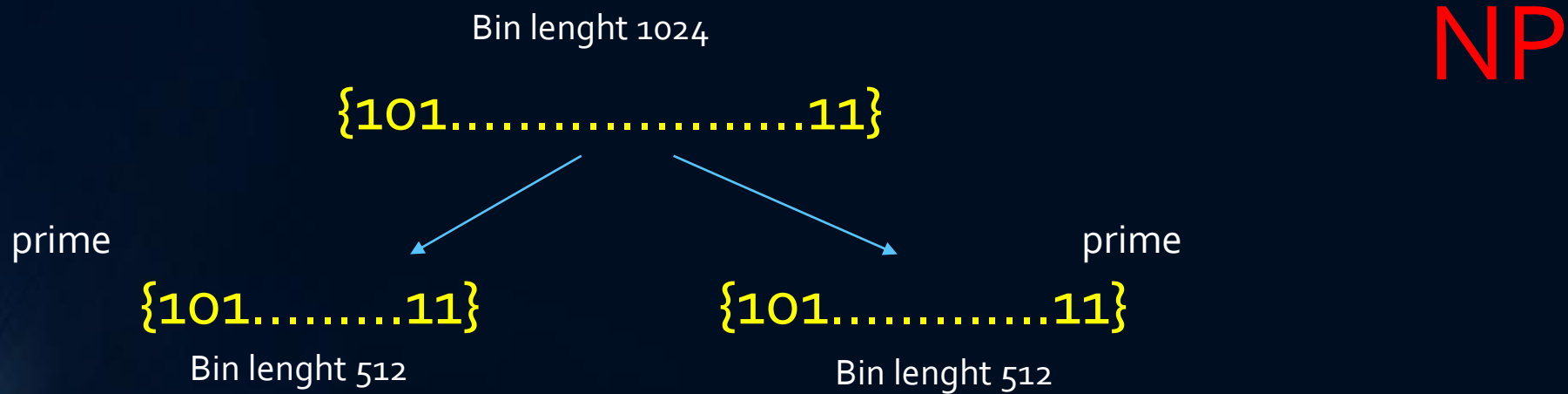
Hard problems and quantum speedup



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



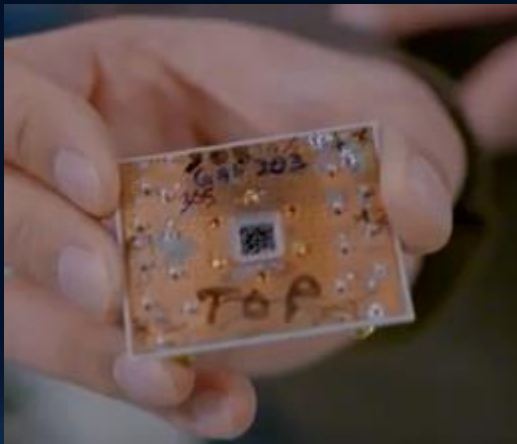
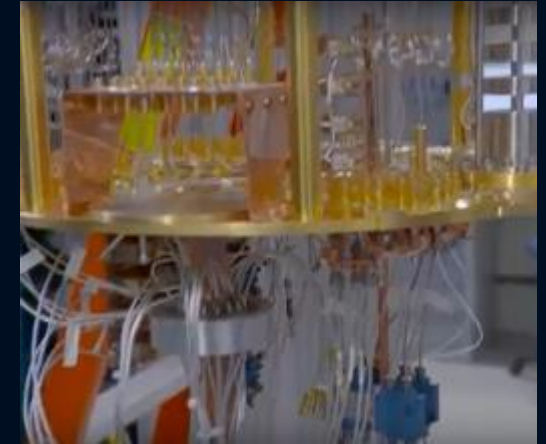
- This task requires time $T(n) = 2^n$
- It cannot be solved efficiently by classical computers
- It can be solved efficiently by quantum computer, because it somehow does anything at once.

Shor's quantum algorithm claims to solve this problem in polynomial 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

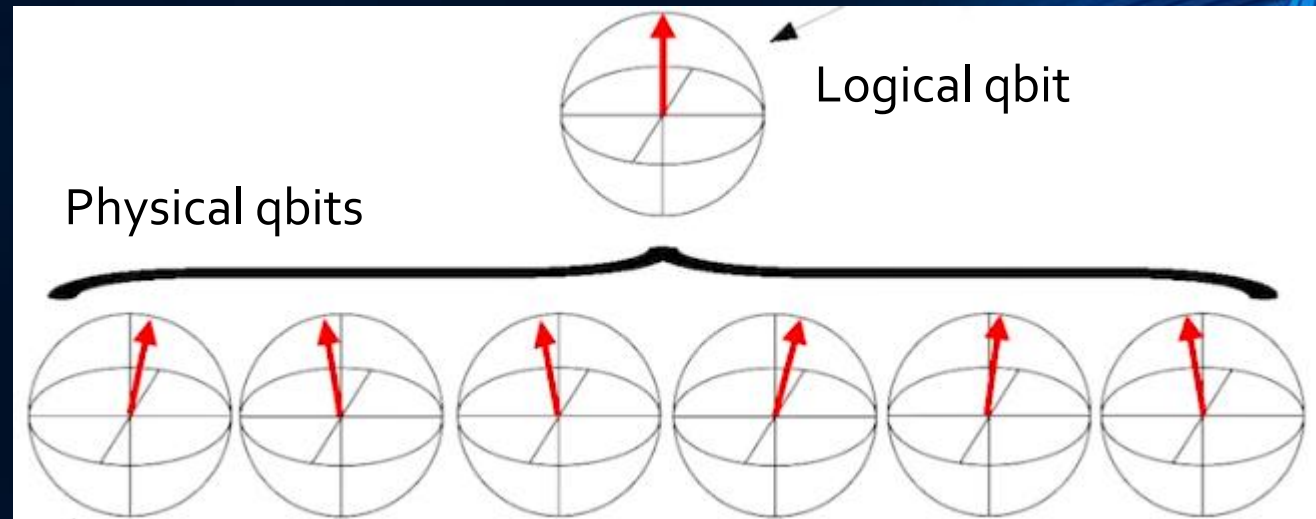
THRESHOLD (FAULT TOLERANCE) THEOREM

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 qubits
for 1 logical qbit





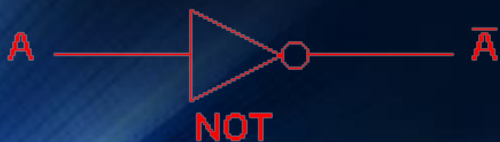
How a Qbit works

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



Not gate	
A	\bar{A}
0	1
1	0

The full logical operations are based on

OR, NOT

or

AND, NOT

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

$$\alpha |00000\rangle + \beta |11111\rangle$$

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.



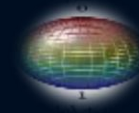
Superposition vs. Parallelism

Exponential Parallelism

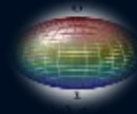
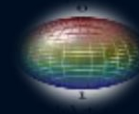


2^n potential classical computers –
unrealistic

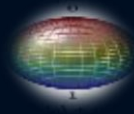
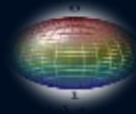
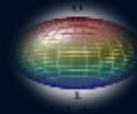
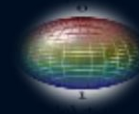
Superposition



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

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

new quantum state vector

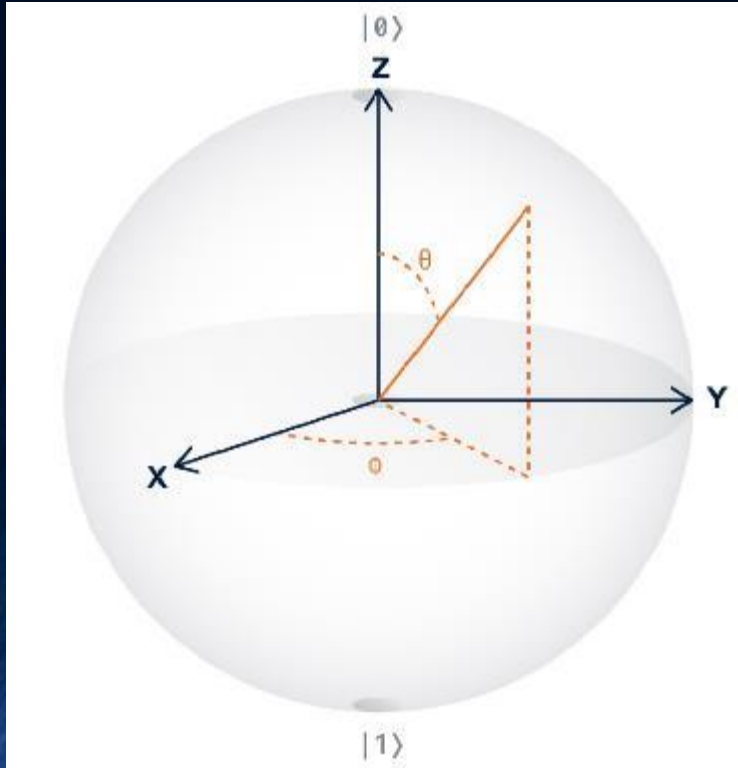
U^\dagger is a complex conjugation and transpose of matrix U

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



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.

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

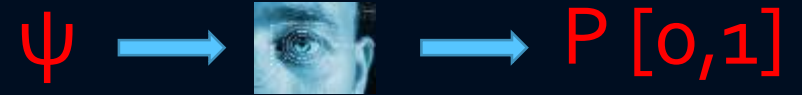
$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

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

Single qubit operations are rotations and reflections within Bloch sphere

Superposition and Entanglement

Superposition



- Quantum theory predicts that a computer with N qubits can exist in a superposition of all 2^N of its distinct logical states $|00 \dots 0\rangle$ through $|11 \dots 1\rangle$ simultaneously.
- This is **exponentially more** than a classical superposition. Playing N musical tones at once can only produce a superposition of N states.



Entanglement

- 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

EPR experiment



qubits

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

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

orthonormal base vectors

superposition

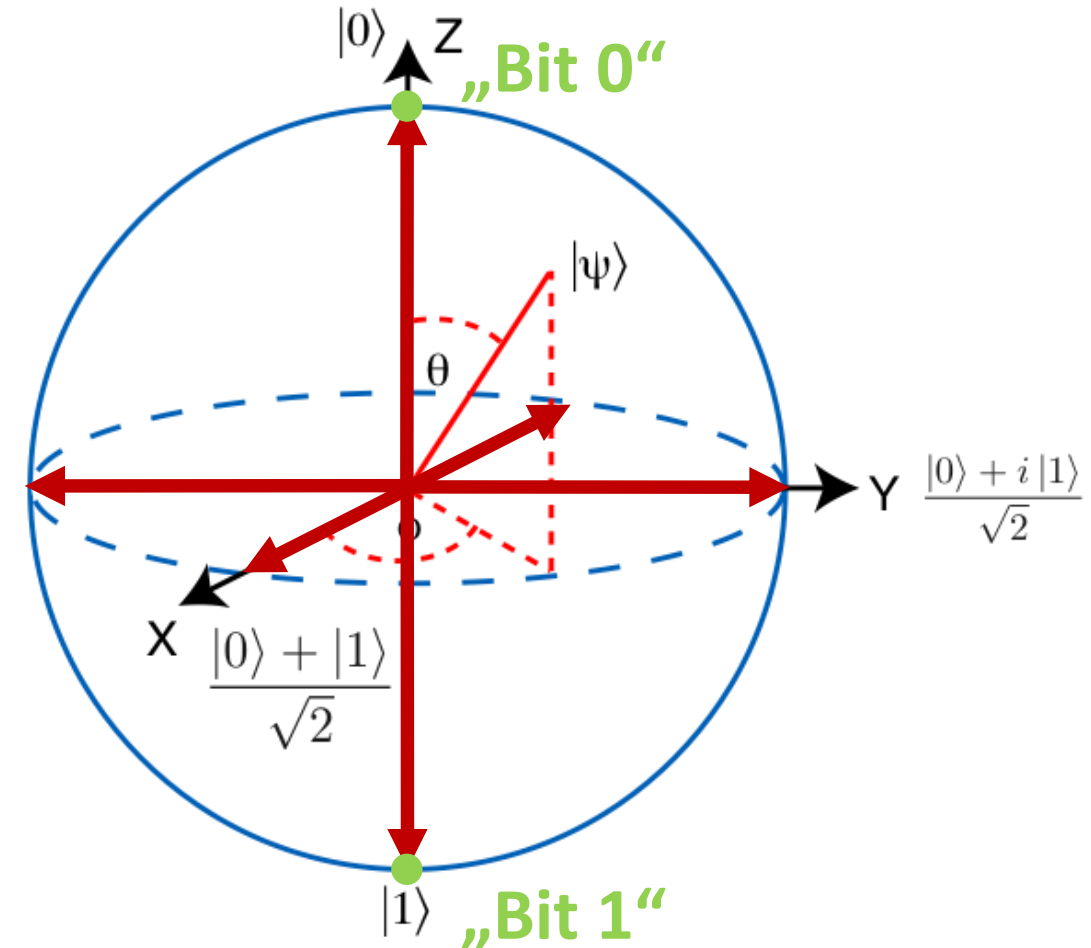
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad |\alpha|^2 + |\beta|^2 = 1$$

z.B.

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

$$|\odot\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle) \quad |\oslash\rangle = \frac{1}{\sqrt{2}}(|0\rangle - i|1\rangle)$$

Bloch sphere

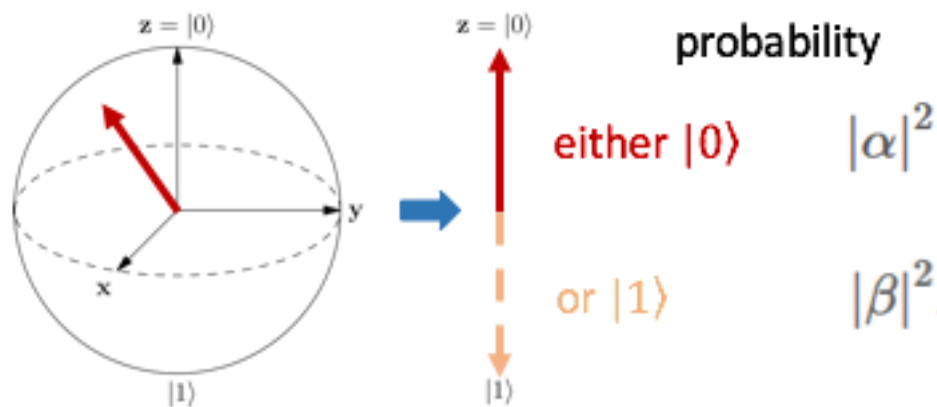


measurement and quantum gates



measurement

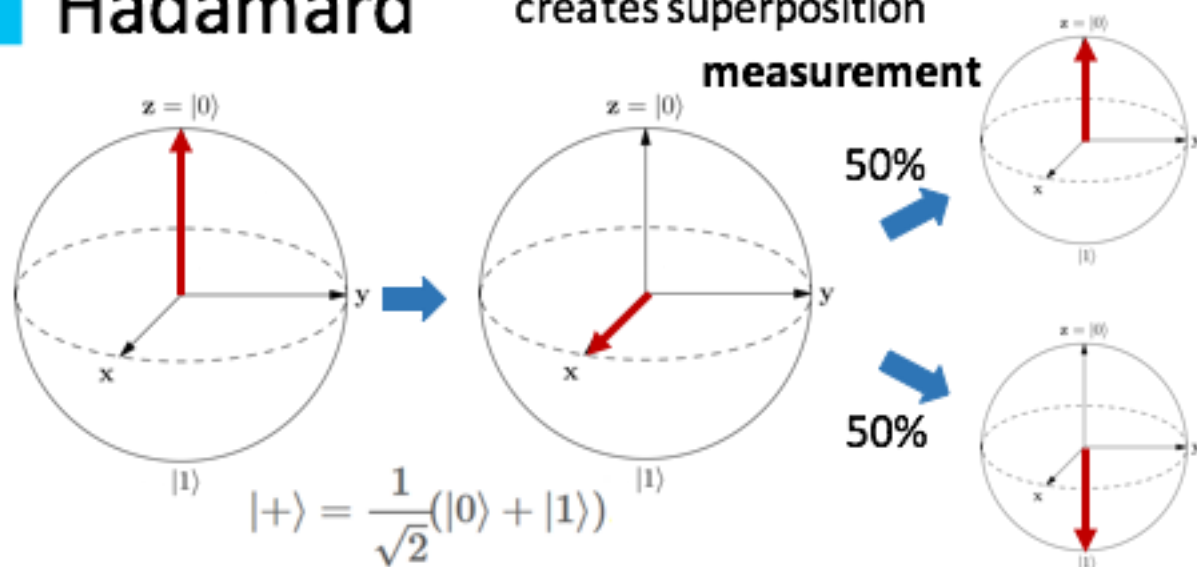
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



Hadamard

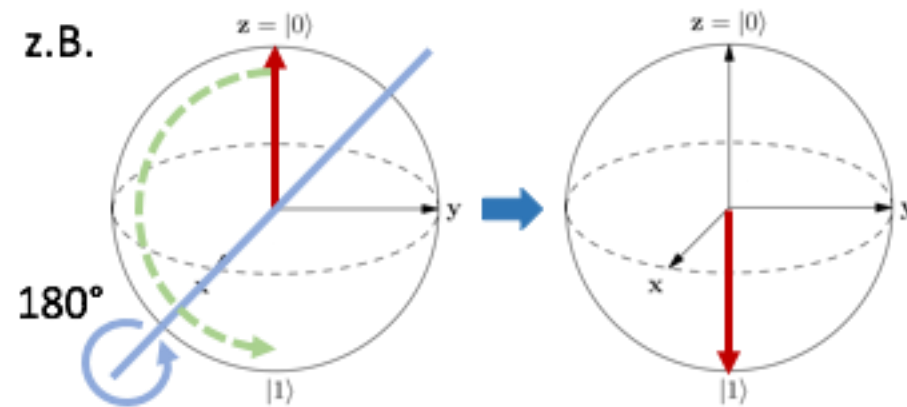
creates superposition

measurement



rotations

z.B.

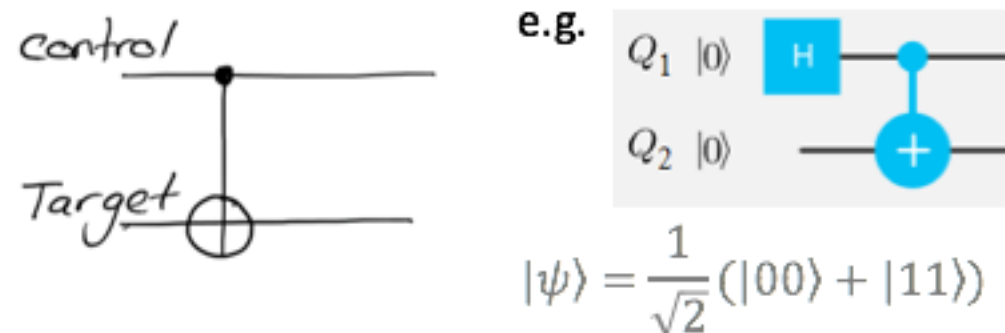


controlled-NOT

„quantum XOR“

for entanglement

e.g.



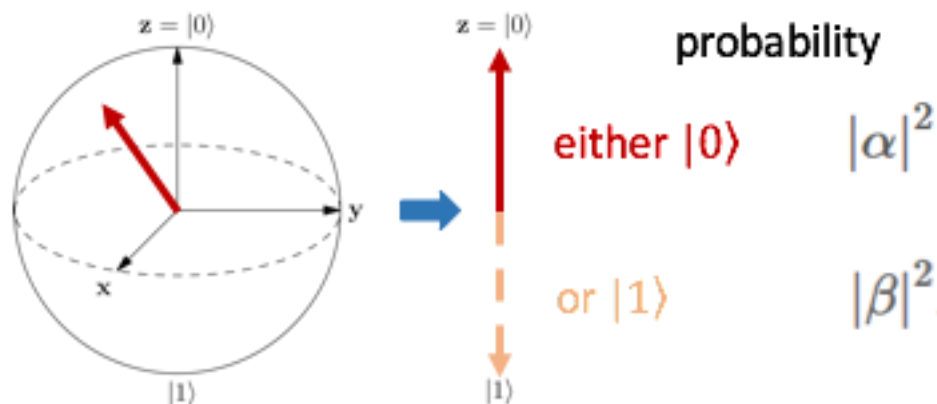
→ no classical equivalent exists

measurement and quantum gates



measurement

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



rotations

z.B.

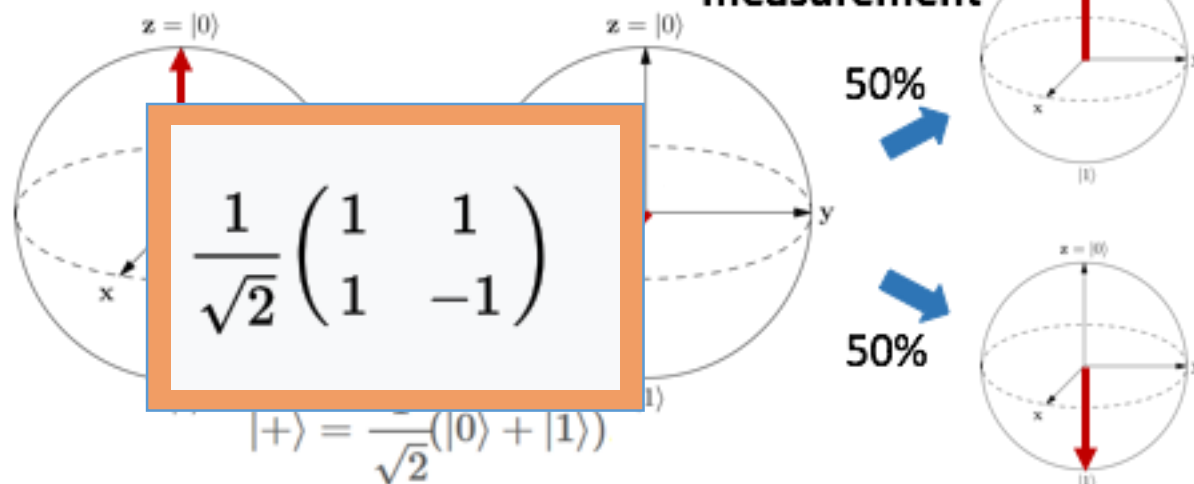
$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$



Hadamard

creates superposition

measurement



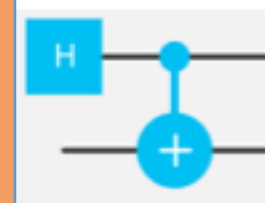
controlled-NOT

„quantum XOR“

control

Target

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



$|00\rangle + |11\rangle$

→ no classical equivalent exists

Quantum algorithm basics

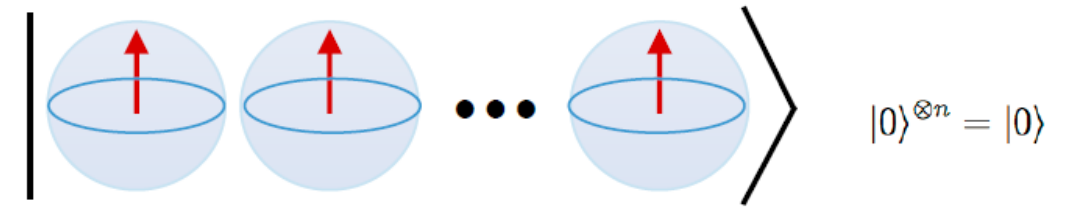
Schrödinger equation \longrightarrow Quantum algorithm

Time evaluation

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

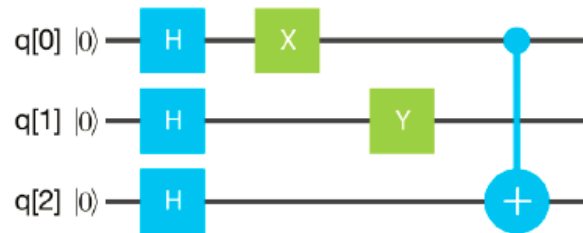
Hamiltonian is an operator describing the system energy

Ψ function describes the full state of the quantum system



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

Hamilton-Operator \hat{H}

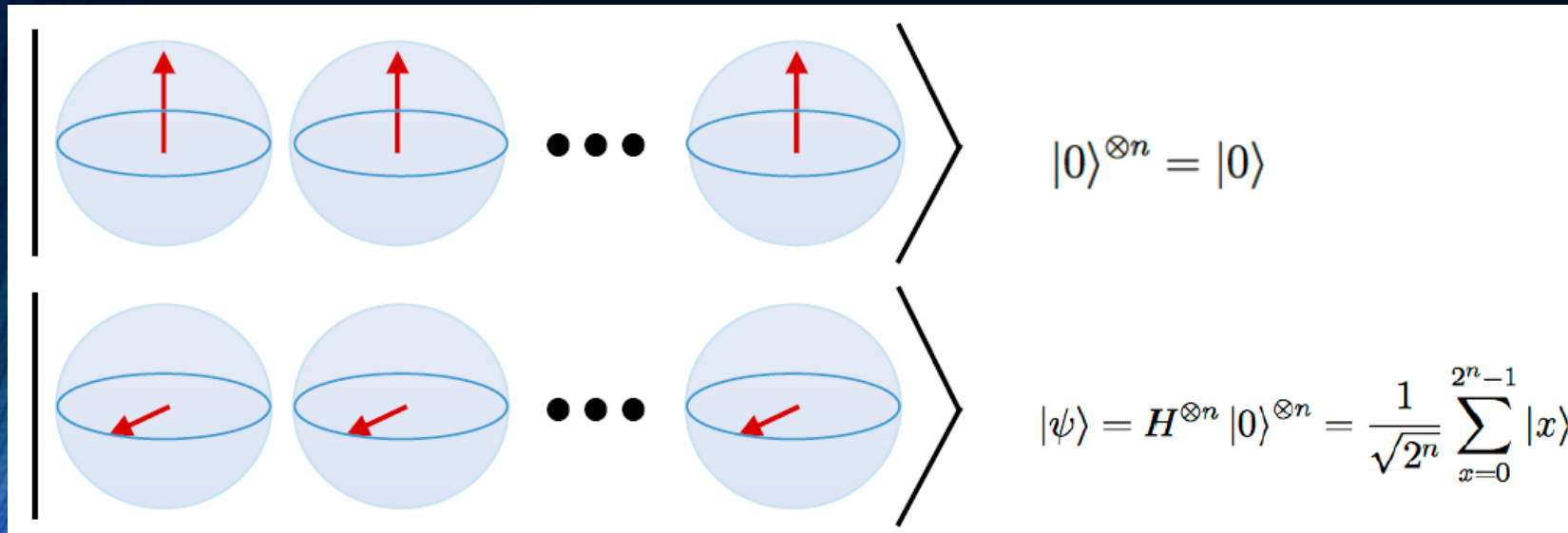


Series of quantum gates applied on quantum state to change the phase of the quantum state.

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

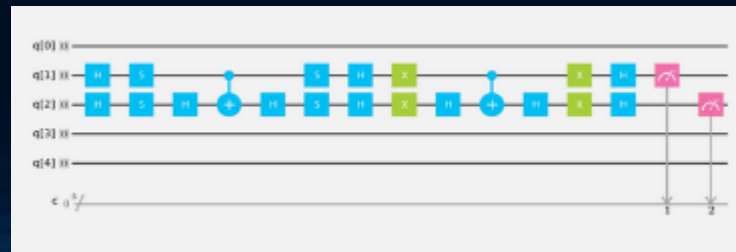


Initial zero state

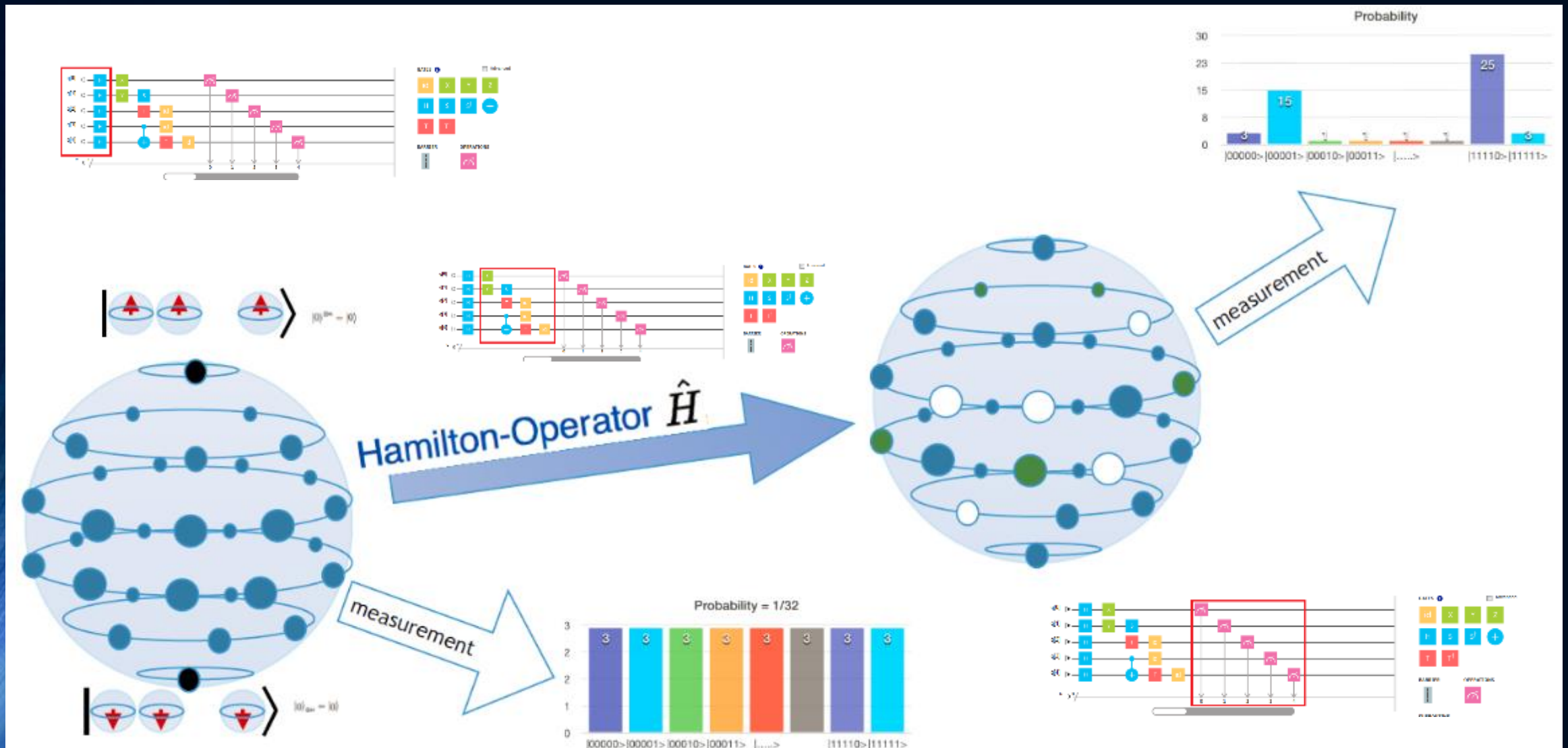


Apply **Hadamard** operator to achieve superposition state for each qbit

Now the computation (algorithm) can begin



Quantum algorithm basic flow



Qiskit & Aqua

Qiskit and Aqua

IBMQ



Terra

Terra is a collection of core, foundational tools for communicating with quantum devices and simulators. Users can write quantum circuits, and address real hardware constraints with Terra. Its modular design simplifies adding extensions for quantum circuit optimizations and backends.



Ignis

Controlling fire was a turning point in human evolution. Learning how to fix or control quantum errors will be a turning point in the evolution of quantum computing. Users can access better characterization of errors, improve gates, and compute in the presence of noise with Ignis. It is designed for researching and improving errors or noise in near-term quantum systems.



Aqua


Aqua is a modular and extensible library for experimenting with quantum algorithms on near-term devices. Users can build domain-specific applications, such as chemistry, AI and optimization with Aqua. It bridges quantum and classical computers by enabling classical programming to run on quantum devices.



Aer





Aer permeates all other Qiskit elements. Users can accelerate their quantum simulator and emulator research with Aer, which helps to better understand the limits of classical processors by demonstrating their ability to mimic quantum computation. Users can also verify current and near-term quantum computer functionality with Aer.

Managing Jupyter Notebooks in IBM Watson Studio

 IBM Watson Studio

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Quantum World

The latest version of this notebook is available on <https://github.com/QISKit/qiskit-tutorial>.

Contributors

Jay Gambetta and Ismael Faro

```
In [3]: import getpass, time
from qiskit import ClassicalRegister, QuantumRegister, QuantumCircuit
from qiskit import available_backends, execute, register, least_busy
```


```
# import basic plot tools
from qiskit.tools.visualization import plot_histogram, cir
```

```
APItoken = getpass.getpass('Please input your token and hit enter: ')
qx_config = {
    "APItoken": APItoken,
    "url": "https://quantumexperience.ng.bluemix.net/api"
}
```

```
try:
    register(qx_config['APItoken'], qx_config['url'])
    print('\nYou have access to great power!')
    print(available_backends({'local': False, 'simulator': True}))
except:
    print('Something went wrong.\nDid you enter a correct token?')
```





Please input your token and hit enter:

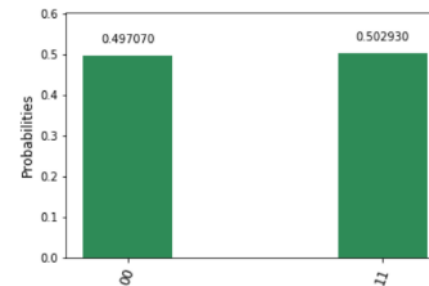
You have access to great power!
['ibmq_16_melbourne', 'ibmqx2', 'ibmqx4', 'ibmqx5']

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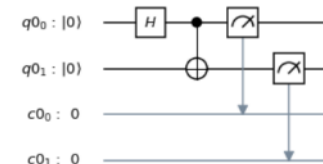




You have made entanglement!

The circuit that was run on the machine is

```
In [8]: circuit_drawer(qc)
```

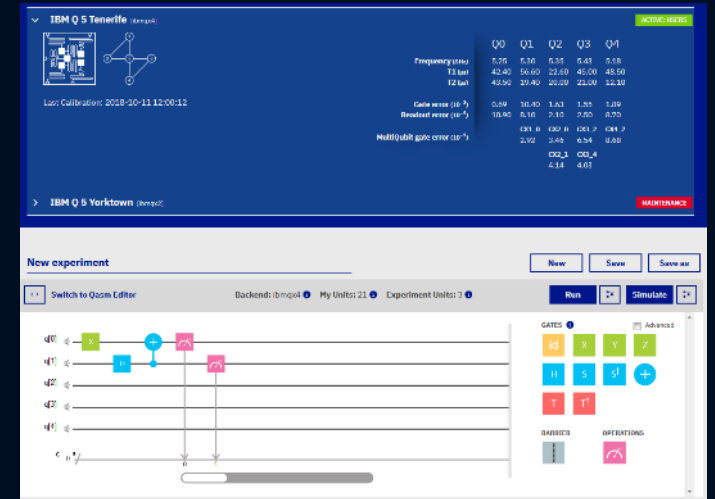
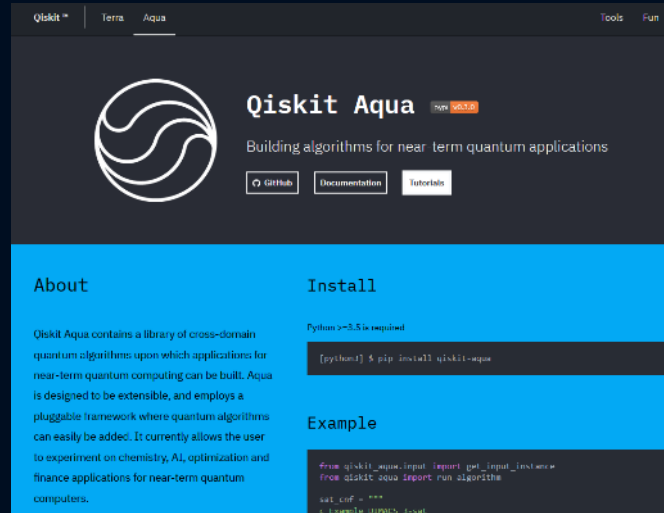


IBM Q Experience: Quantum Composer:

<https://quantumexperience.ng.bluemix.net/qx/editor>

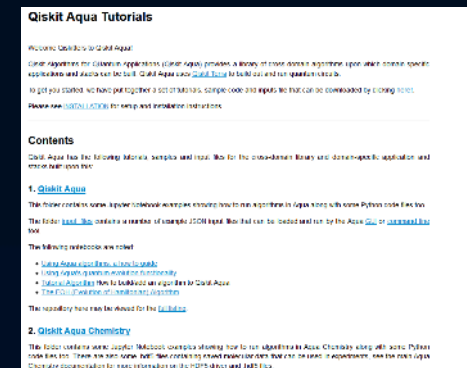
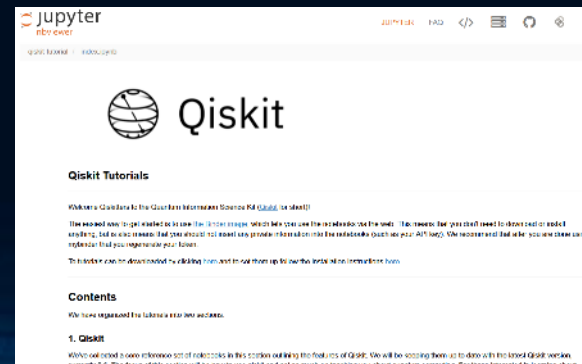
Qiskit Aqua:

<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 chemistry, 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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