

# Quantum computing as a future technology

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The background features a dark blue gradient on the left, transitioning into a series of curved, glowing blue lines on the right. These lines form a tunnel-like structure that leads towards a bright, glowing blue light source. A grid of fine lines is visible on the right side, suggesting a digital or data-related theme.

# 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

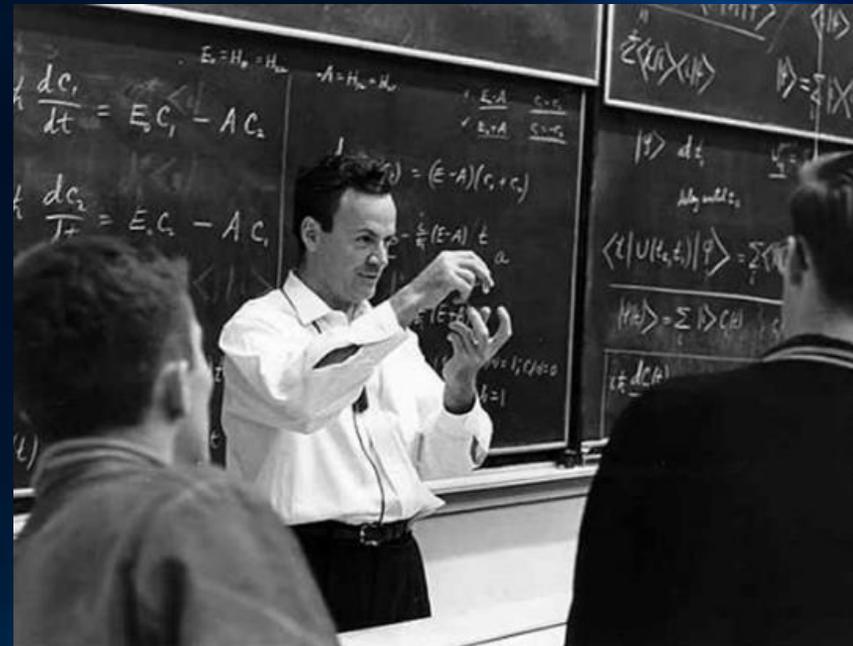
I'm not happy with all the analyses that go with just the classical theory, *because nature isn't classical*, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical ...

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

### **Simulating Physics with Computers**

**Richard P. Feynman**

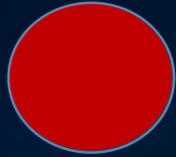
Department of Physics, California Institute of Technology, Pasadena, California 91107



# The idea of Quantum Computer

Bit

0

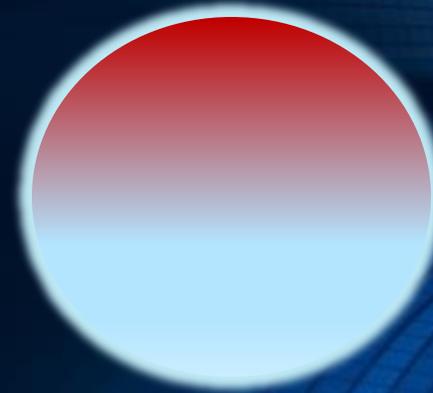


1



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.”

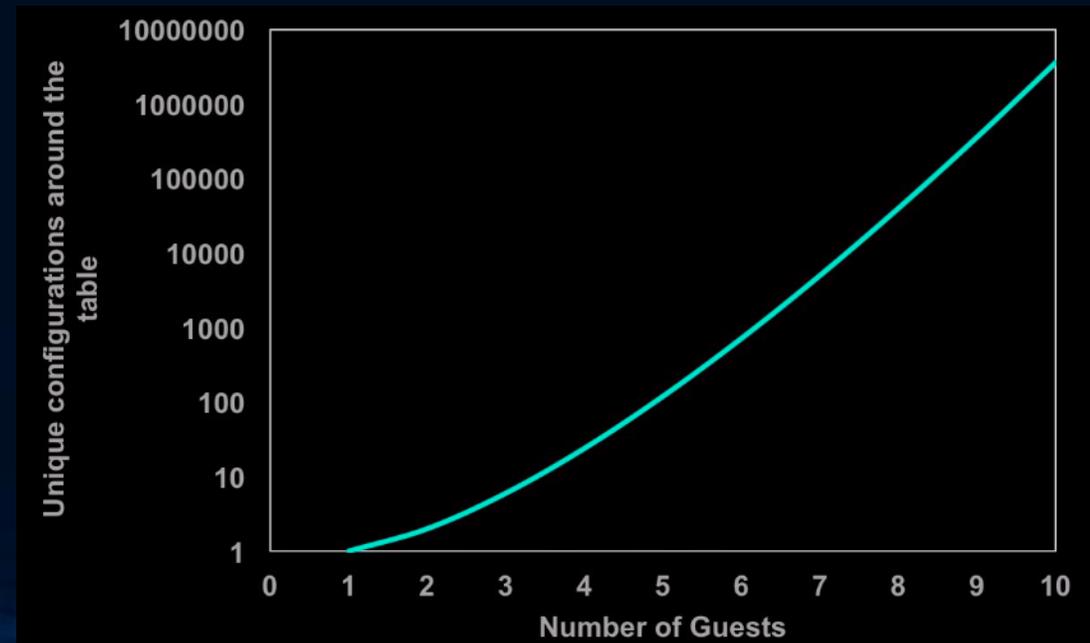
— Richard Feynman



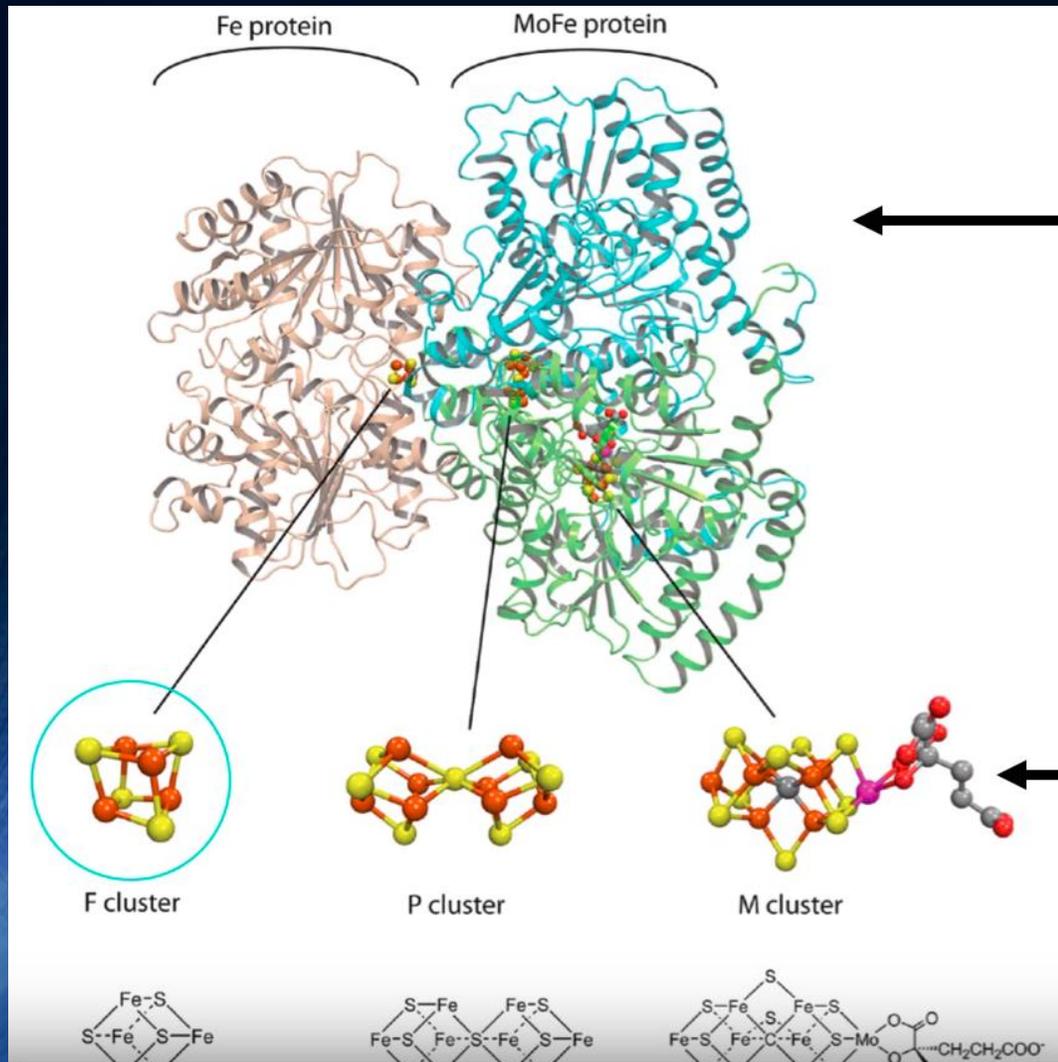
# Optimization



10 people  
# permutations ~3,6 Mio



# Chemistry



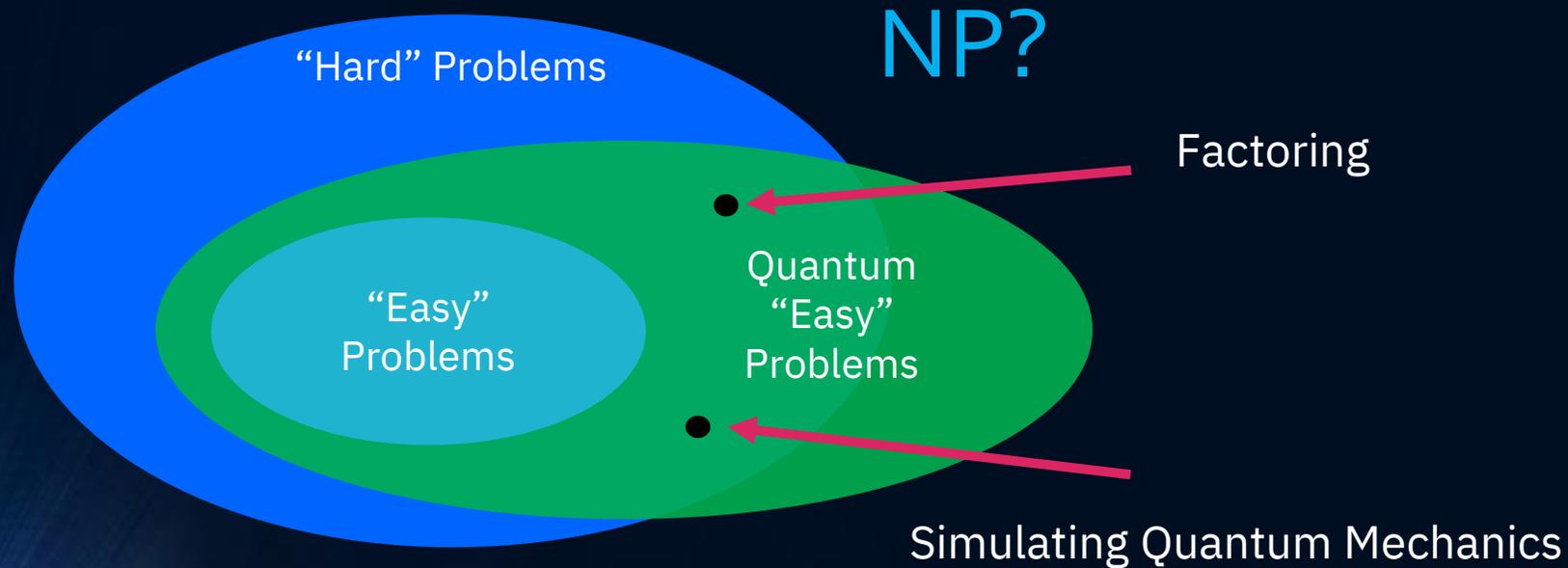
**Nitrogenase** enzyme  
involved in  $\text{N}_2$  to  $\text{NH}_4$  reaction

These regions are involved in  
different reaction **stages**

Iron sulfide clusters ( $\text{Fe}_x\text{S}_y$ ) of  
different sizes.

Simulation of this cluster is on the **limit of**  
**classical computer**

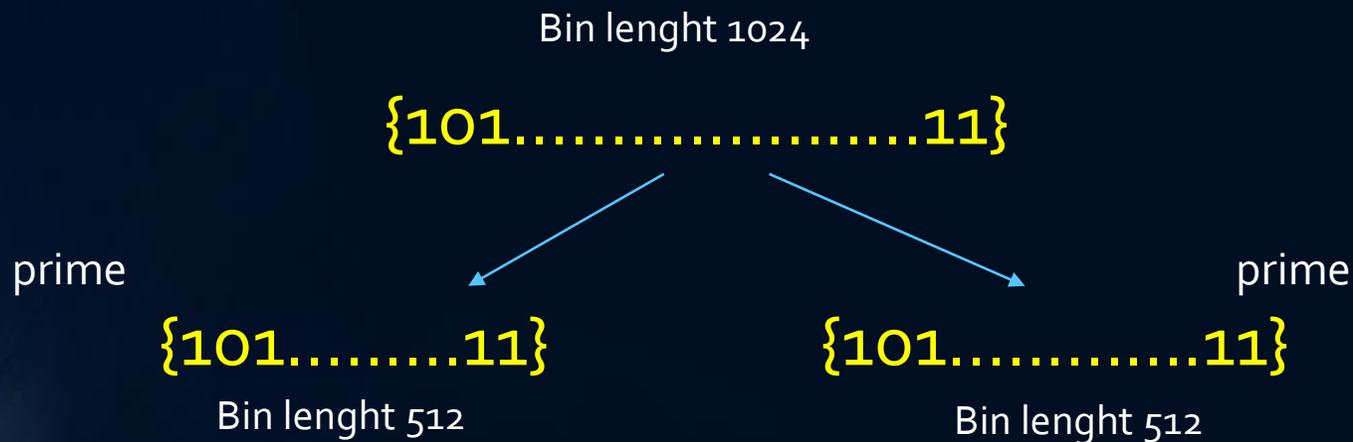
# Hard problems and quantum speedup



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

# Cryptography as example

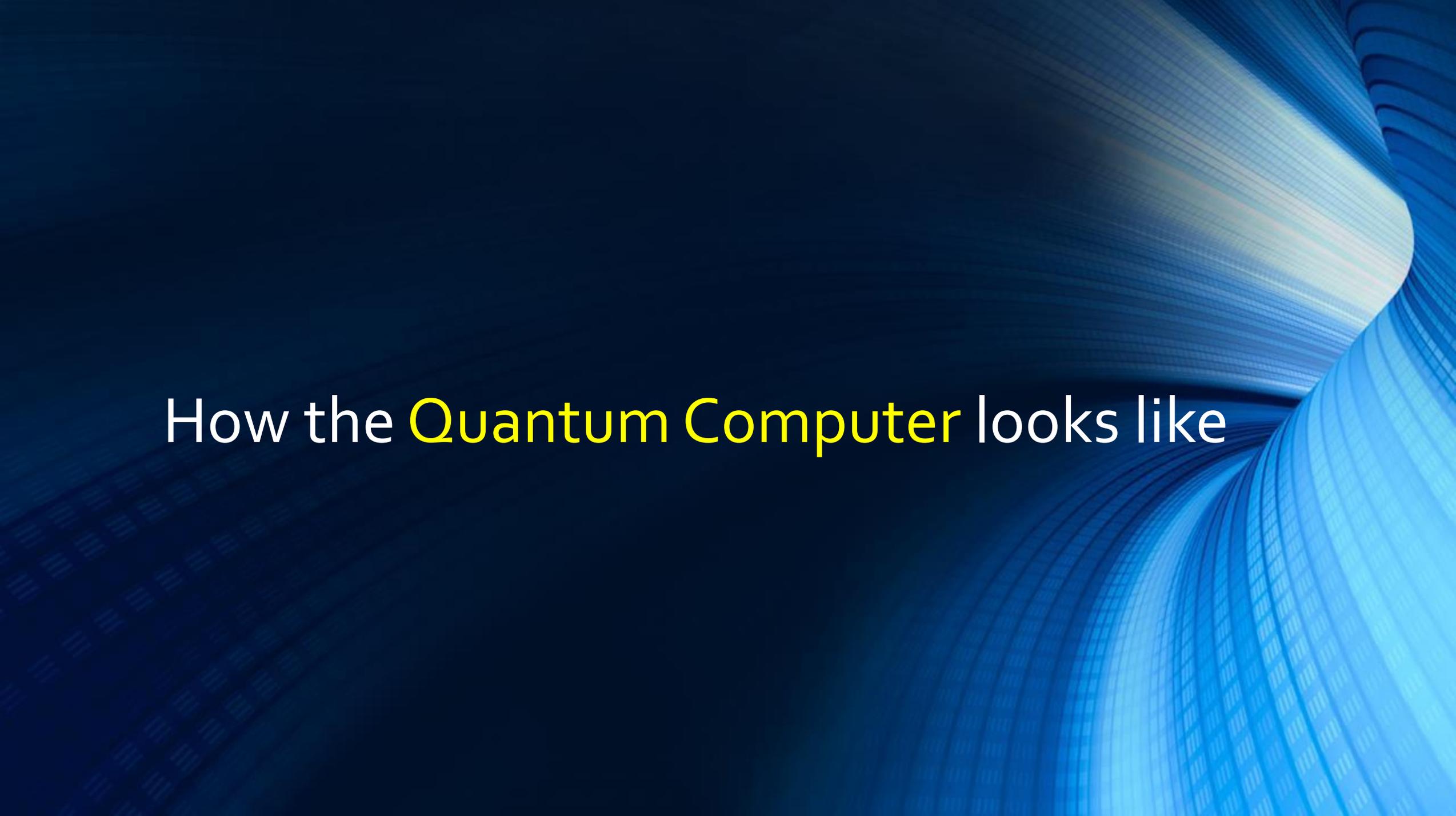
- RSA algorithm (private & public keys) is based on prime factorization problem
- Factorize a big number in two prime numbers



NP

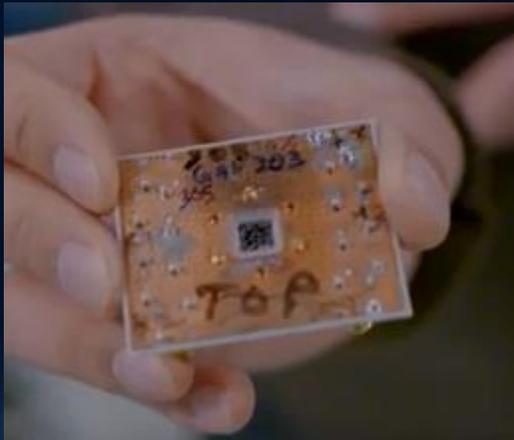
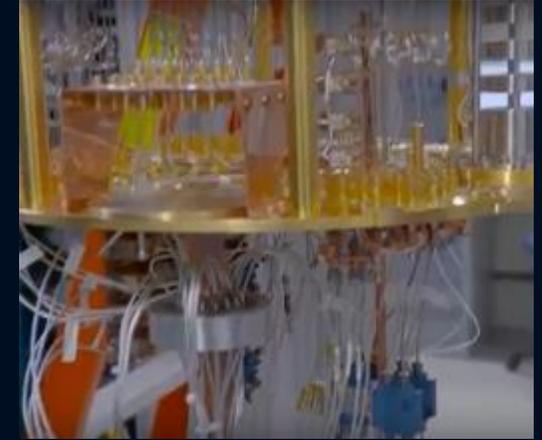
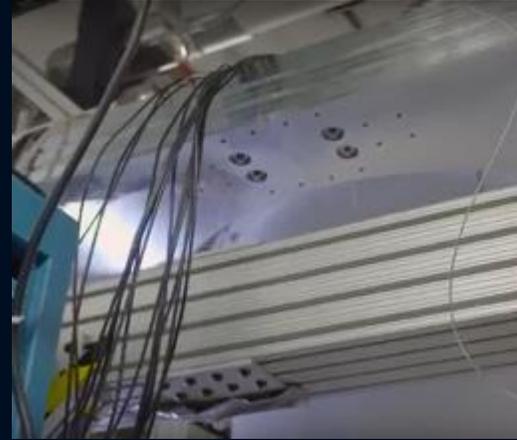
- This task requires time  $T(n) = 2^n$
- It cannot be solved efficiently by classical computers
- It can be solved efficiently by quantum computer, because it somehow does anything at once.

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

The background features a dark blue field on the left, transitioning into a series of curved, glowing blue lines on the right. These lines form a tunnel-like structure that leads towards a bright, glowing light source at the top right. A grid of fine lines is visible within the curved structure, suggesting a digital or quantum theme.

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

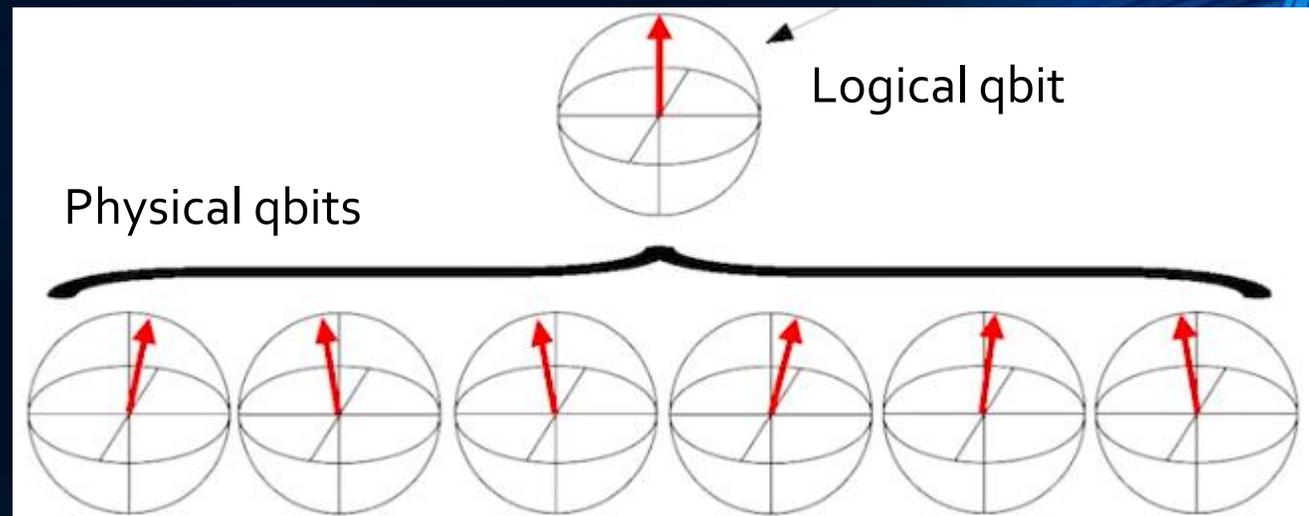
## THRESHOLD (FAULT TOLERANCE) THEOREM

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 qubit



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# 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



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.



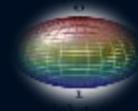
# Superposition vs. Parallelism

## Exponential Parallelism

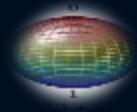
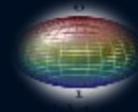


$2^n$  potential classical computers –  
unrealistic

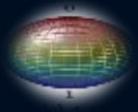
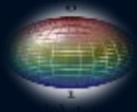
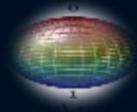
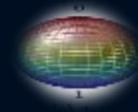
## Superposition



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

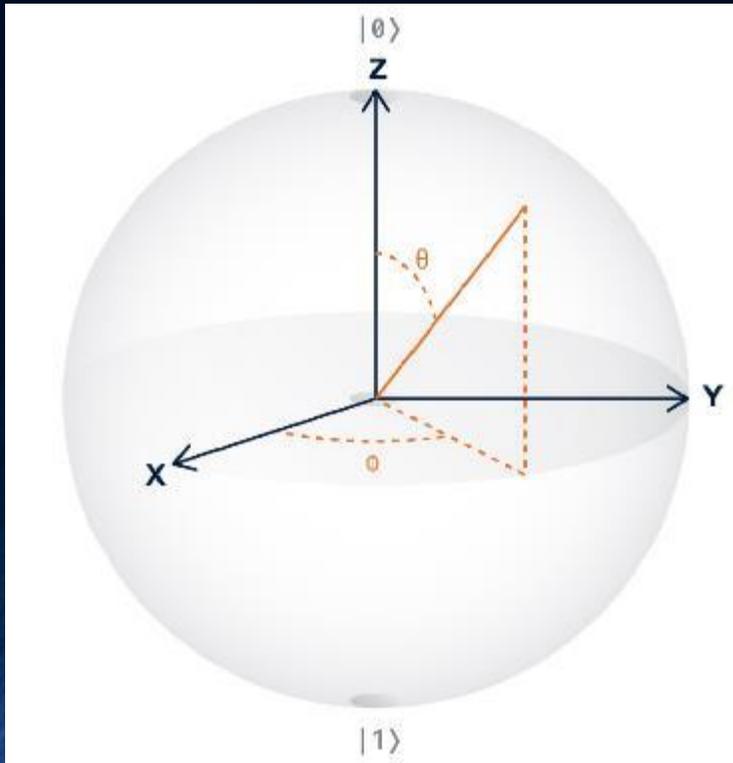
$U^\dagger$  is a complex conjugation and transpose of matrix  $U$

$I$  – identity matrix

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



# 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  $\alpha, \beta$  – complex numbers, that

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

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

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

The angle  $\phi$  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



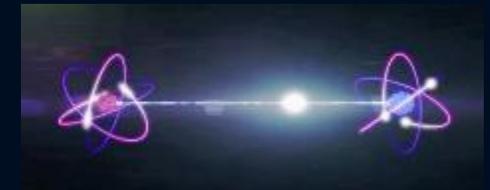
- Quantum theory predicts that a computer with  $N$  qubits can exist in a superposition of all  $2^N$  of its distinct logical states  $|00 \dots 0\rangle$  through  $|11 \dots 1\rangle$  simultaneously.
- This is **exponentially more** than a classical superposition. Playing  $N$  musical tones at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

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

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

z.B.

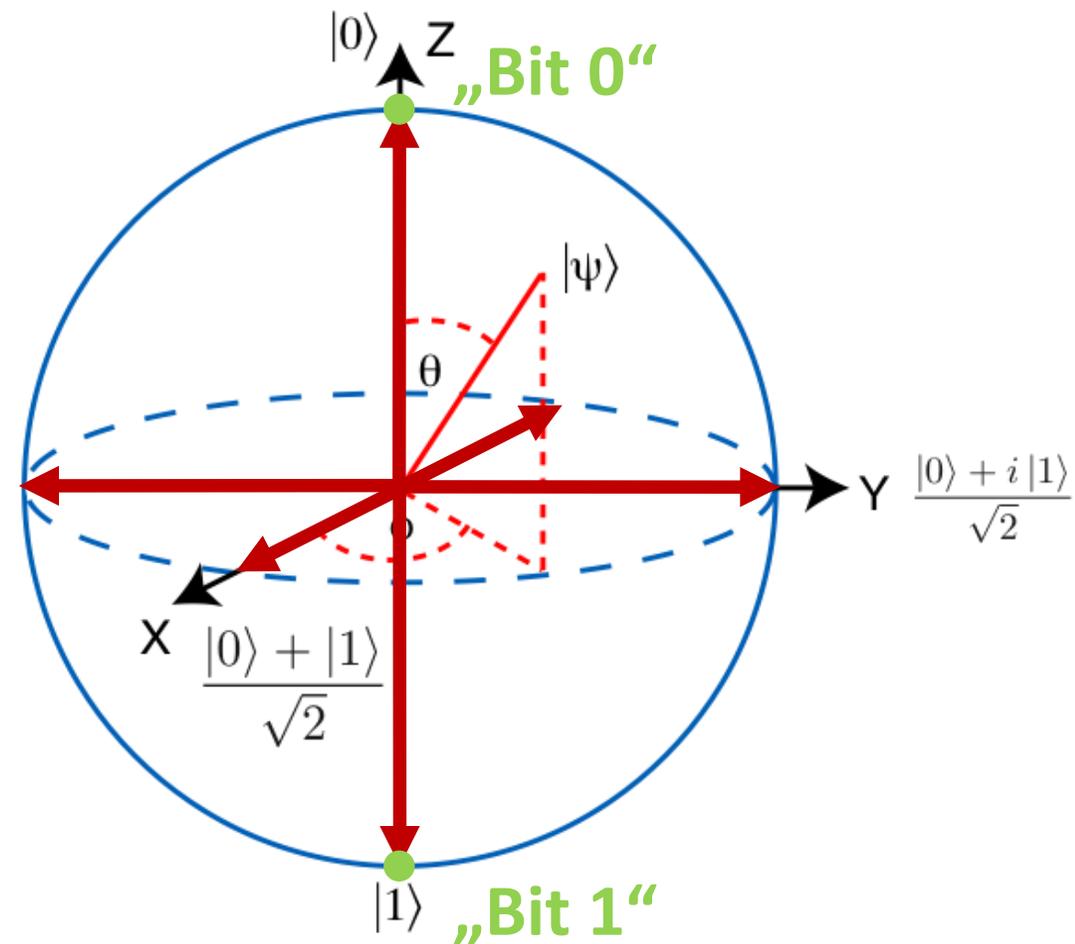
$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

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

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

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

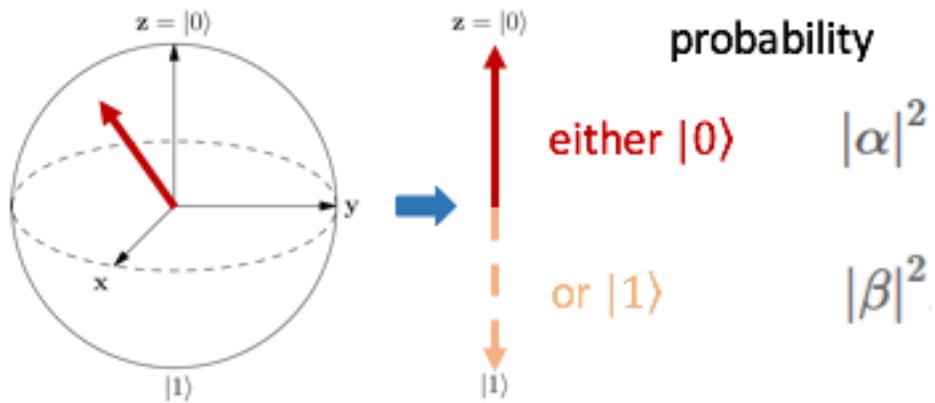
## Bloch sphere



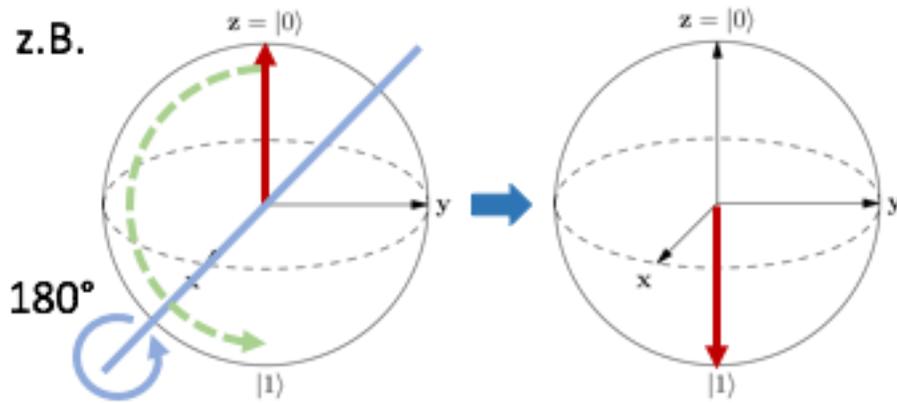
# measurement and quantum gates



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



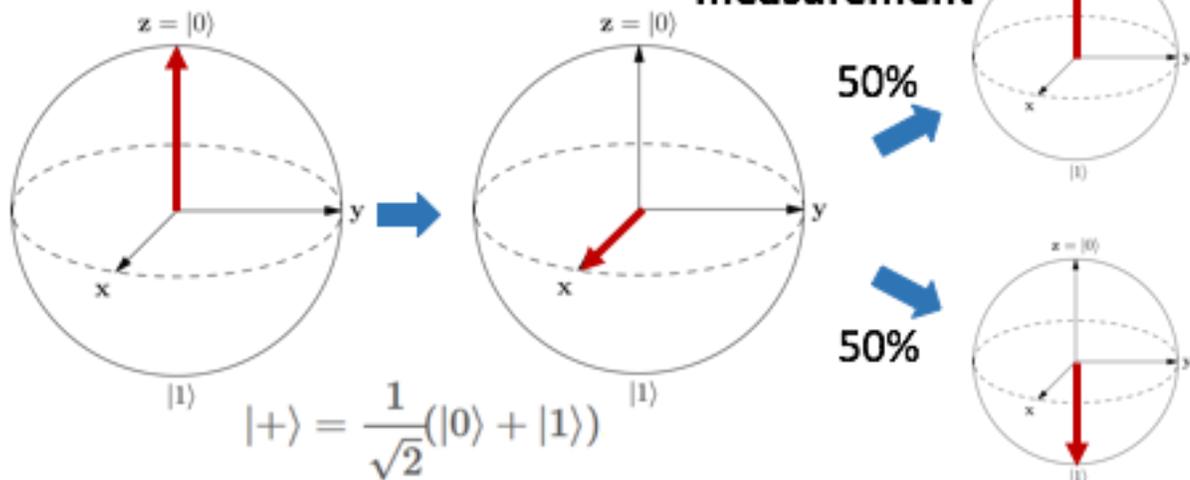
**rotations**



**Hadamard**

creates superposition

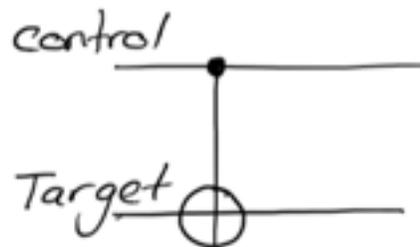
measurement



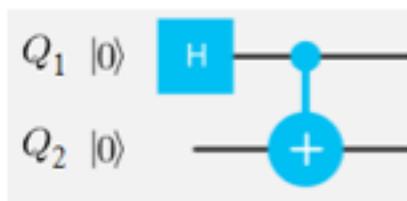
**controlled-NOT**

„quantum XOR“

for entanglement



e.g.



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

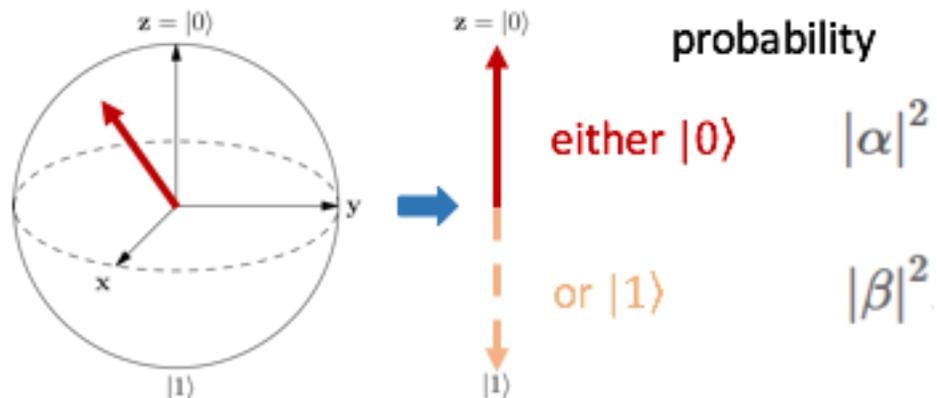
**→ no classical equivalent exists**

# measurement and quantum gates



## measurement

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



## rotations

z.B.

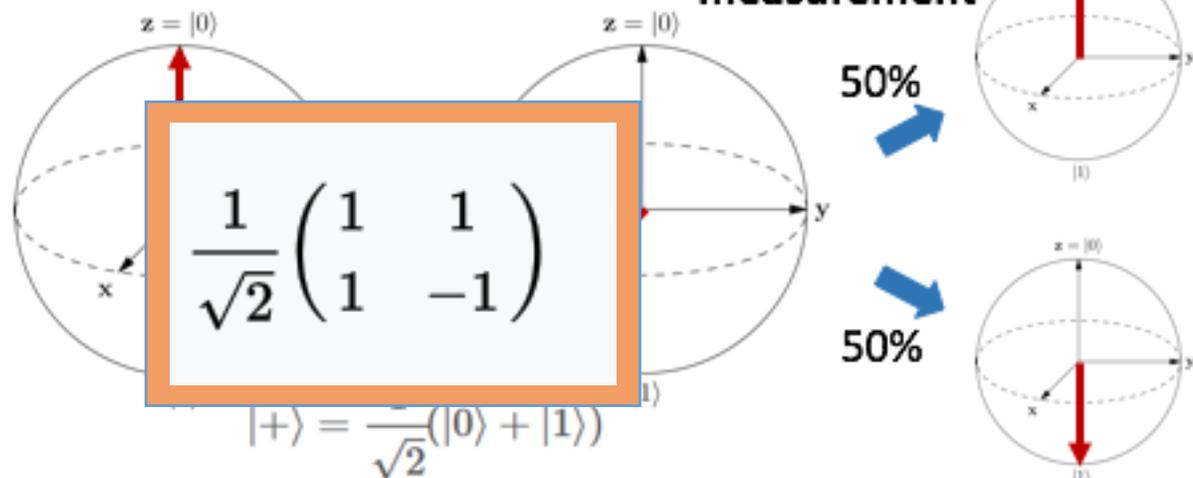
$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$



## Hadamard

creates superposition

measurement



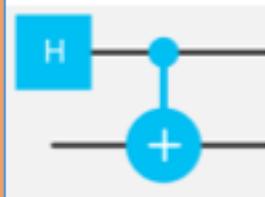
## controlled-NOT

„quantum XOR“

Control

Target

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



→ no classical equivalent exists

# Quantum algorithm basics

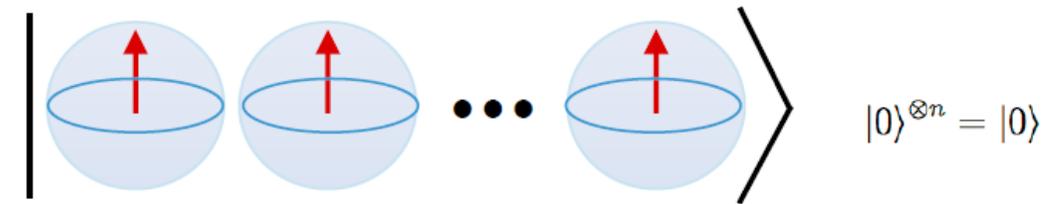
Schrödinger equation  $\rightarrow$  Quantum algorithm

Time evaluation

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

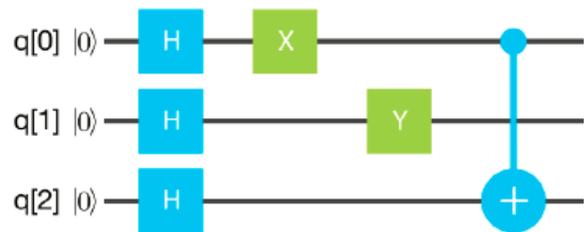
Hamiltonian is an operator describing the system energy

$\Psi$  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

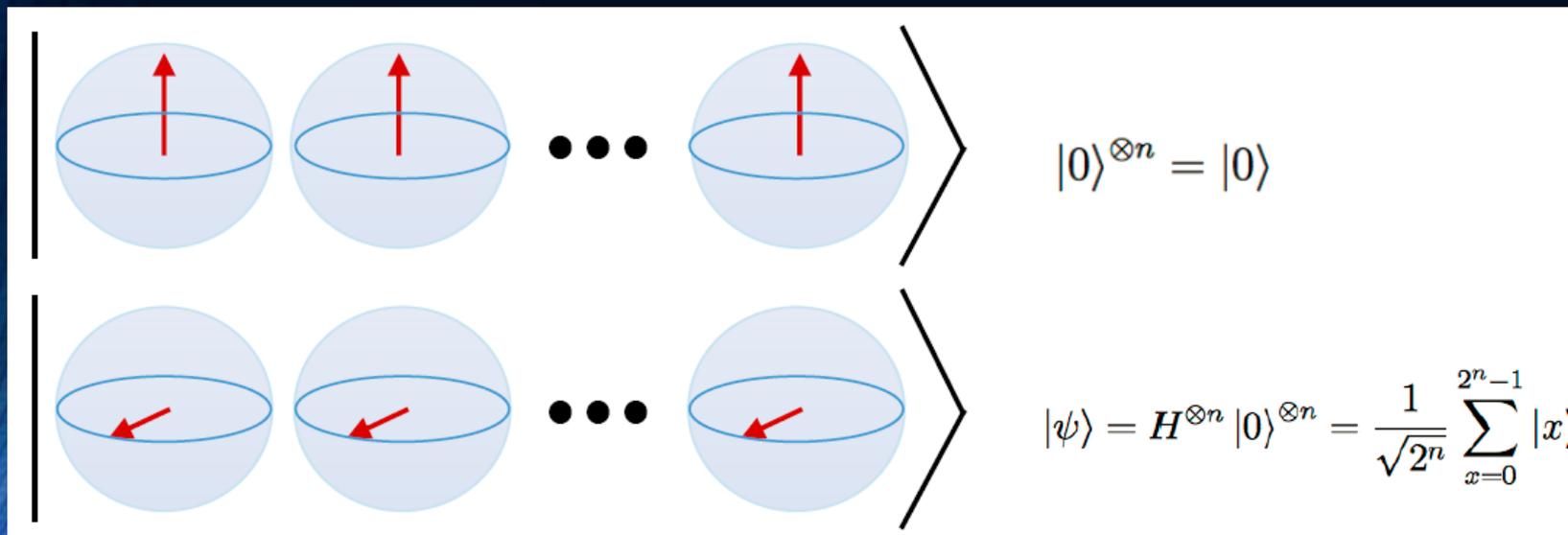
Hamilton-Operator  $\hat{H}$ :



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

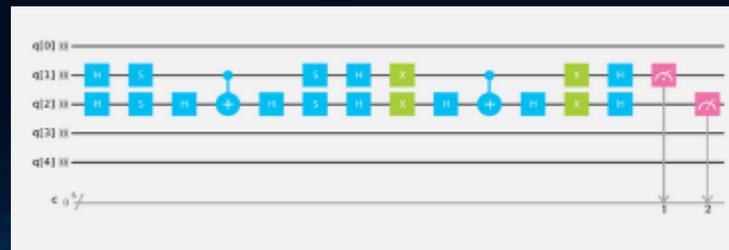


Initial zero state

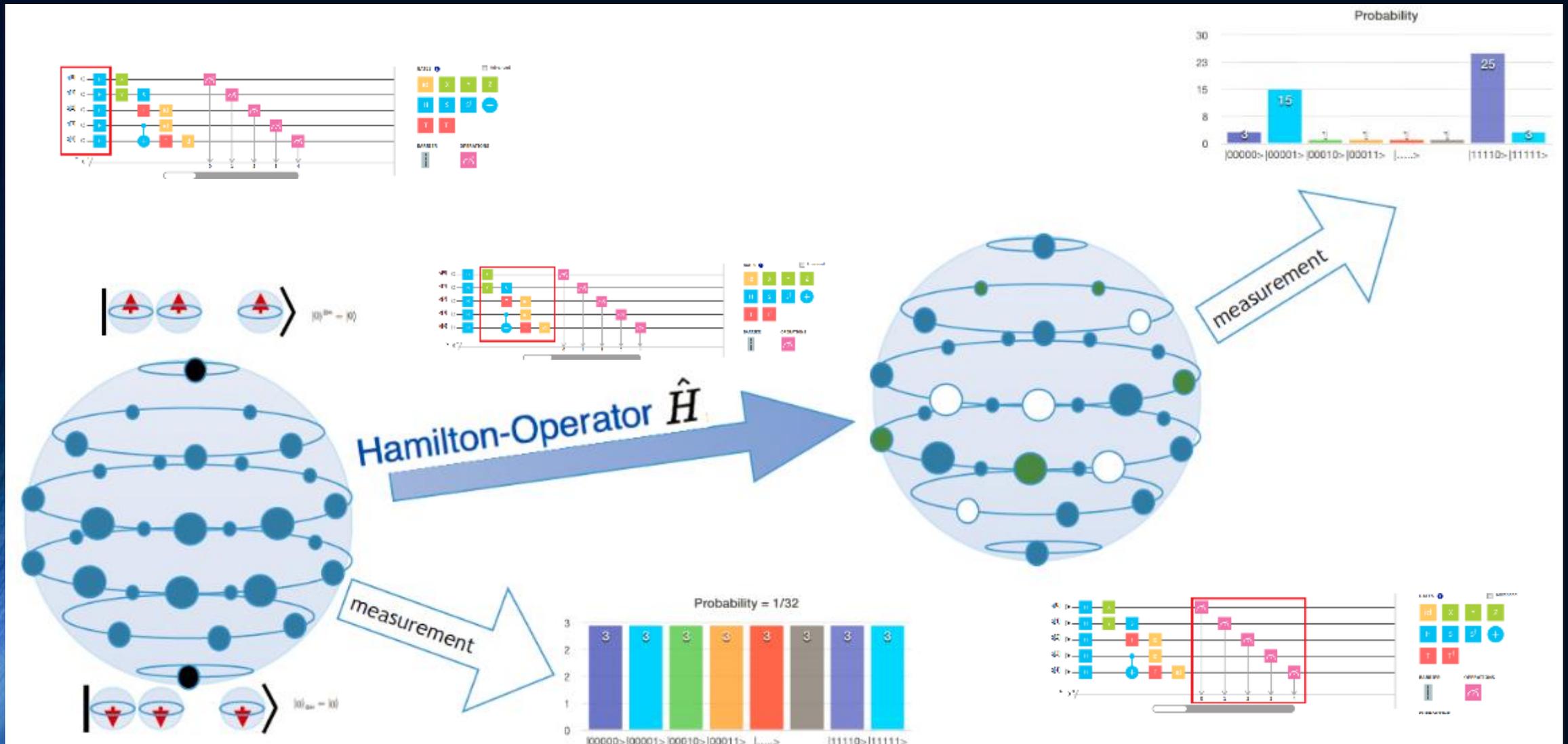


Apply **Hadamard** operator to achieve superposition state for each qbit

Now the computation (algorithm) can begin



# Quantum algorithm basic flow



The background features a dark blue gradient on the left, transitioning into a series of curved, overlapping lines on the right. These lines form a tunnel-like perspective, with a grid pattern of small squares visible on the inner surfaces. The overall effect is a sense of depth and movement, reminiscent of a digital or architectural space.

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

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My Projects / qiskit / quantum\_world

## 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"}

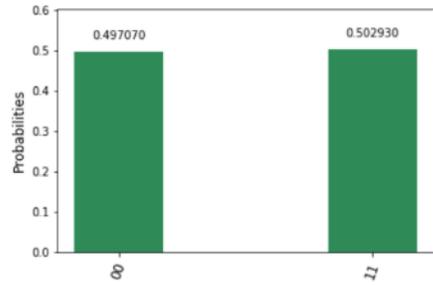
try:
    register(qx_config['APItoken'], qx_config['url'])
    print('\nYou have access to great power!')
    print(available_backends({'local': False, 'simulator': True}))
except:
    print('Something went wrong.\nDid you enter a correct token?')

Please input your token and hit enter: .....

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

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My Projects / qiskit / quantum\_world

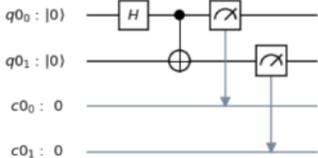


Qubit	Probability
q0	0.497070
q1	0.502930

You have made entanglement!

The circuit that was run on the machine is

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

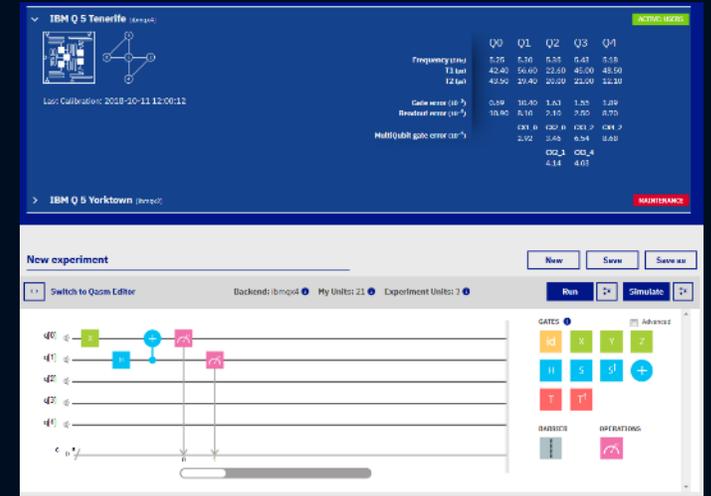


# IBM Q Experience: Quantum Composer:

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

# Qiskit Aqua:

<https://qiskit.org/aqua>



The screenshot shows the Qiskit Aqua website landing page. The header includes the Qiskit logo and navigation links for 'Terra' and 'Aqua'. The main heading is 'Qiskit Aqua' with a 'New 2023.0' badge and the tagline 'Building algorithms for near-term quantum applications'. There are links for 'GitHub', 'Documentation', and 'Tutorials'. The 'About' section describes Aqua as a library of cross-domain quantum algorithms. The 'Install' section provides the command: `[python3] $ pip install qiskit-aqua`. The 'Example' section shows a code snippet: `from qiskit_aqua.input import get_input_text as get_input_text from qiskit_aqua import run_algorithm`.

# Qiskit & Aqua tutorials with Jupyter notebooks:

<https://nbviewer.jupyter.org/github/Qiskit/qiskit-tutorial/blob/master/index.ipynb>

The screenshot shows a Jupyter Notebook interface displaying the Qiskit tutorial landing page. The header includes the Jupyter logo and navigation icons. The main heading is 'Qiskit' with the Qiskit logo. Below it, there's a section for 'Qiskit Tutorials' and a 'Contents' section with a link to '1. Qiskit'. The page content is rendered in a clean, white background with a dark header.

The screenshot shows the 'Qiskit Aqua Tutorials' page. It includes a 'Welcome to Qiskit Aqua!' section, a 'Contents' section with a link to '1. Qiskit Aqua', and a '1. Qiskit Aqua' section with a link to '1.1. Qiskit Aqua'. The page content is rendered in a clean, white background with a dark header.

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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