Introduction to **Quantum Computing**

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Expectations for the next hour

- Introduction
  - History
  - Difference between quantum and classical
- Hardware
  - Structure and Parts of QC
- Technical Concepts
  - Quantum bits [Qubits]
  - Quantum Gates
  - Quantum Circuits
- Practical
- Quantum and Us
  - Promises
  - Research Front
  - Conclusion

The what-when-why of Quantum Computing

A GENTLE HANDSHAKE

Introduction

- FACT-1:

CLASSICAL COMPUTERS HAVE ENABLED AMAZING THINGS

Introduction

- FACT-1:

CLASSICAL COMPUTERS HAVE ENABLED AMAZING THINGS

- FACT-2:

THERE ARE THINGS CLASSICAL COMPUTERS

CAN'T DO

Classical 'Failure' examples

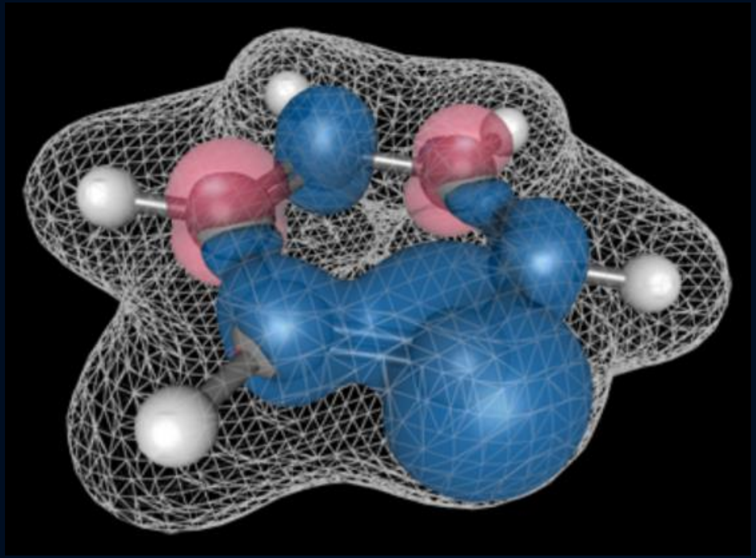
1- OPTIMIZATION

The possible ways of arranging 10 people around a table grows exponentially with increasing number of people.

Classical ‘Failure’ examples

2- CHEMISTRY

The best supercomputer in the world can only simulate a 40 50 electron orbital system.



Main Problem

Classical Computing fails terribly at 'Exponential Scaling' problems.

History

Very early 1980s

Researchers realized that quantum mechanics had unanticipated implications for information processing.

Early 1980s

Richard Feynman, Yuri Manin and others recognized that certain quantum phenomena (associated with entangled particles) could not be simulated by a Turing Machine, i.e. this quantum phenomena could be used to speedup computation.

Early 1990s

David Deutsch developed a notion of a quantum mechanical Turing Machine. Bernstein, Vazirani and Yao improved upon his model and showed that a quantum Turing Machine could simulate a classical Turing Machine with at most a polynomial time slowdown.

1990s

Researchers developed first truly quantum algorithms

1994

Peter Shor gave the factoring algorithm

(polynomial time)

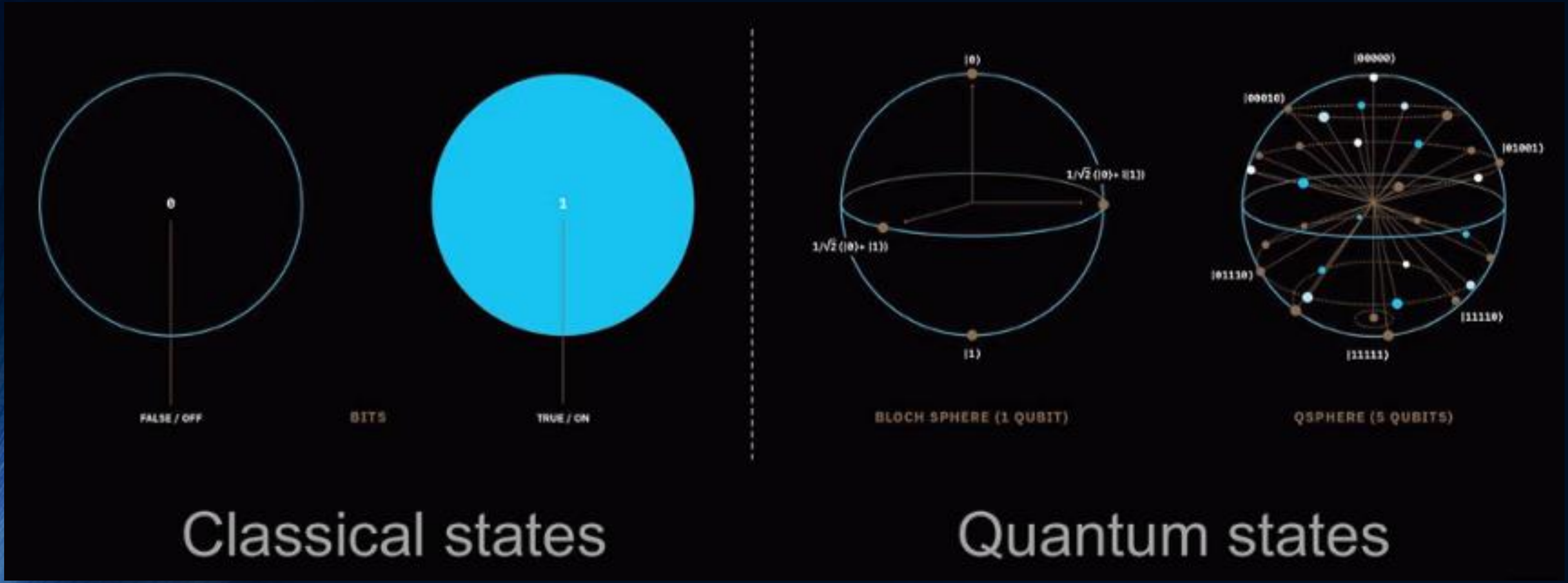
Mid 1990s

Grover's (Unstructured) Search Algorithm

2000s

More algorithms.

Why Quantum?


0
FALSE / OFF
BITS
1
TRUE / ON
|0⟩
1/√2 (|0⟩+ i|1⟩)
1/√2 (|0⟩+ |1⟩)
|1⟩
BLOCH SPHERE (1 QUBIT)
|00000⟩
|00010⟩
|01001⟩
|01110⟩
|11110⟩
|11111⟩
QSPHERE (5 QUBITS)
Classical states
Quantum states

"Nature isn't classical, and if you want to make simulation of nature, you'd better make it quantum mechanical, and it's a wonderful problem, because it doesn't look so easy."

- Dr. Richard Feynman, 1981.

The Differences-in a nutshell

CLASSICAL COMPUTING

- Computations are based on classical physics.
- Information storage is in bits which can be either 0 or 1 at a time.
- Deterministic approach
- Logical gates are used for information processing- OR, AND, NOT etc.
- Operations are defined as per Boolean algebra.

QUANTUM COMPUTING

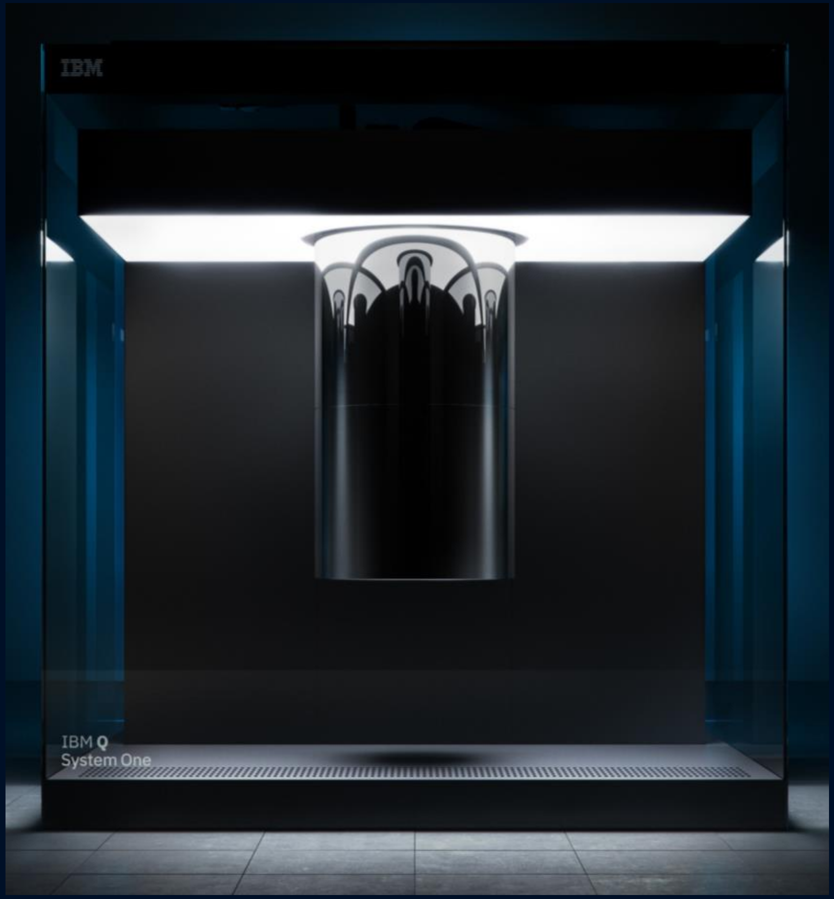
- Computations are based on quantum physics.
- Information storage is in qubits, which can be both 0 and 1 at any given point.
- Probabilistic approach
- Quantum logic gates are used for information processing- Hadamard gate, CX etc.
- Operations are defined as per linear algebra.

What’s inside a Quantum Computer?

A LOOK INSIDE

IBM Q – Lab Fridge

IBM Q System One
[at CES 2019]

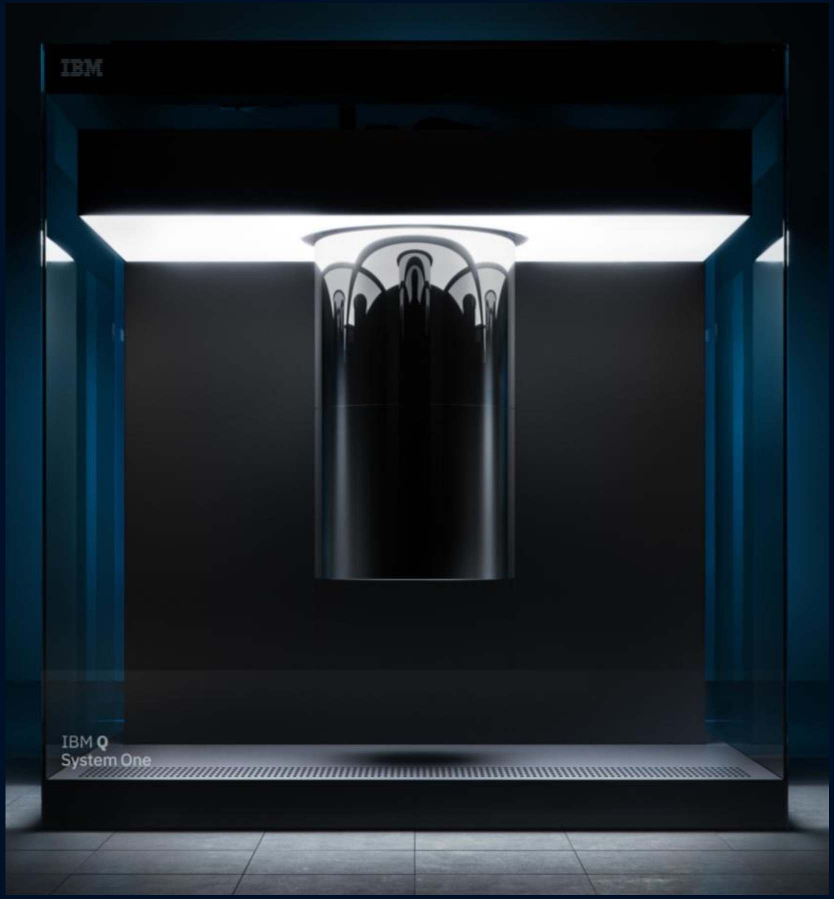


IBM Q – Lab Fridge

The Mona Lisa Case

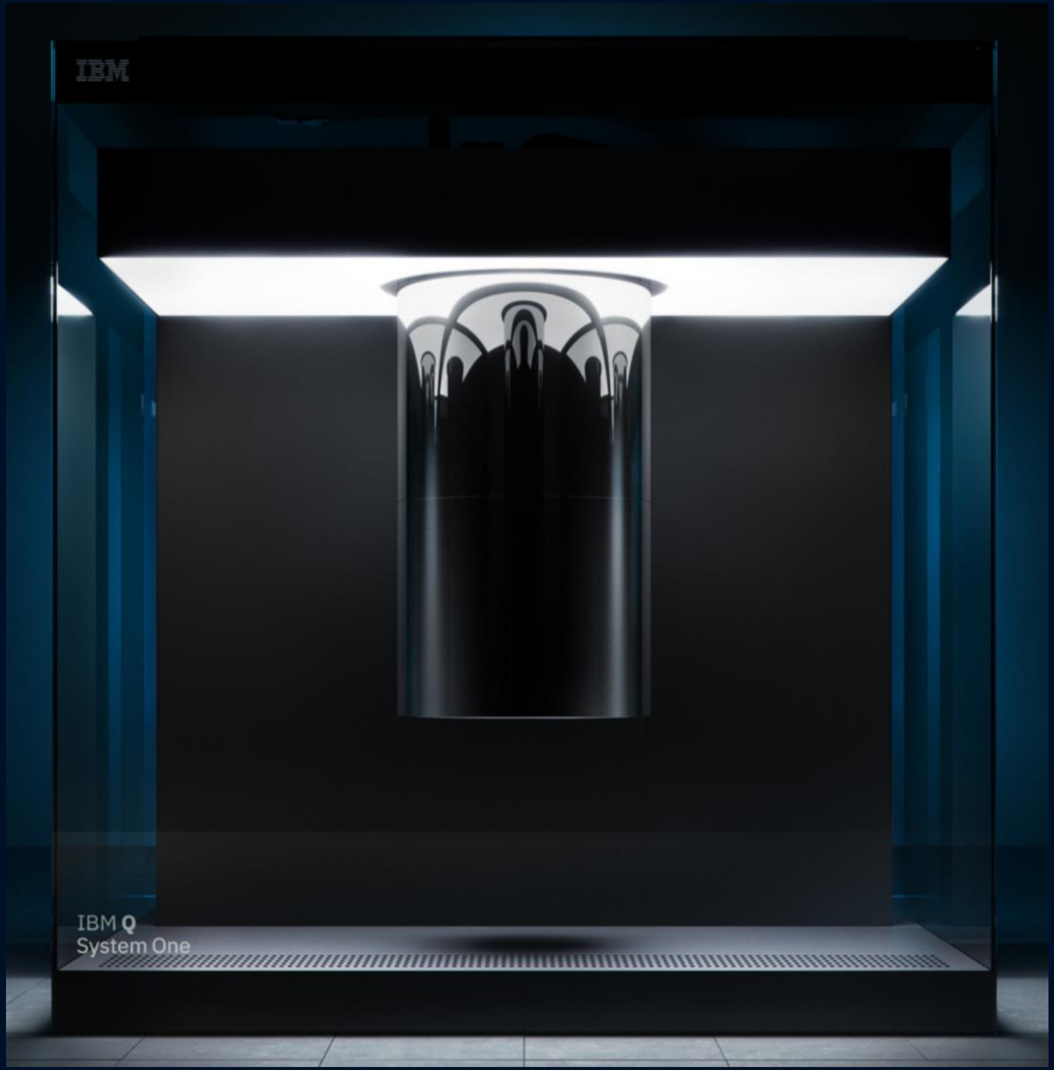
IBM Q System One
[at CES 2019]

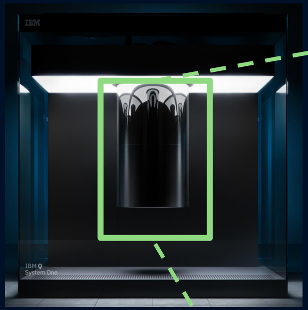
IBM Q – Lab Fridge

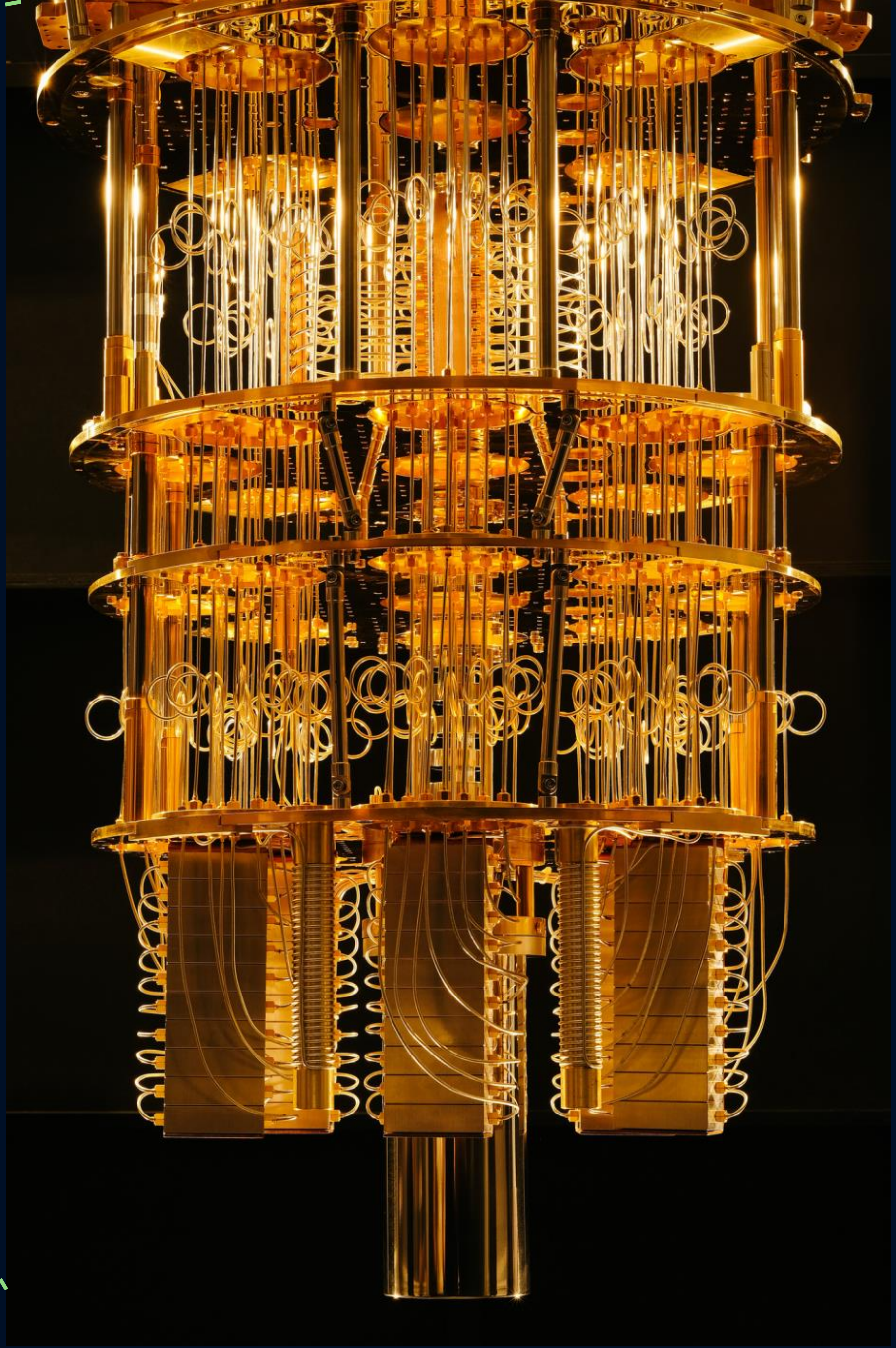


The Mona Lisa Case

The Golden Chandelier

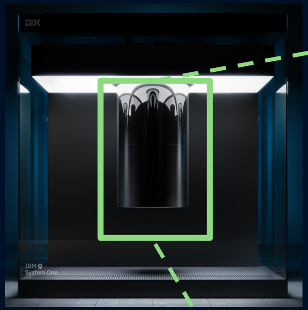

IBM
IBM Q
System One

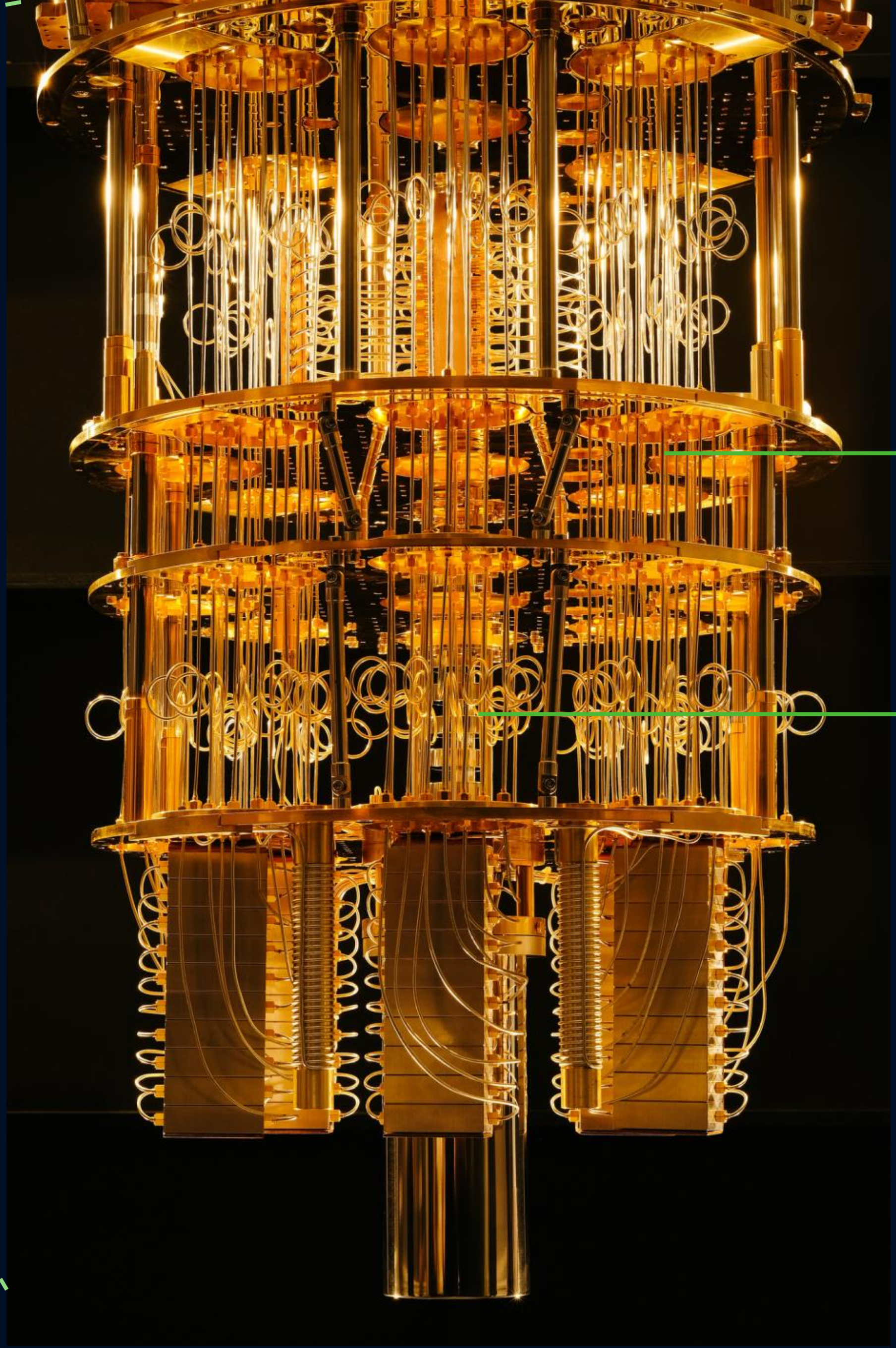




Operations at 300 K $\approx$ 27 $\circ$ C

Operations at 0.015 K = -273.13 $\circ$ C



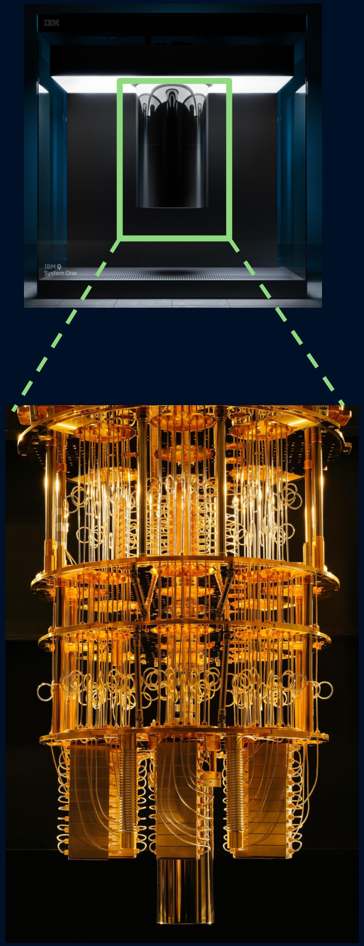


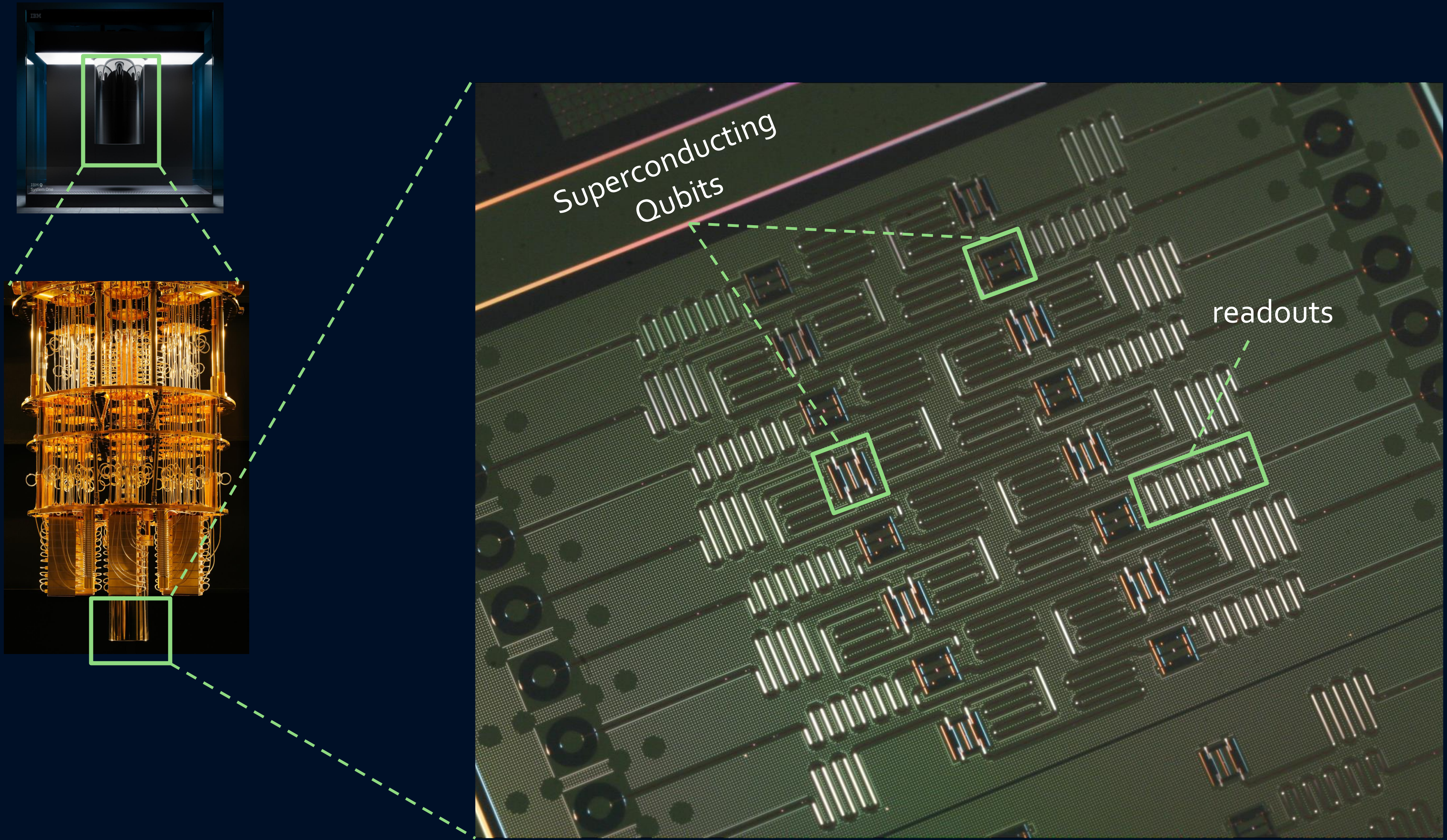
Operations at 300 K ≈ 27 ∘ C

Gold plated wires

Mixing chamber

Operations at 0.015 K = -273.13 ∘ C




Superconducting
Qubits
readouts

Technical Concepts

LET'S DIVE A LITTLE DEEPER

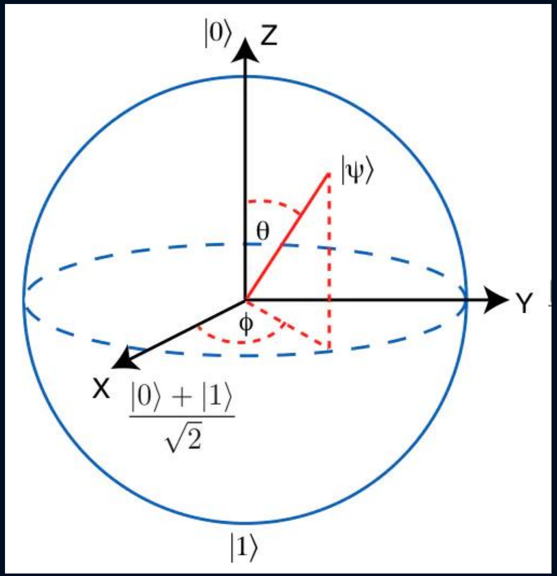
Bits vs Qubits

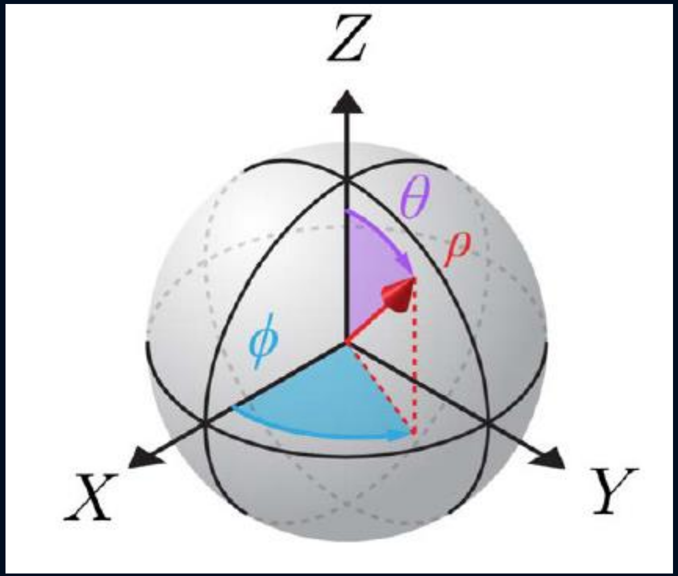
CLASSICAL BITS [BITS]

- Either 0 or 1 at a time.

QUANTUM BITS [QUBITS]

- Both 0 and 1 at any given point.



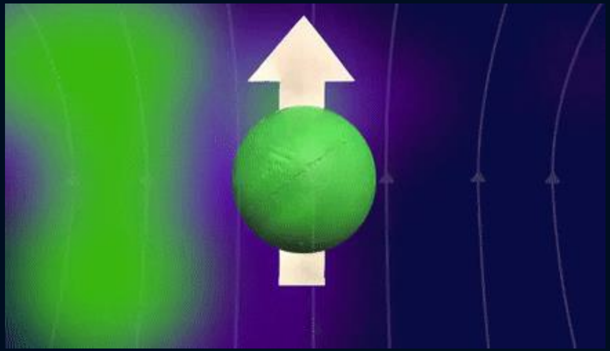


Qubit-facts

- In quantum computing the information is encoded in qubits. A qubit is a two-level quantum system where the two basis qubit states are usually written as $|0\rangle$ and $|1\rangle$.
- A qubit can be in state $|0\rangle$, $|1\rangle$ or (unlike a classical bit) in a linear combination of both states.
- Several different physical implementations of qubits are possible. Like the polarizations of a photon, two of the (multiple) discrete energy levels of an ion, **a superconducting Transmon qubit**, the nuclear spin states of an atom or the spin states of an electron.

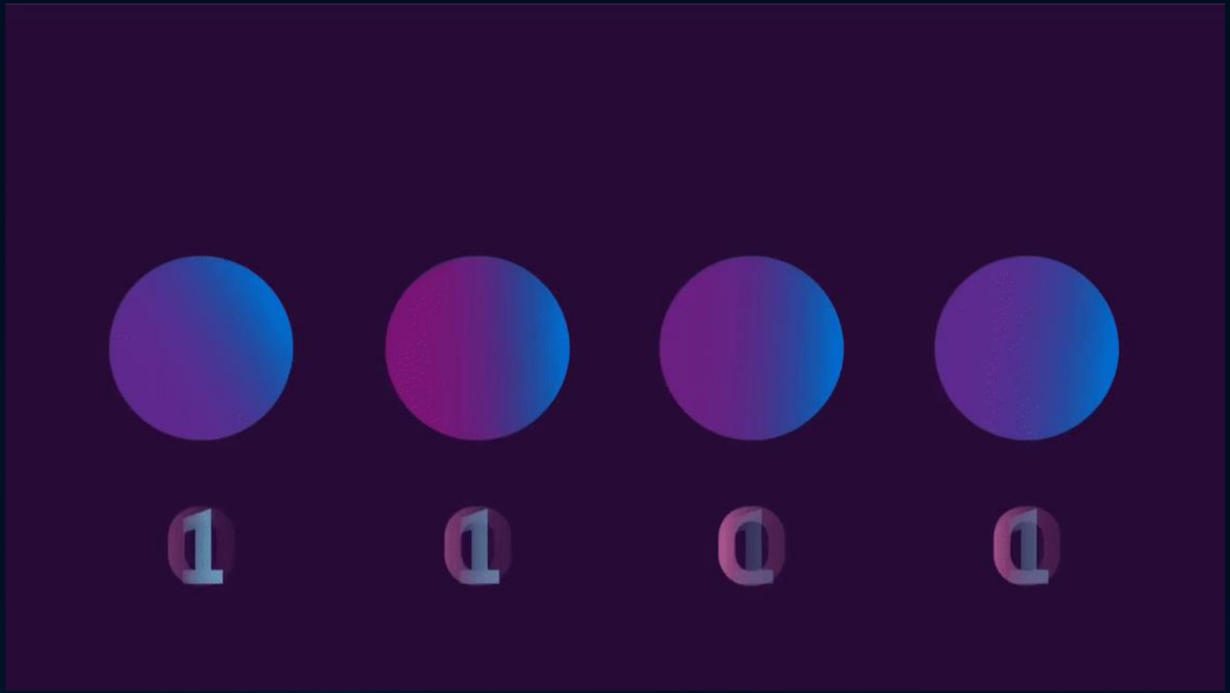
Qubits

- Imagine the qubit as an electron:



Spin-up state
|1⟩

Spin-down state
|0⟩



Exponential growth

Number of qubits (n)	Formula for qubit state vector	Number of states
1	$a\|0\rangle + b\|1\rangle$	2^1
2	$a\|00\rangle + b\|01\rangle + c\|10\rangle + d\|11\rangle$	2^2
3	$a\|000\rangle + b\|001\rangle + c\|010\rangle + d\|011\rangle$ $+ e\|100\rangle + f\|101\rangle + g\|110\rangle + h\|111\rangle$	2^3
.	.	.
.	.	.
n	$a\|00\ldots0\rangle + b\|00\ldots0\rangle + \ldots + y\|11\ldots0\rangle + z\|11\ldots1\rangle$	2^n

If we manage to have a 300 qubit quantum computer, the number of possible states would be:

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$$2^{300}$$

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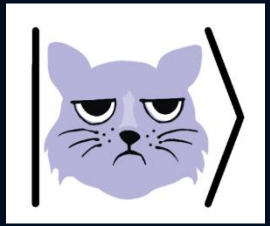
$$2^{300}$$

More basis states than there are atoms in the observable universe

Quantum States

I have a Cat, and he is often ‘grumpy’. 

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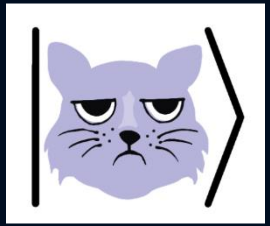
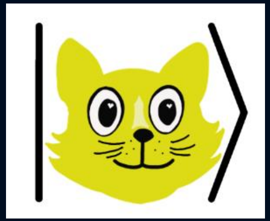
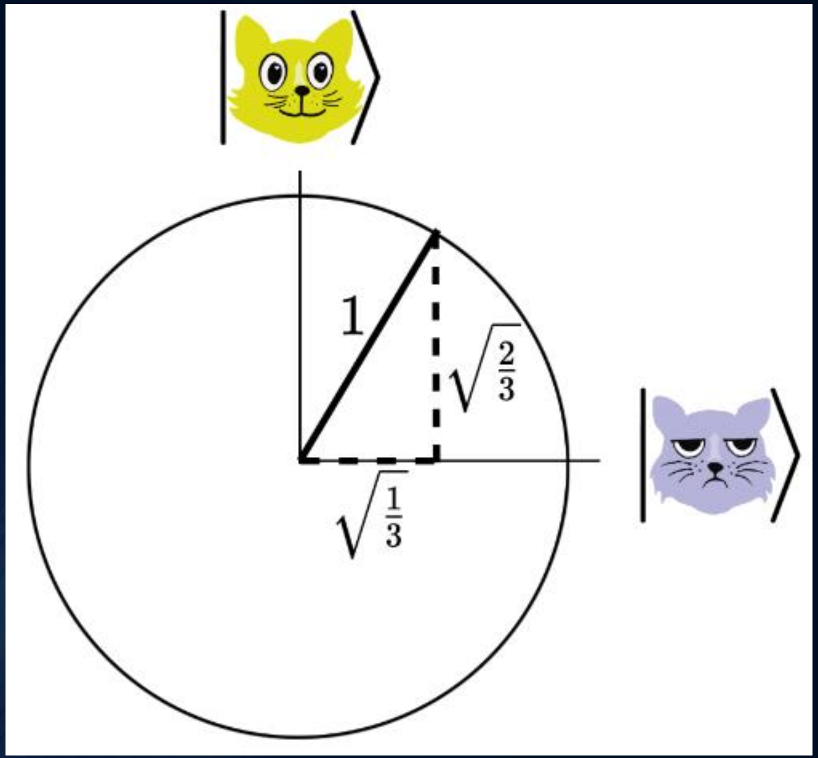
I have a Cat, and he is often ‘grumpy’. 

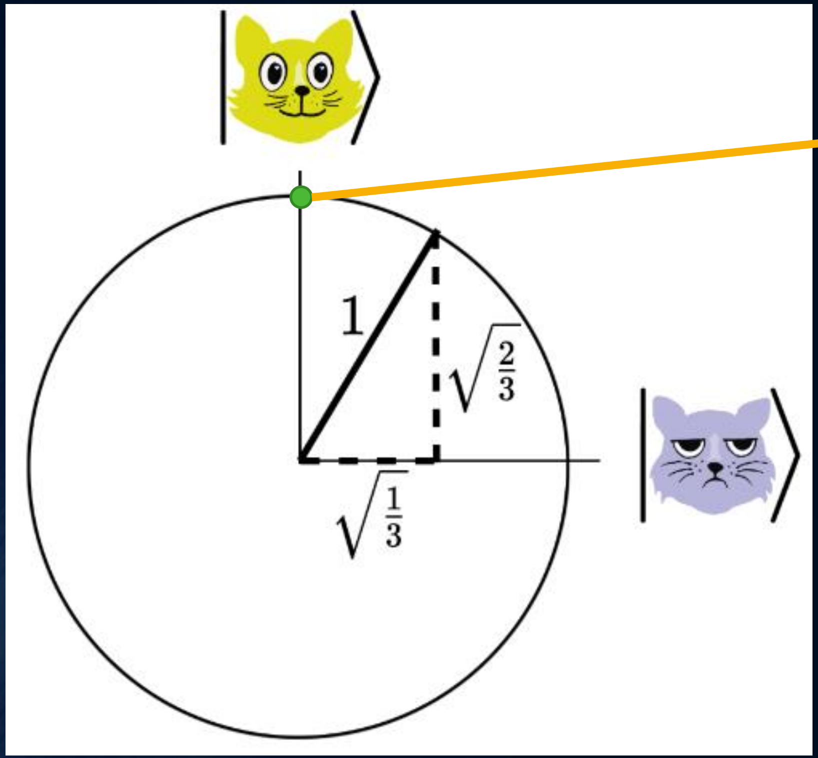
Okay, he is sometimes happy too. 

But, I’ve never seen him in between those states.

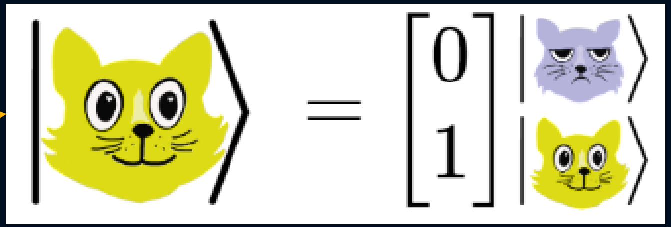
Quantum States



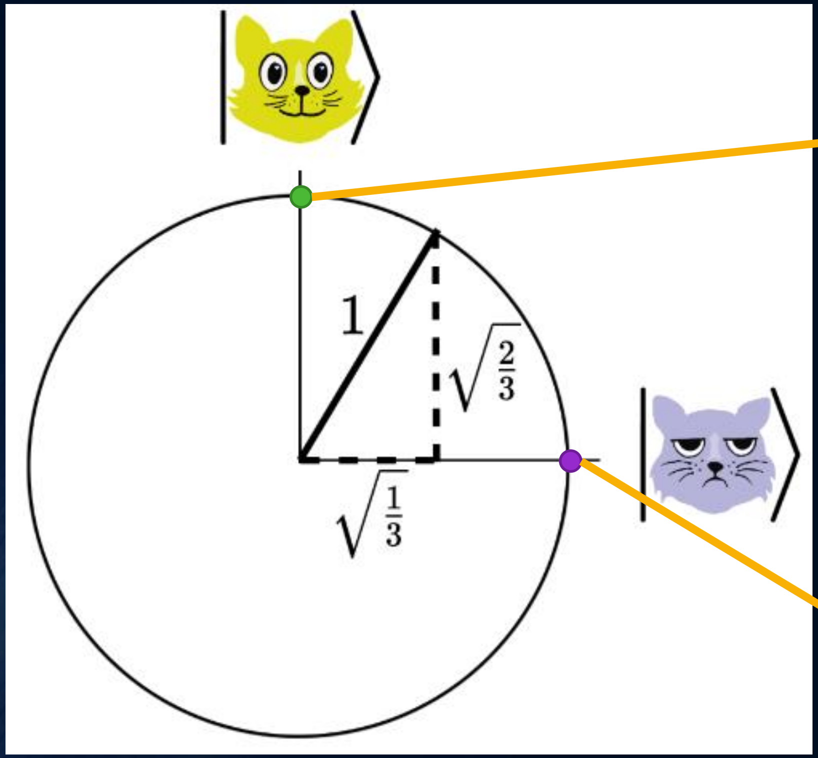
Quantum States



Vector notation



Quantum States



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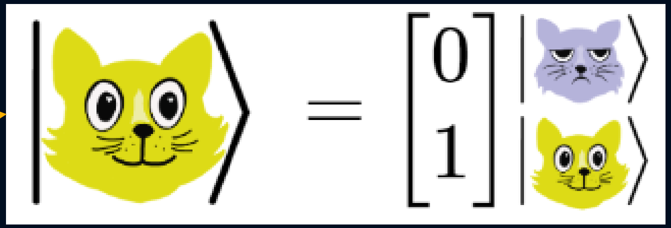

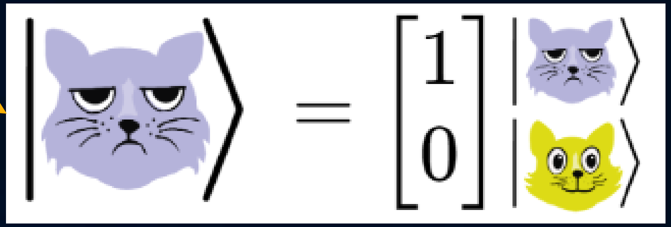

Quantum States

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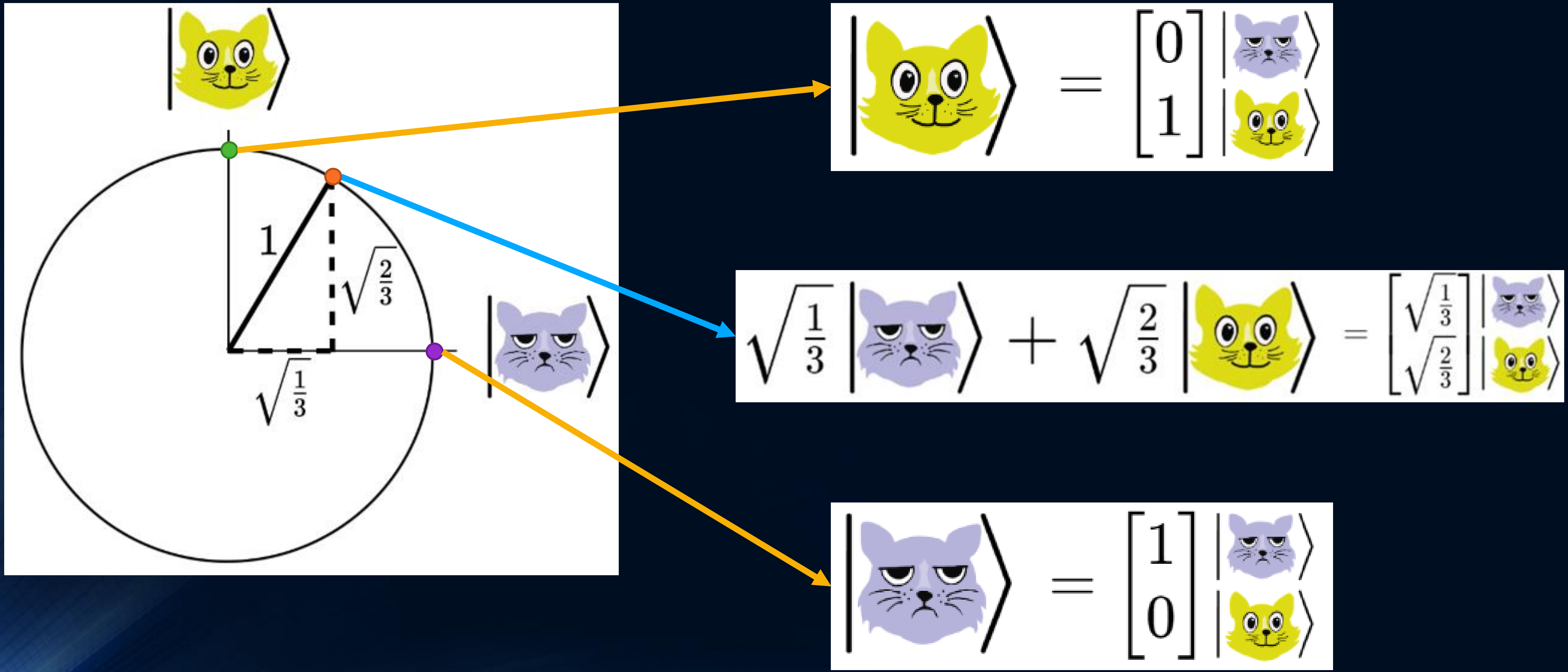
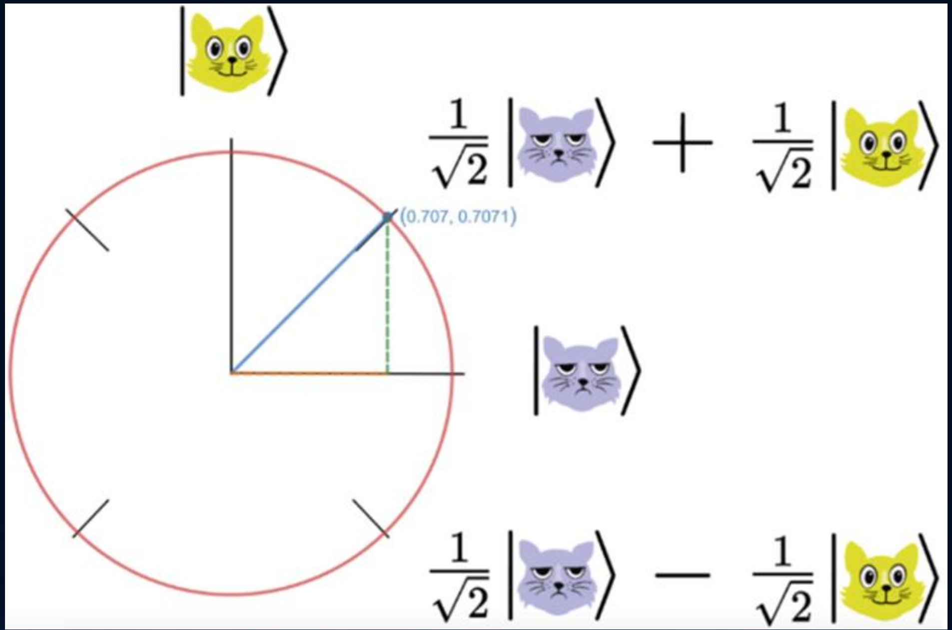


Superposition

- Superposition is the ability of a quantum system to be in multiple states at the same time until it is measured.

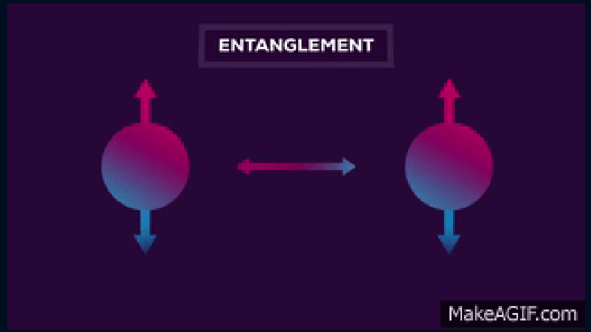
Superposition

- Superposition is the ability of a quantum system to be in multiple states at the same time until it is measured.
- It means my cat can be in any combination of grumpy and happy.



Entanglement

- When the states of two quantum particles are linked (or correlated) to each other, such that the state of one particle controls the state of other particle, the phenomena is called Entanglement.



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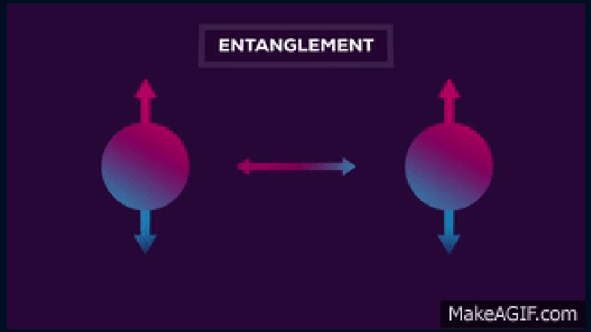

- Suppose we have two qubits:

$\boxed{q_0}$ $\boxed{q_1}$

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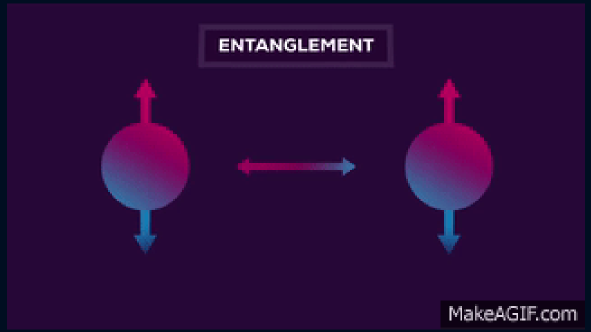

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$$\boxed{q_0} \longleftrightarrow \boxed{q_1}$$

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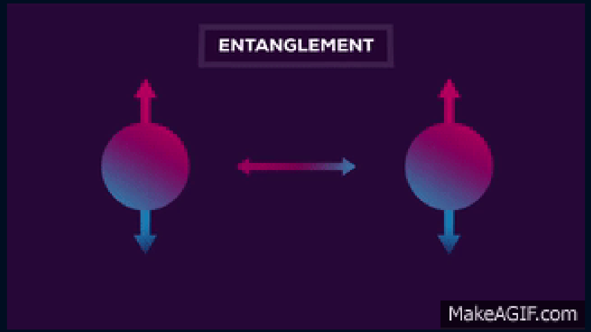

- Suppose we have two qubits:

$\boxed{q_0} \longleftrightarrow \boxed{q_1}$

Entanglement Rule:

$|0\rangle \longleftrightarrow$ Leave the state as it is

$|1\rangle \longleftrightarrow$ Flip the state

Entanglement

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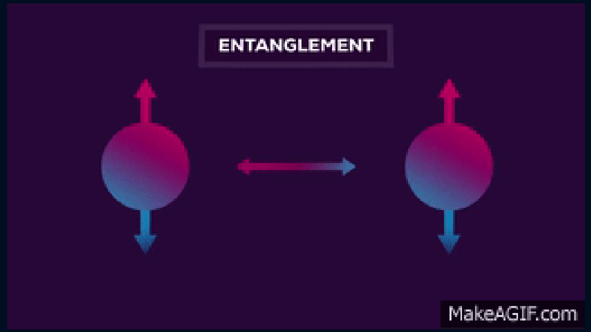

- Let's see an example:

$|0\rangle$ q_0 —— $|0\rangle$

$|1\rangle$ q_1 —— $|1\rangle$

Initial state

Case-1

Final state

Entanglement

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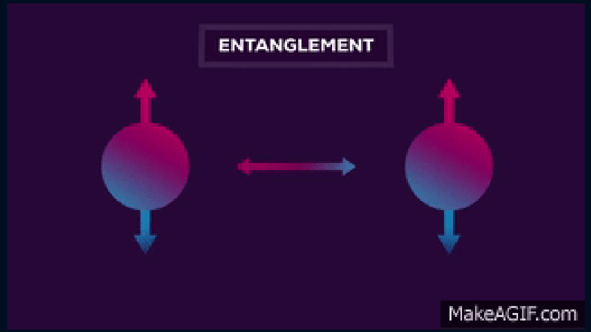

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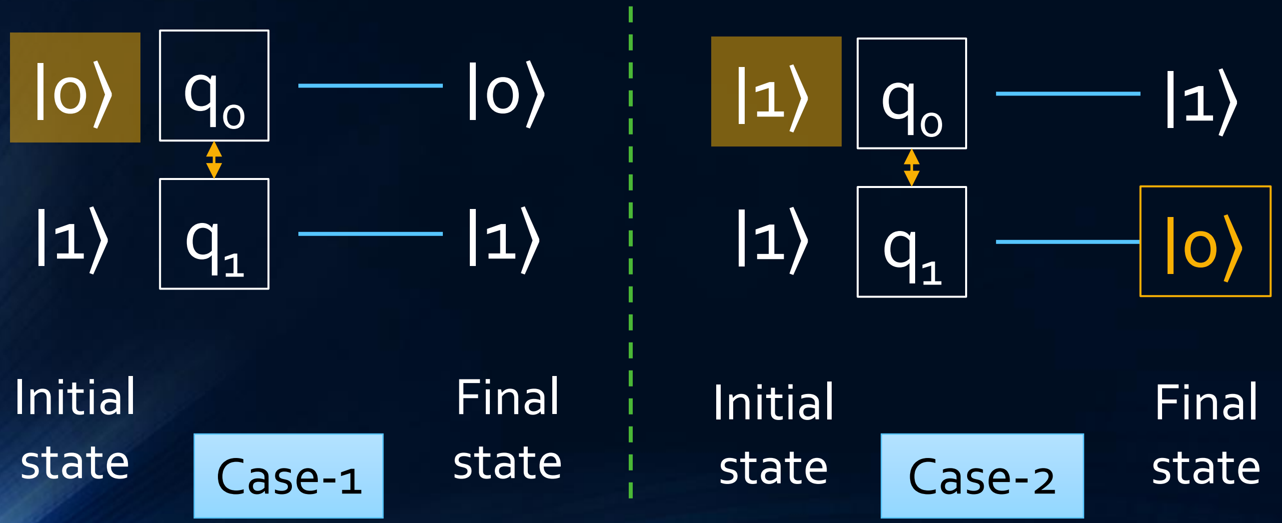
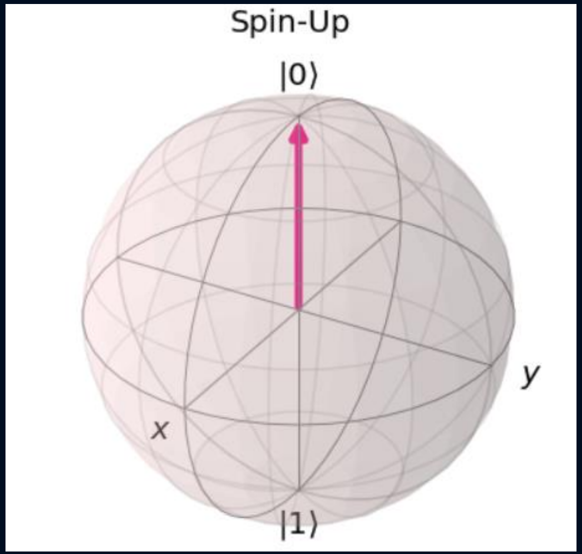
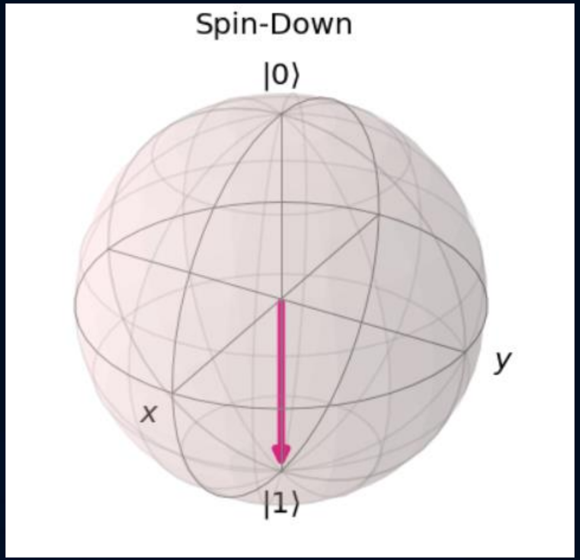


Bloch Sphere and Q-sphere

A Bloch sphere is used to visualize quantum state for individual qubits.





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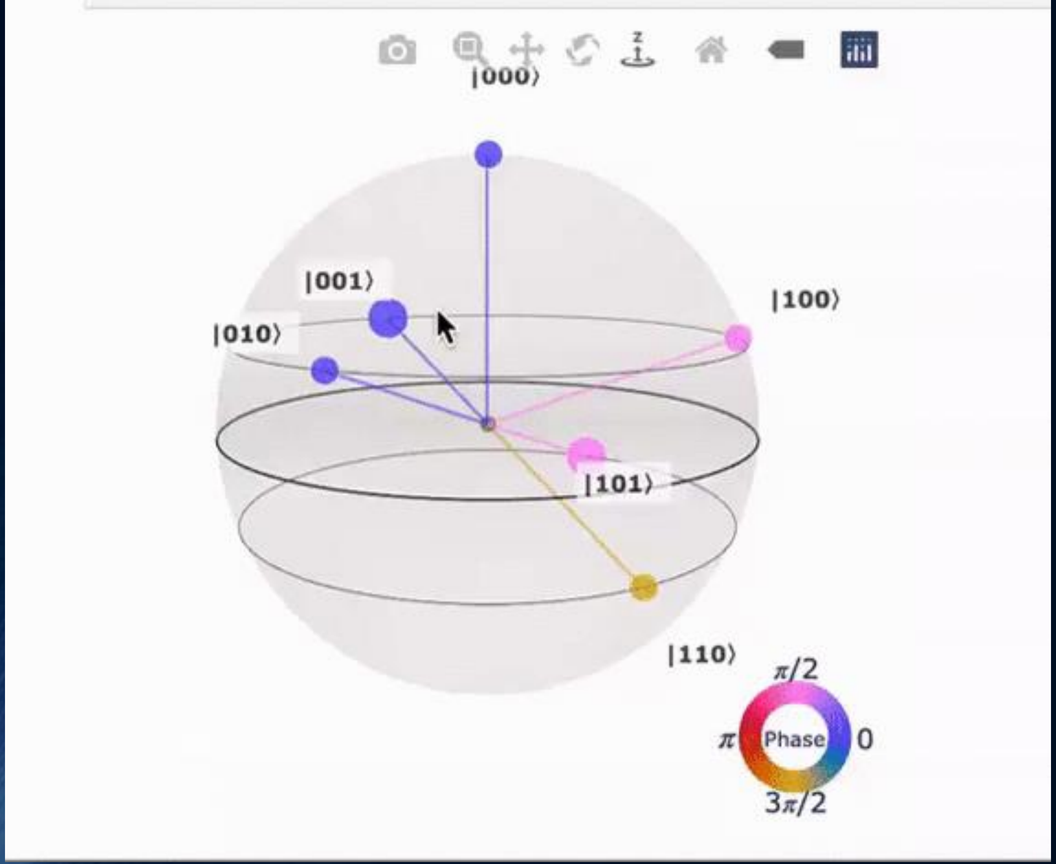
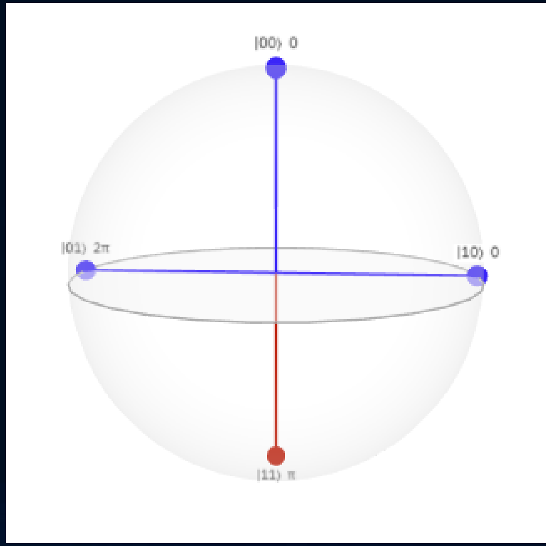
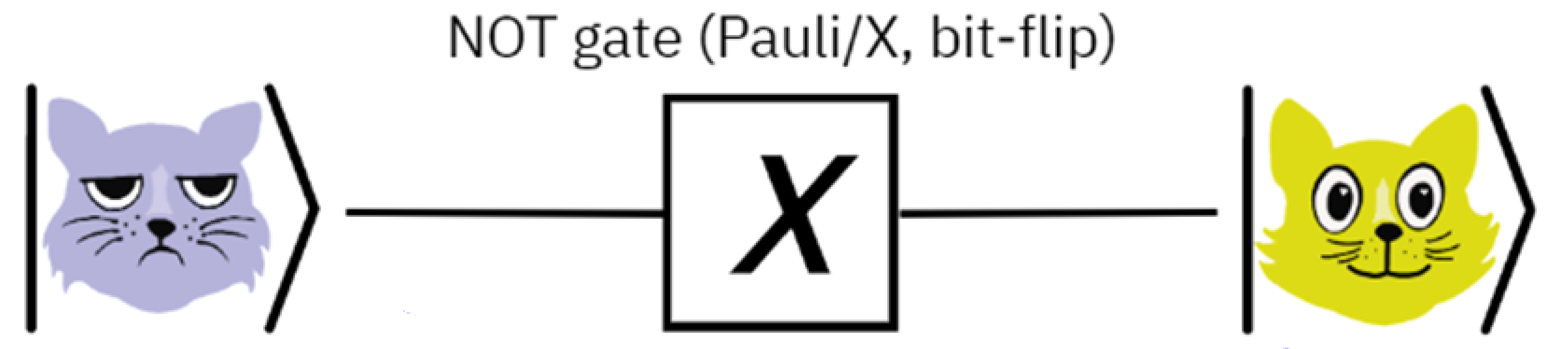


A Q-sphere is used to visualize quantum state for individual as well as multiple qubits.

The adj. picture has been downloaded from IBM Quantum Experience which shows different states in different phases for multiple qubits.



Few Quantum Gates



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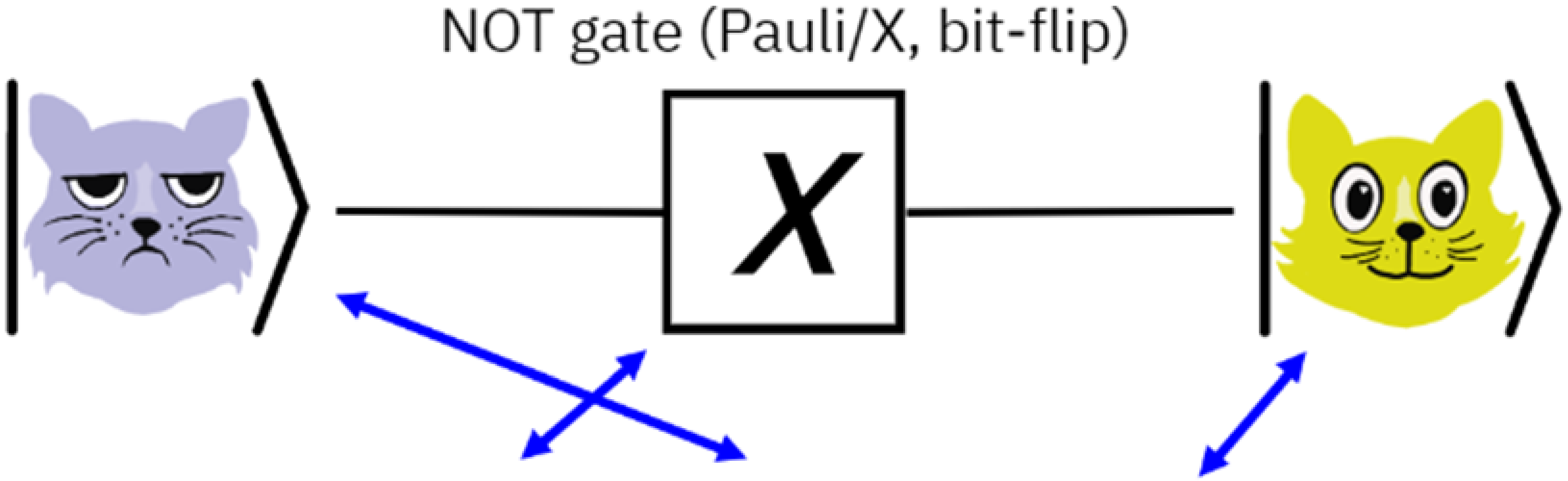
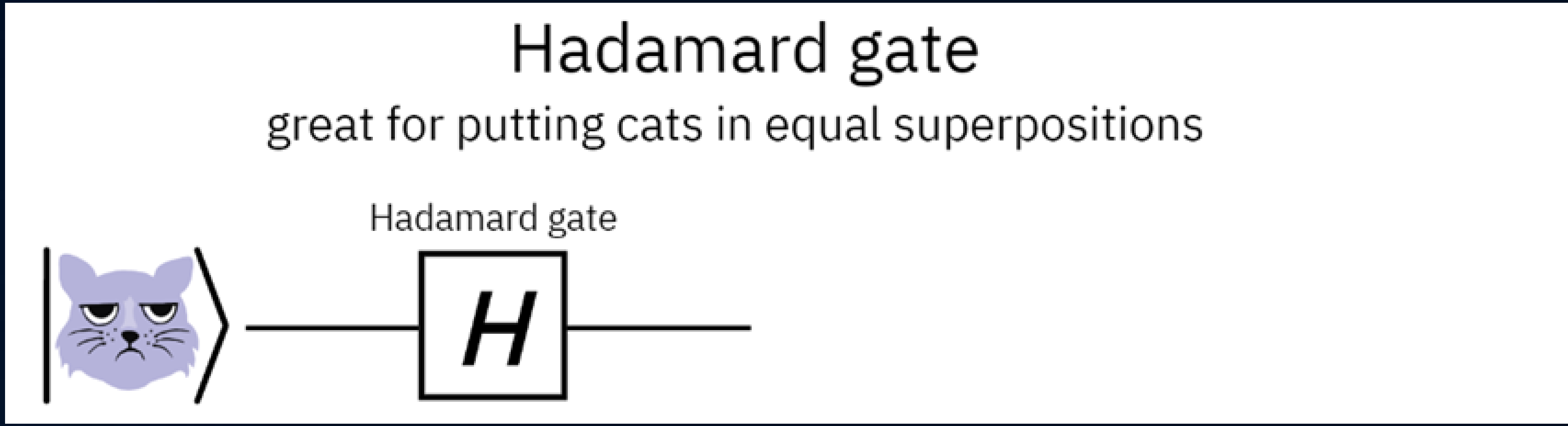
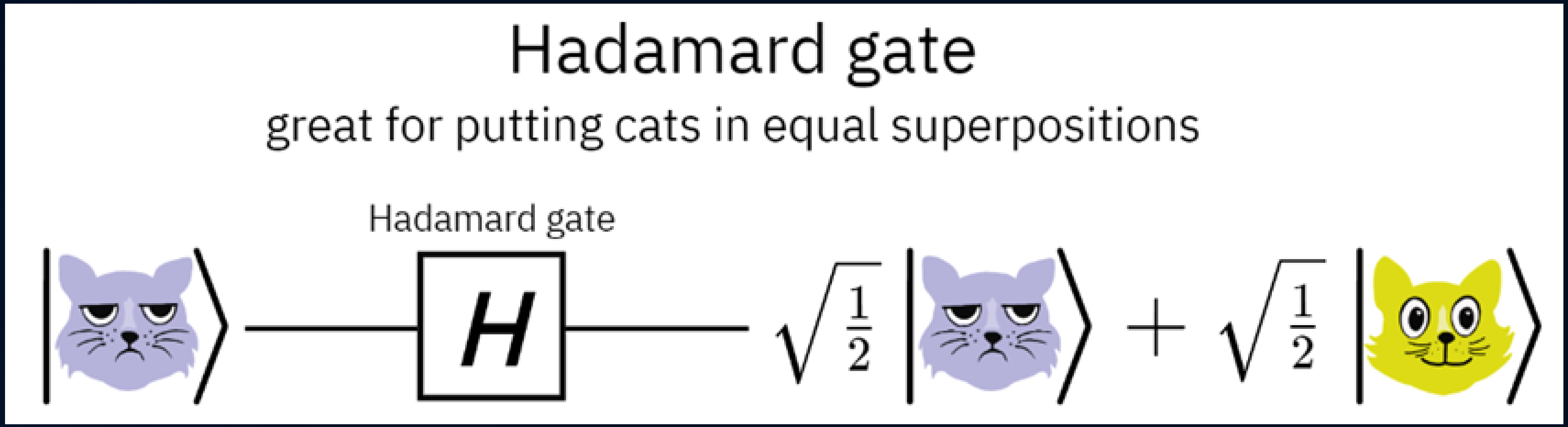


$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

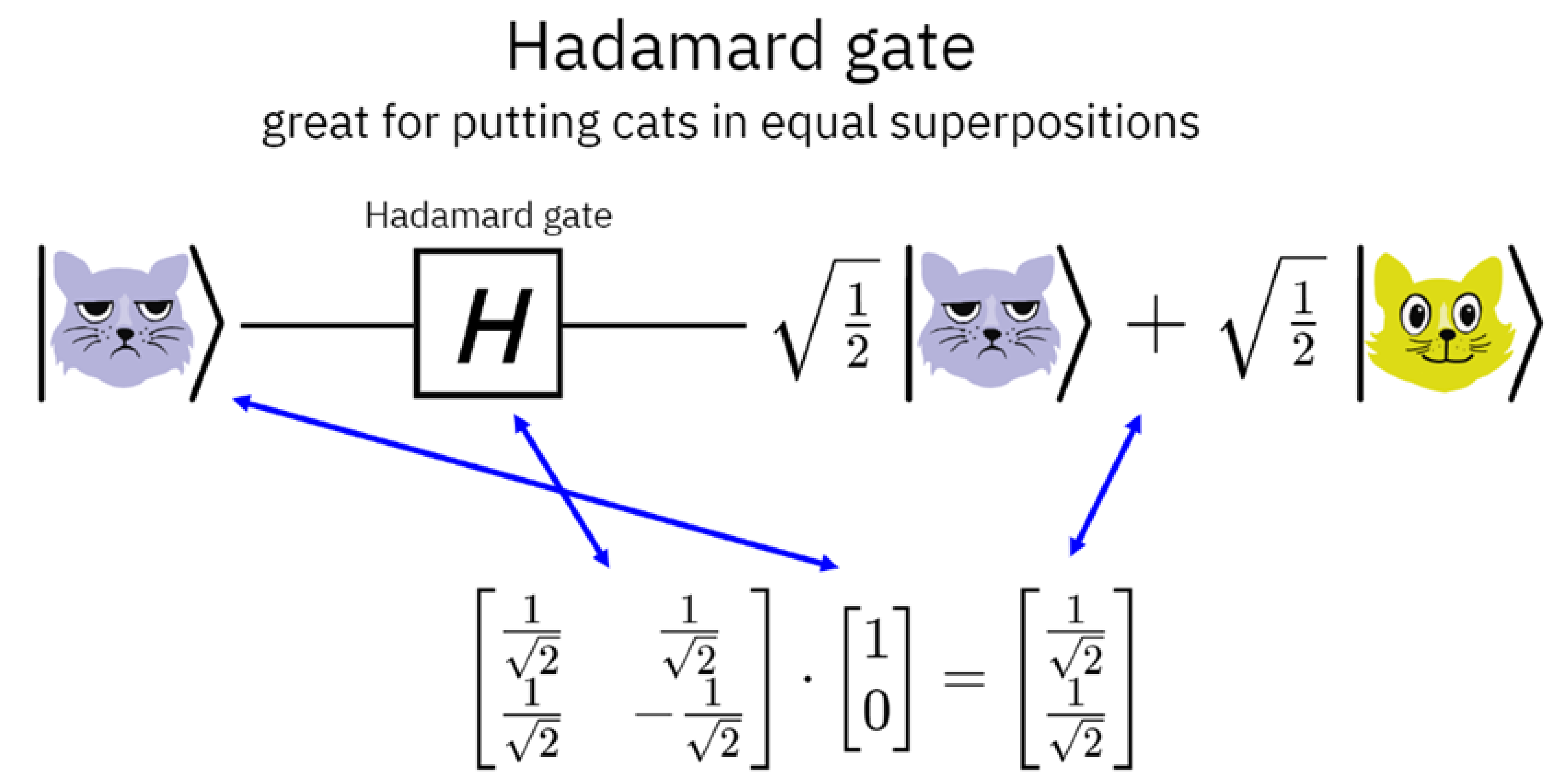
Few Quantum Gates



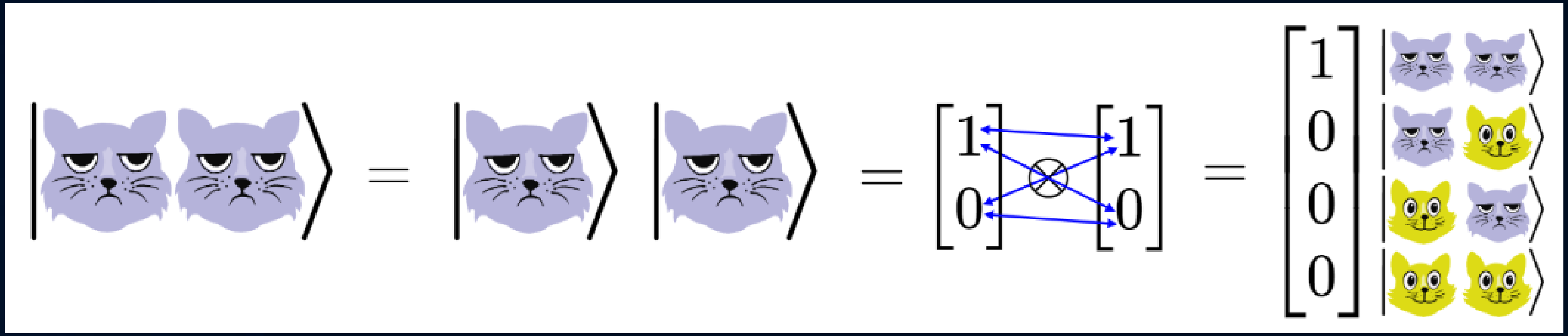
Few Quantum Gates

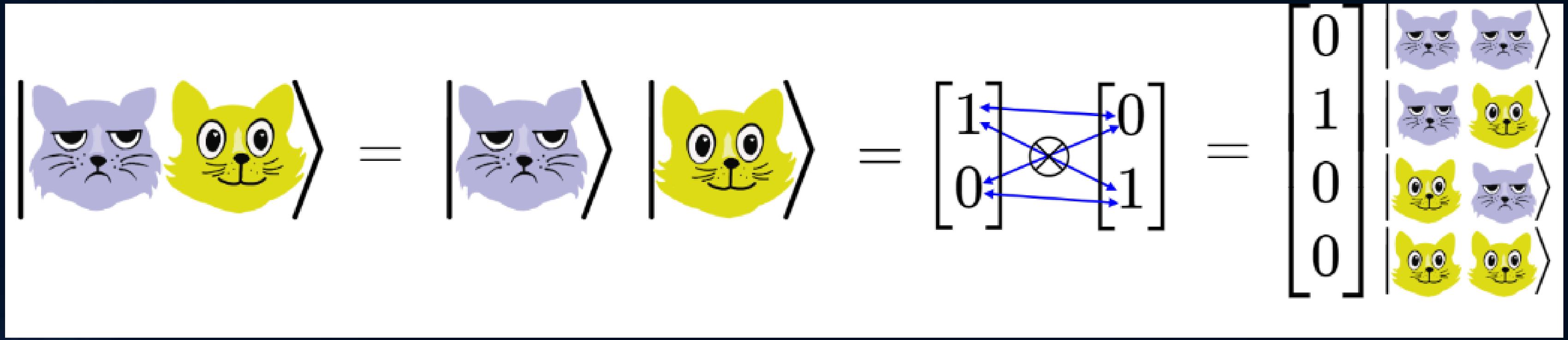


Few Quantum Gates

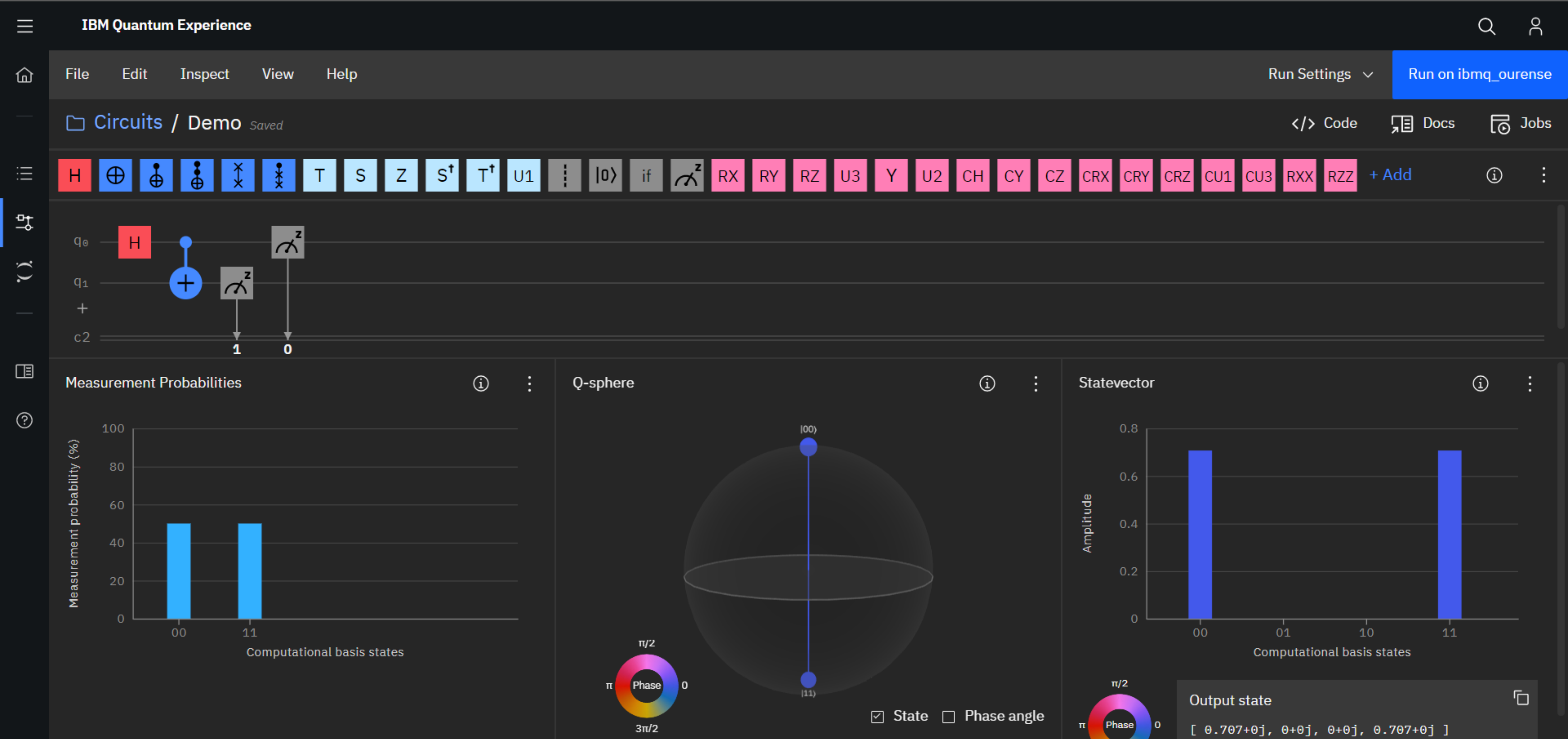


Multiple Qubits





Quantum Circuits



Quantum Programming using Qiskit in Python

USING JUPYTER NOTEBOOKS AND IBM QUANTUM EXPERIENCE

Quantum and Us

ROLE OF QUANTUM COMPUTING IN OUR LIVES

Promises of Quantum Computing

- By using the quantum mechanical capabilities of entanglement, superposition and interference, we can tackle problems being practically impossible using classical computers.
- Using quantum algorithms, we can make better optimization of financial scenarios, model physical processes of nature, simulate chemical reactions, predict the impact of diseases based on simulations, etc.
- The possibilities are endless when you have the exponential computing power of a quantum computer available.

Research Fronts

- A lot of technology giants including IBM, Google and Microsoft are investing a lot in quantum research.
- IBM has launched several quantum computers with different qubit capacity all over the world and allows users to play with those via IBM quantum experience.
- Google, in a recent paper with Nature, claimed it achieved 'Quantum Supremacy'.

Article

Quantum supremacy using a programmable superconducting processor

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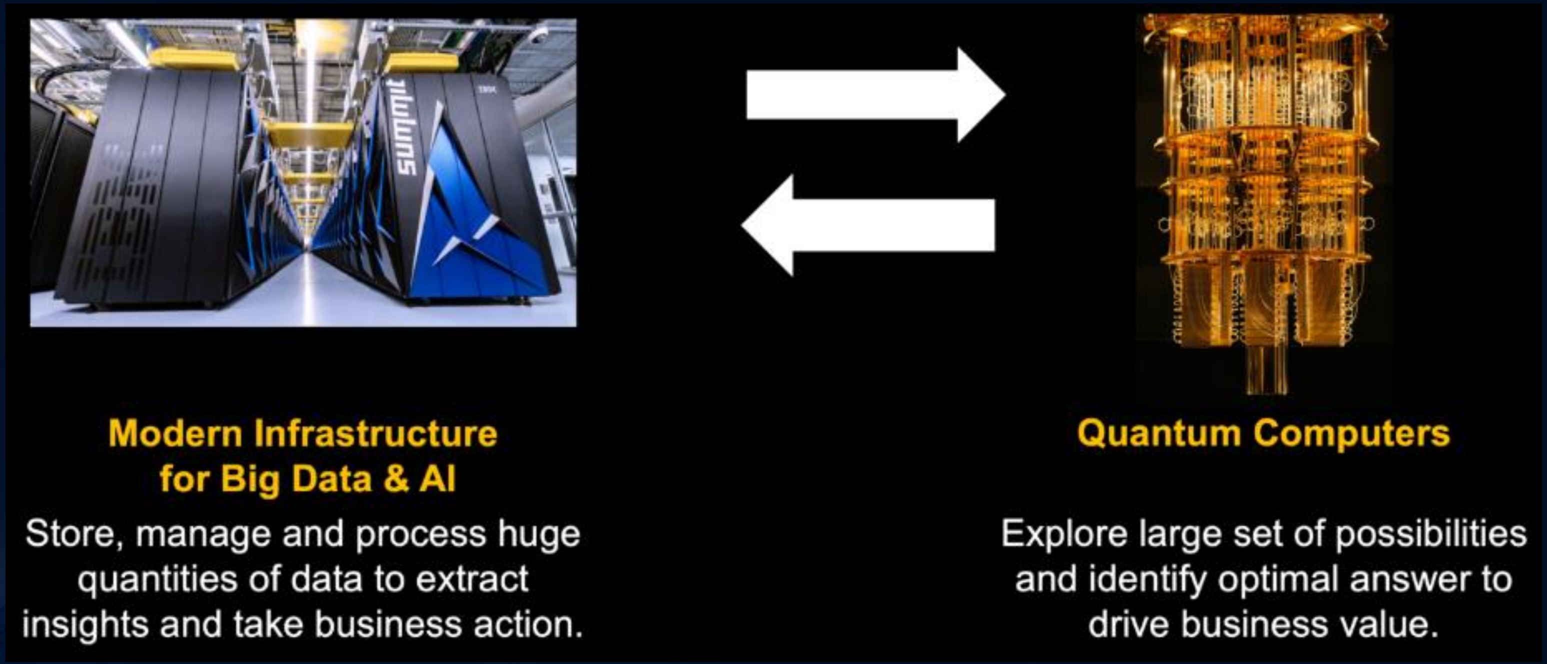
The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8–14] for this specific computational task, heralding a much-anticipated computing paradigm.

Conclusion

- Yes, Quantum Computing is the future!
- No, Classical Computers aren't going away.



Some Good Reference Books

- Quantum Computation and Quantum Information- Textbook by Isaac Chuang and Michael Nielsen.
- Quantum Computing for Computer Scientists- Book by Mirco A. Mannucci and Noson S. Yanofsky.
- Quantum Computing-A gentle Introduction- Book by Eleanor Rieffel and Wolfgang Polak.
- Quantum Computer Science- Book by N. David Mermin

References

- James Weaver presentation at https://slides.com/javafxpert/qiskitblocks
- Book: Quantum Computing-A gentle Introduction- Book by Eleanor Rieffel and Wolfgang Polak.
- The Qiskit Textbook: https://qiskit.org/
- Practical sessions at: https://quantum-computing.ibm.com/
- Learnings from Qiskit Global Summer School-2020

THANK Y$|0\rangle$U!

FEEL FREE TO ASK QUESTIONS / GIVE FEEDBACK.