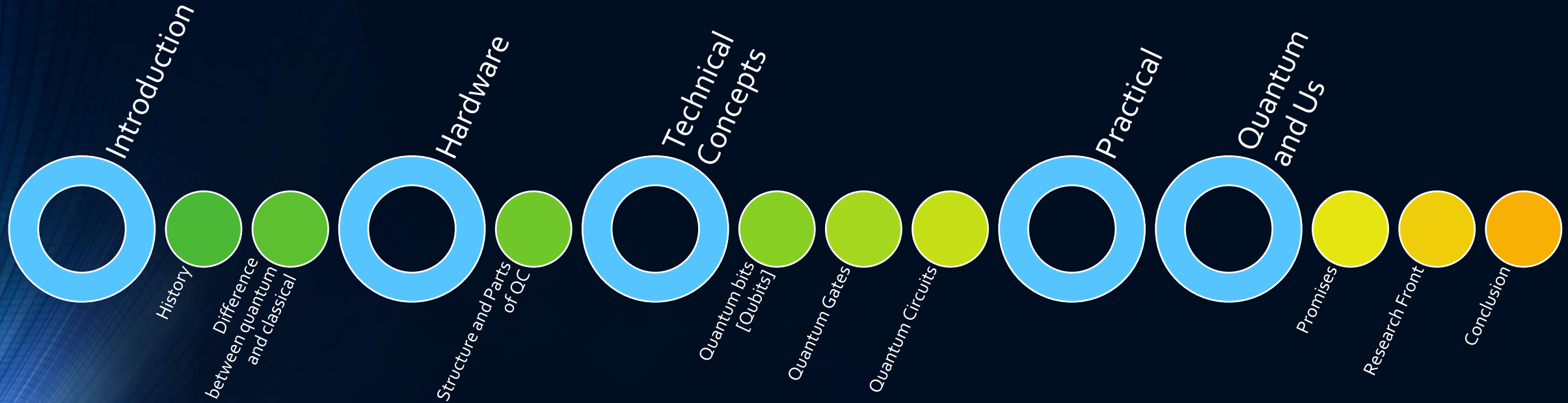


Introduction to Quantum Computing

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Expectations for the next hour



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



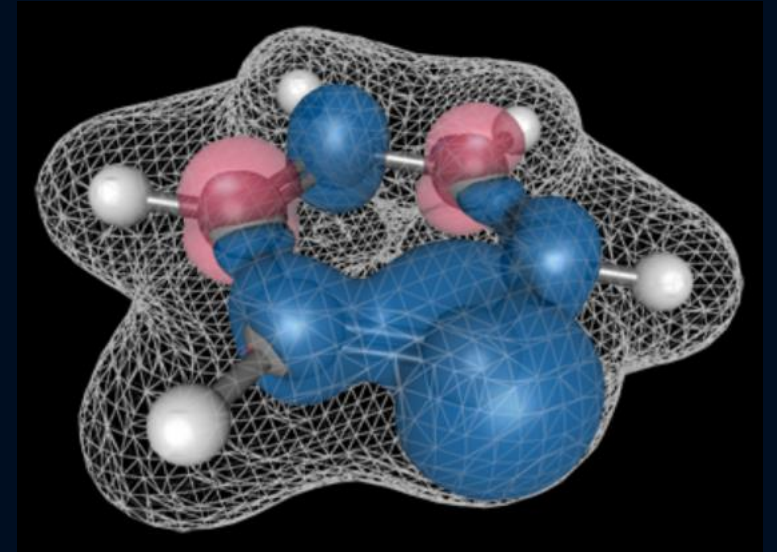
1- OPTIMIZATION

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 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.

1994

Peter Shor gave the factoring algorithm (polynomial time)

2000s

More algorithms.

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 1980s

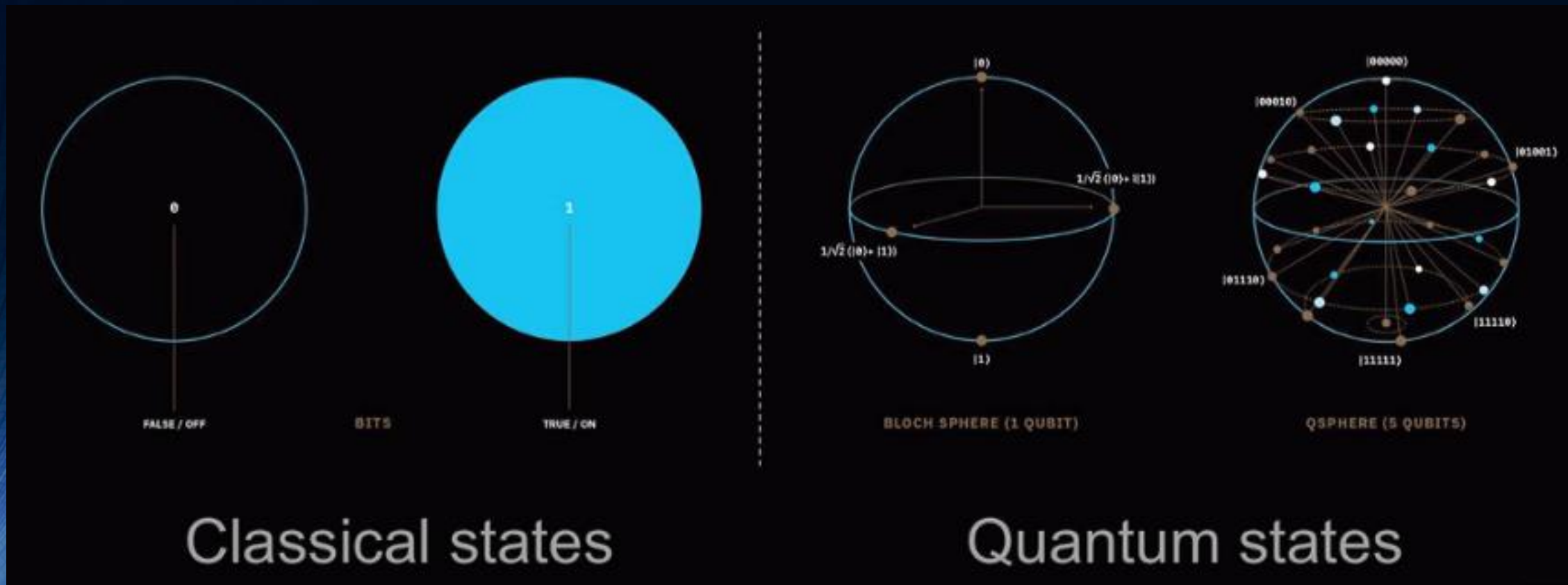
Researchers developed first truly quantum algorithms

1990s

Grover's (Unstructured) Search Algorithm

Mid 1990s

Why Quantum?





"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



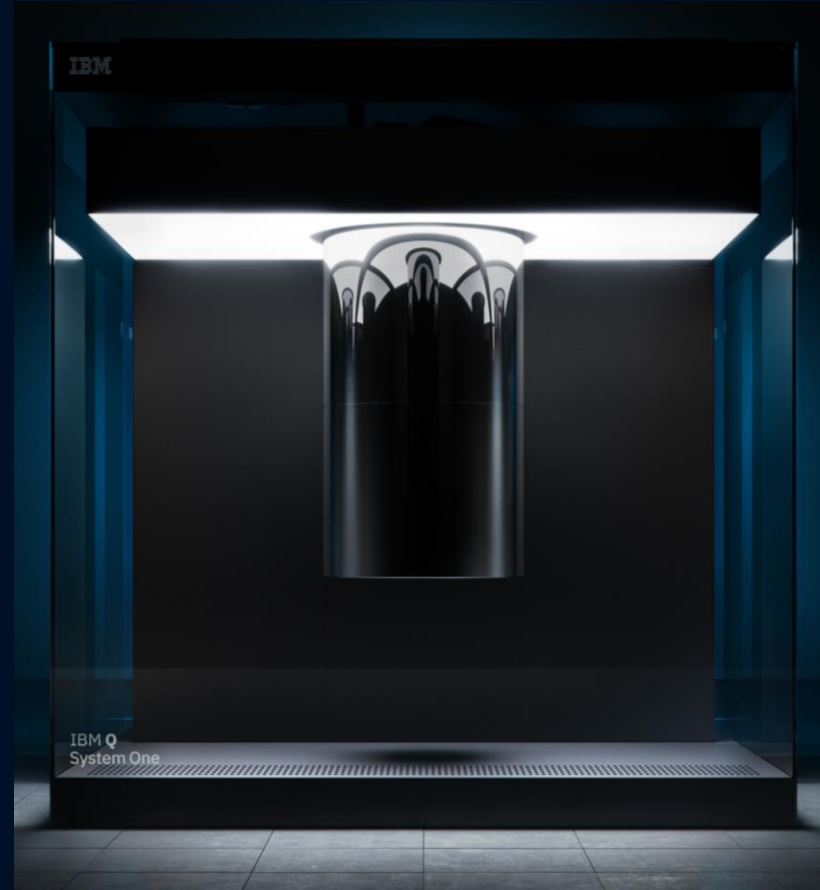
IBM Q – Lab Fridge



IBM Q System One [at CES 2019]



IBM Q – Lab Fridge



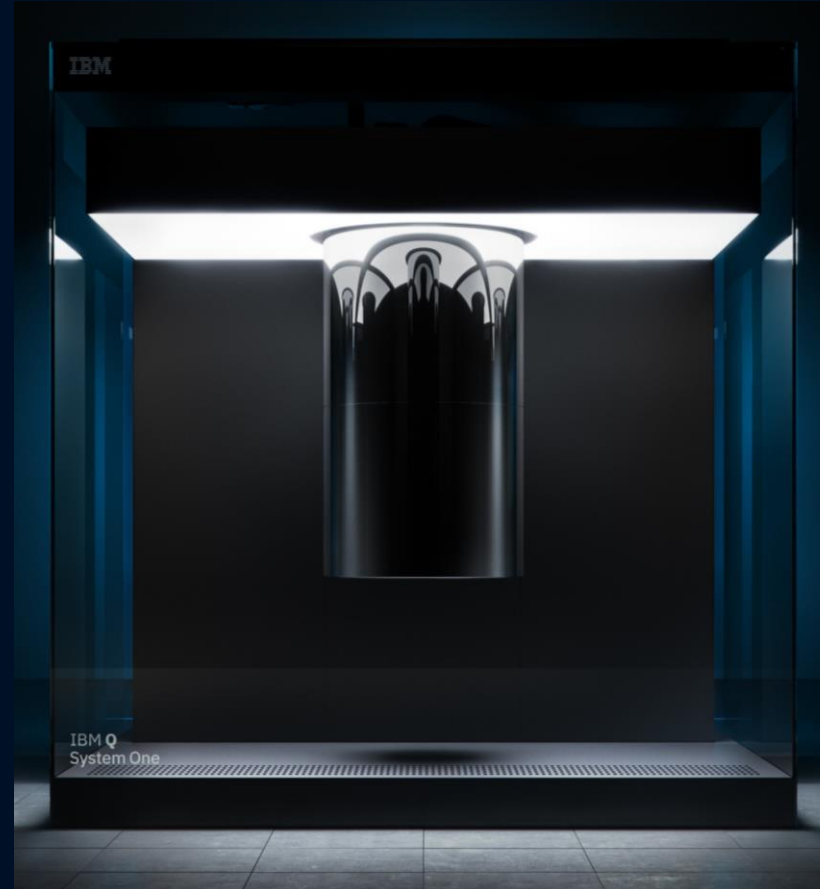
The Mona Lisa Case



IBM Q System One [at CES 2019]



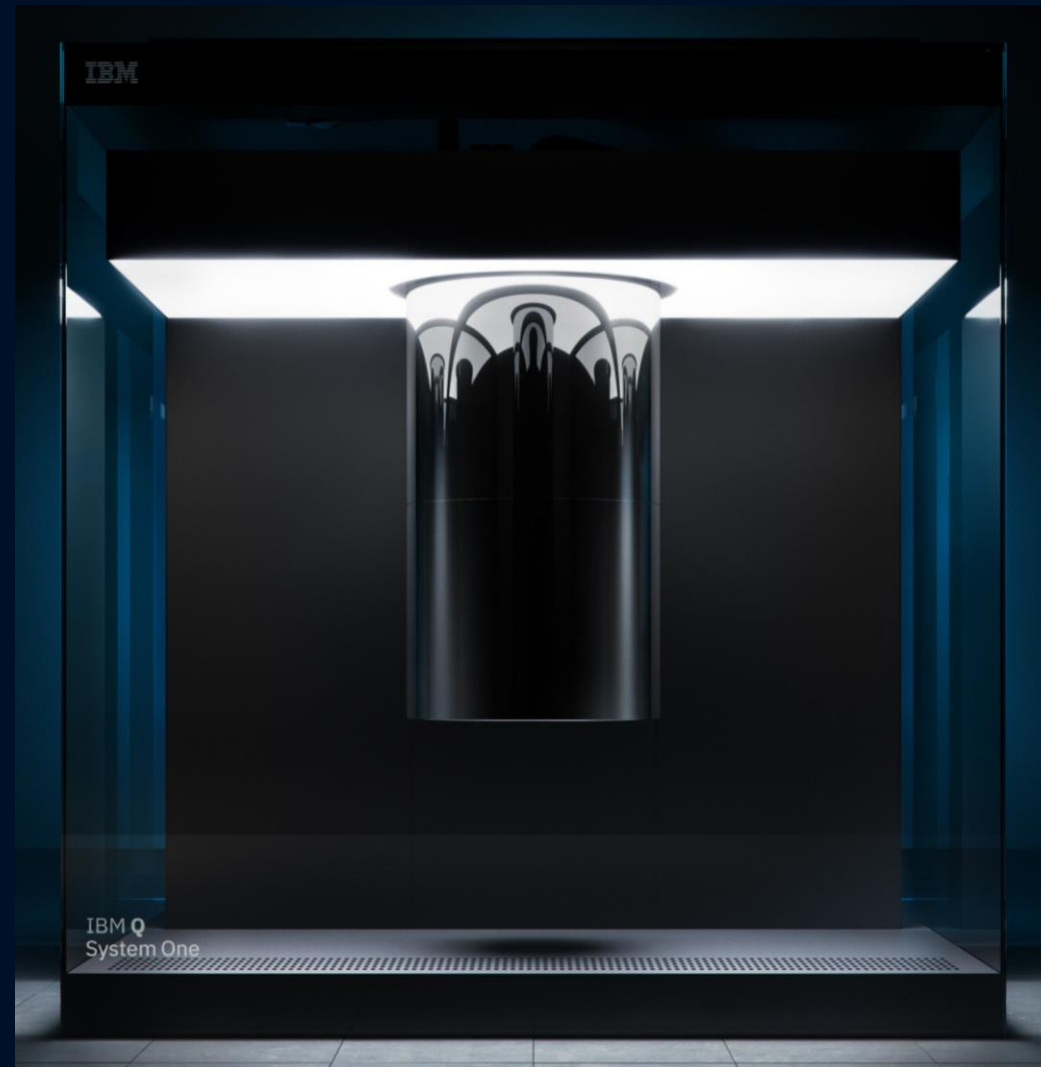
IBM Q – Lab Fridge

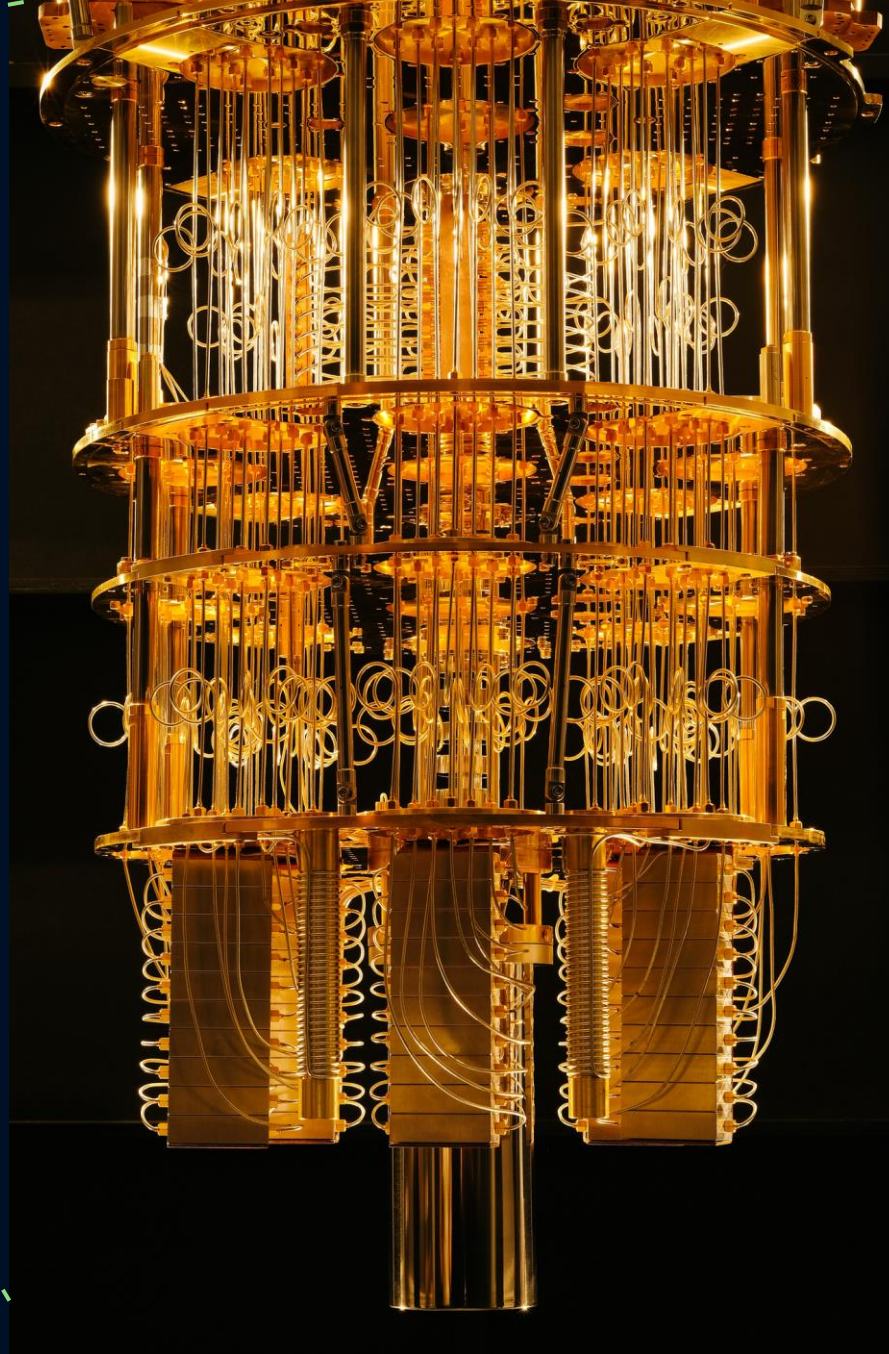
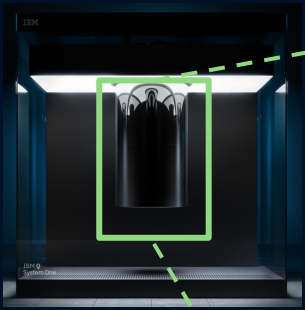


The Mona Lisa Case



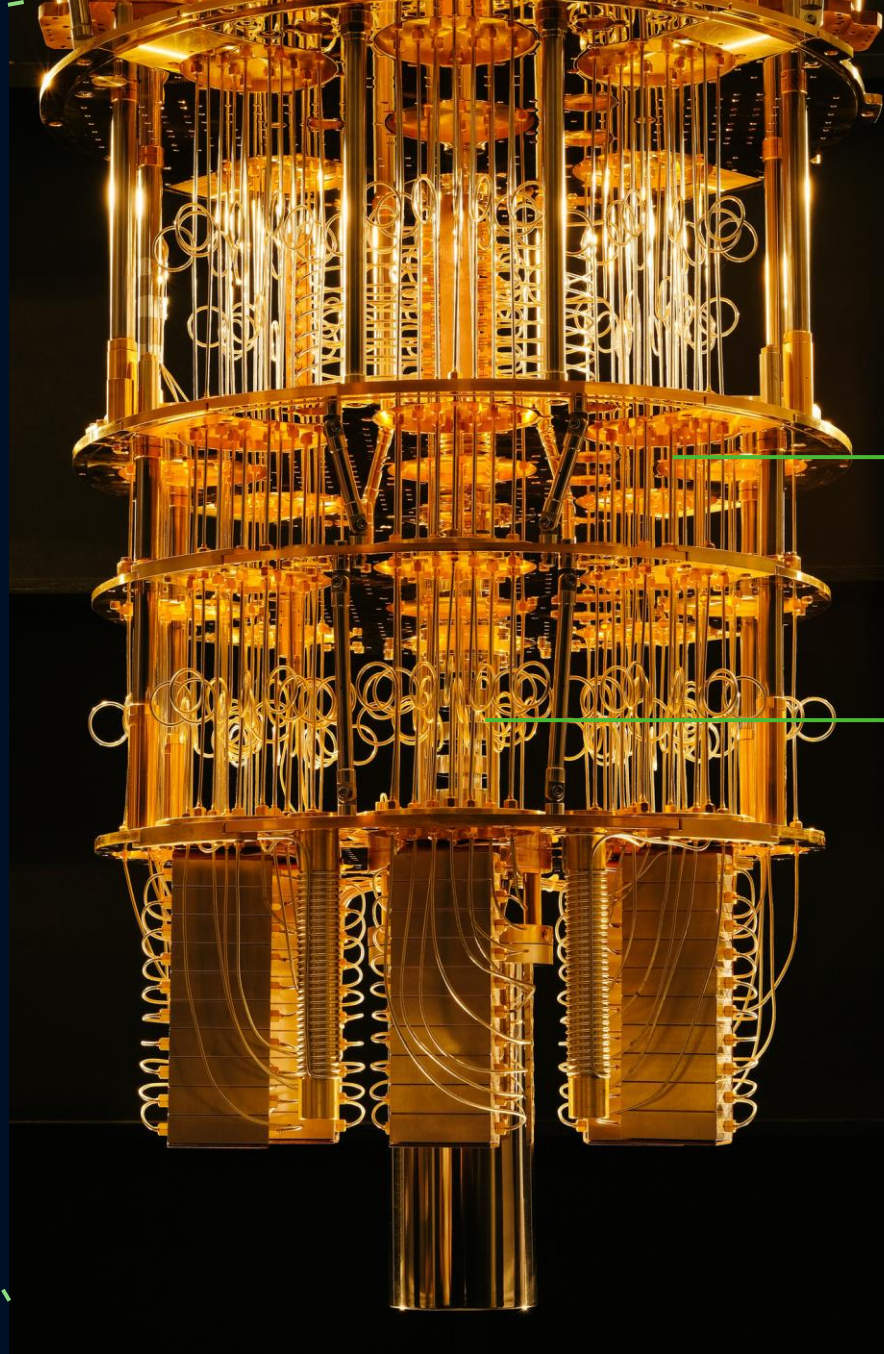
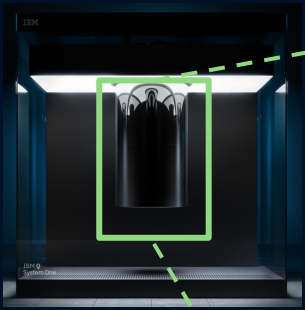
The Golden Chandelier





Operations at $300\text{ K} \approx 27^\circ\text{C}$

Operations at $0.015\text{ K} = -273.13^\circ\text{C}$

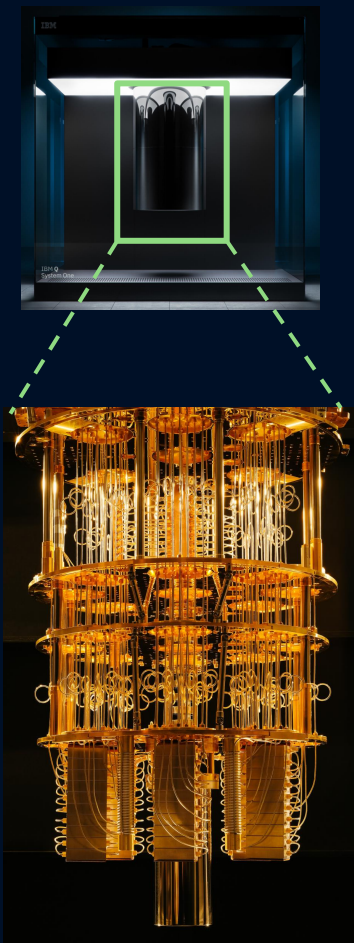


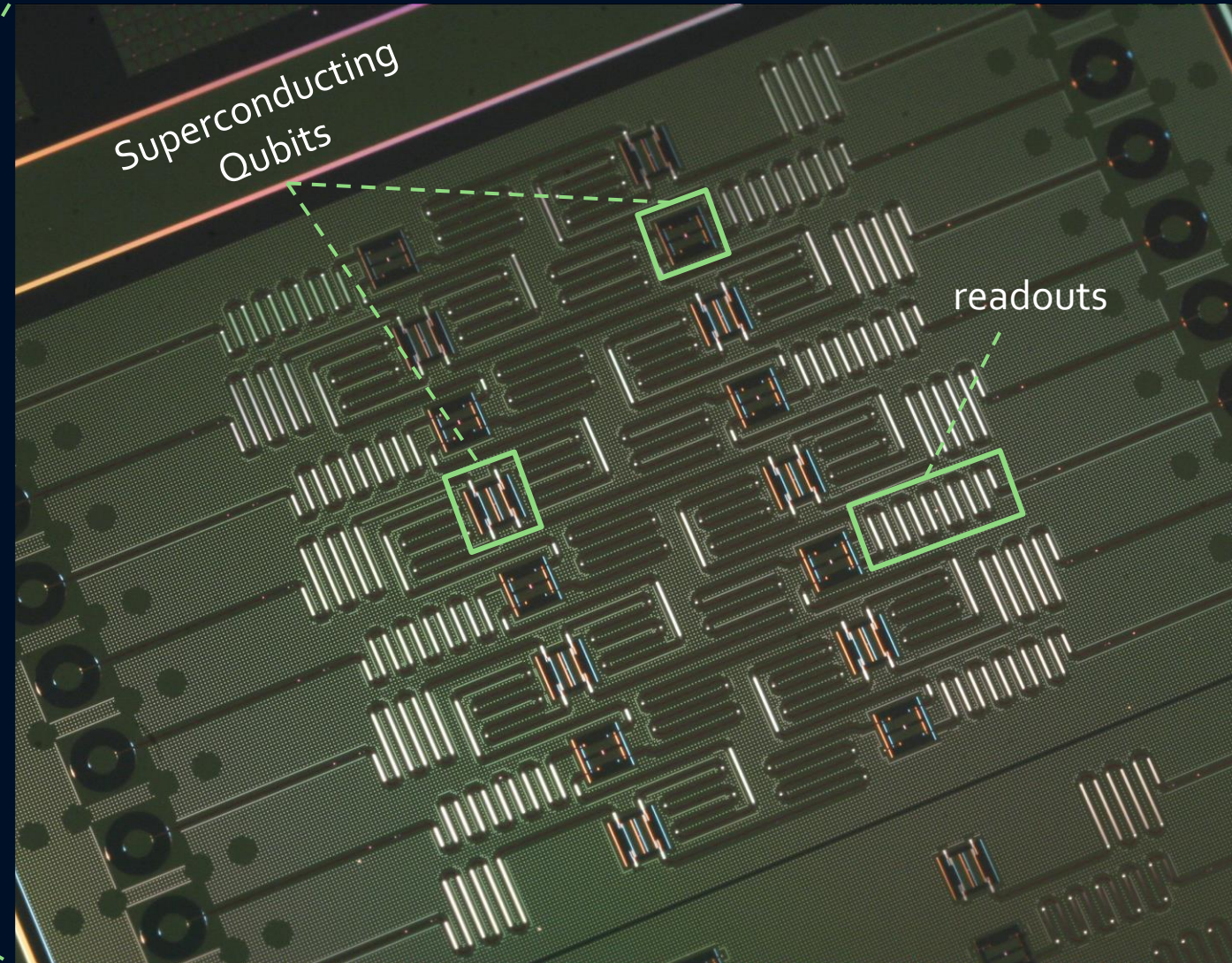
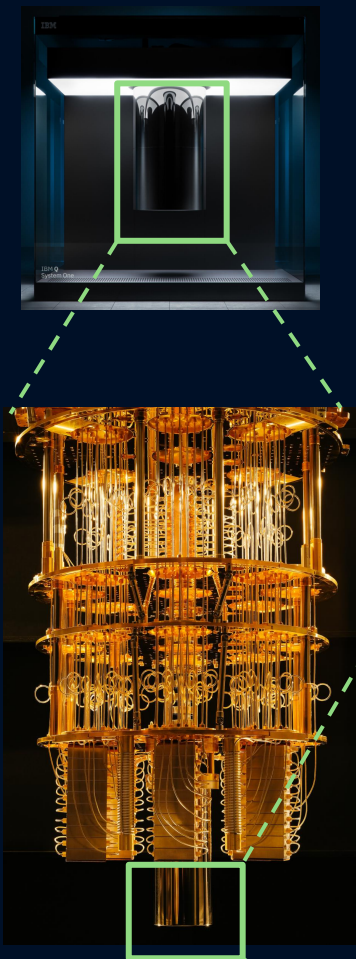
Operations at $300\text{ K} \approx 27^\circ\text{C}$

Gold plated wires

Mixing chamber

Operations at $0.015\text{ K} = -273.13^\circ\text{C}$





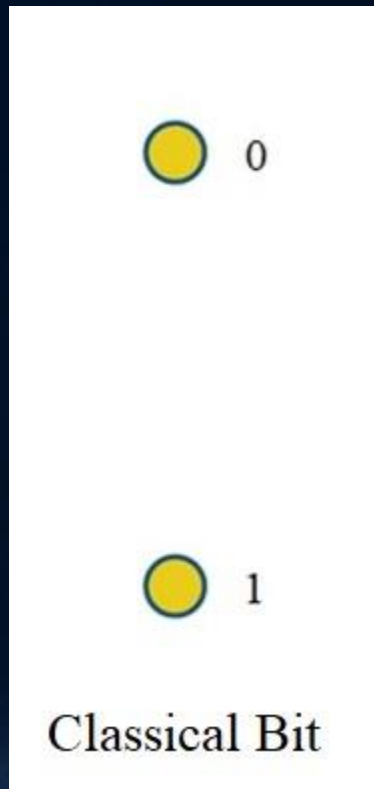
Technical Concepts

LET'S DIVE A LITTLE DEEPER

Bits vs Qubits

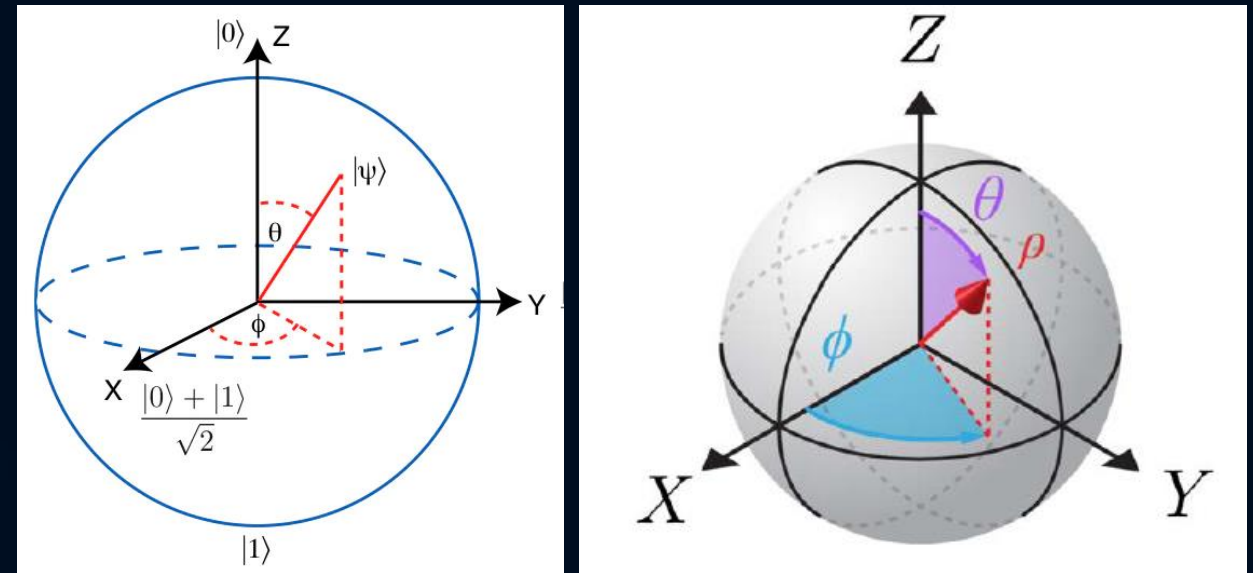
CLASSICAL BITS [BITS]

- Either 0 or 1 at a time.



QUANTUM BITS [QUBITS]

- Both 0 and 1 at any given point.

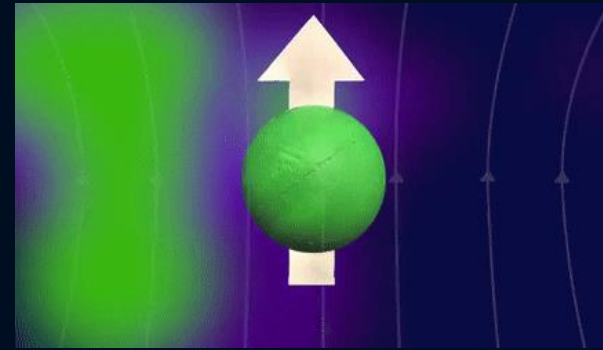


Qubit-facts

- 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.

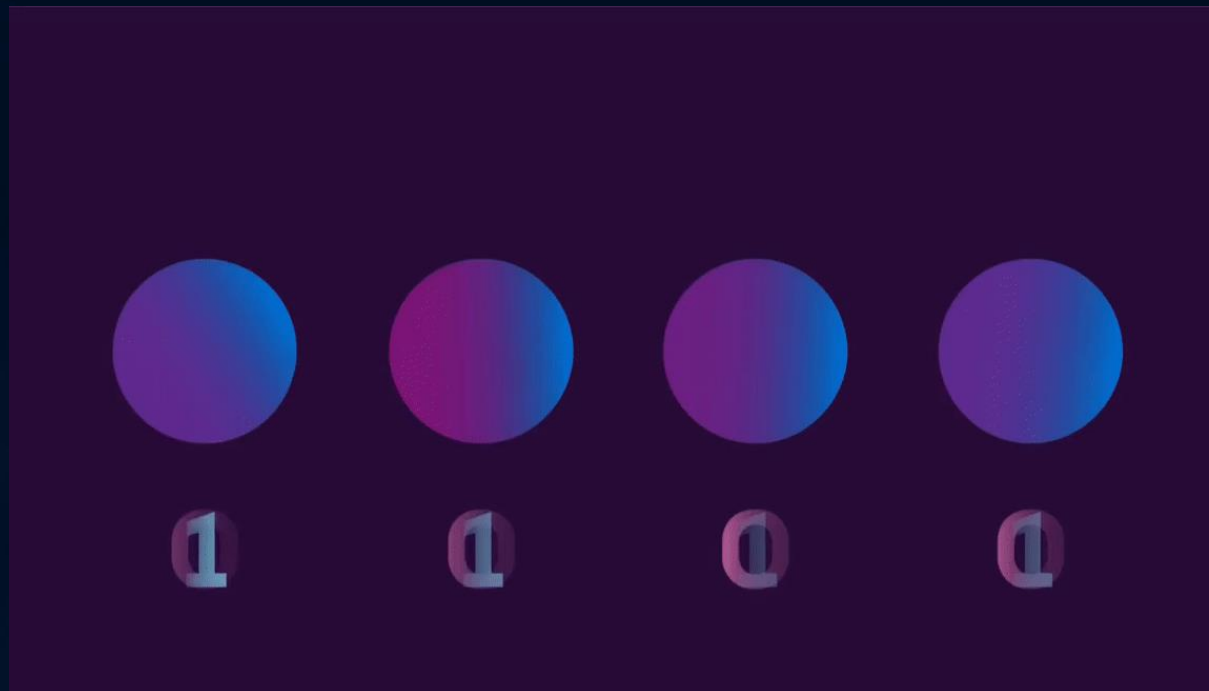
Qubits

- Imagine the qubit as an electron:



Spin-up state
 $|1\rangle$

Spin-down state
 $|0\rangle$



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	$a 00\dots0\rangle + b 00\dots0\rangle + \dots + y 11\dots0\rangle + z 11\dots1\rangle$	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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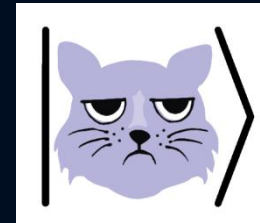
$$2^{300}$$

More basis states than there are atoms in the observable universe



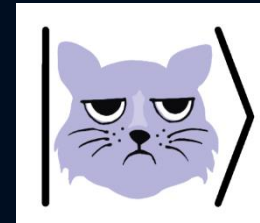
Quantum States

I have a Cat, and he is often 'grumpy'.

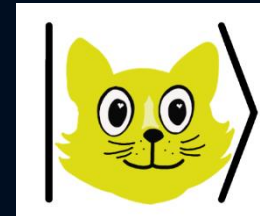


Quantum States

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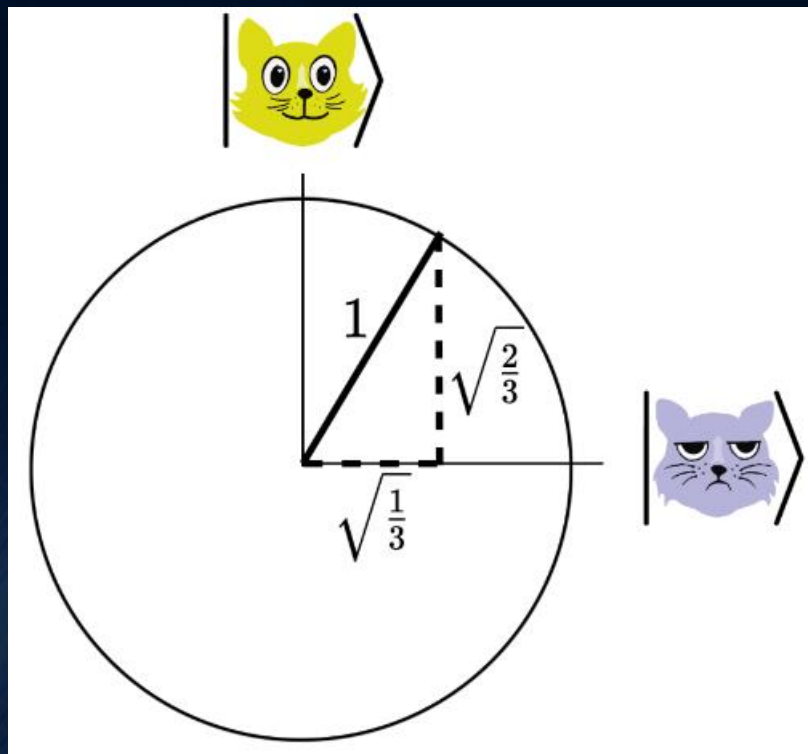


Okay, he is sometimes happy too.



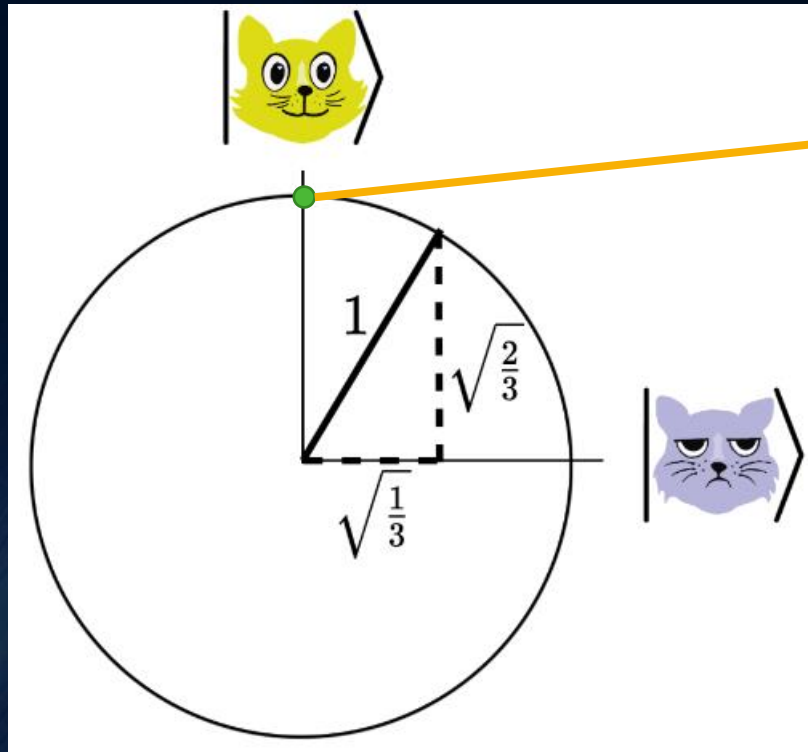
But, I've never seen him in between those states.

Quantum States



Quantum States

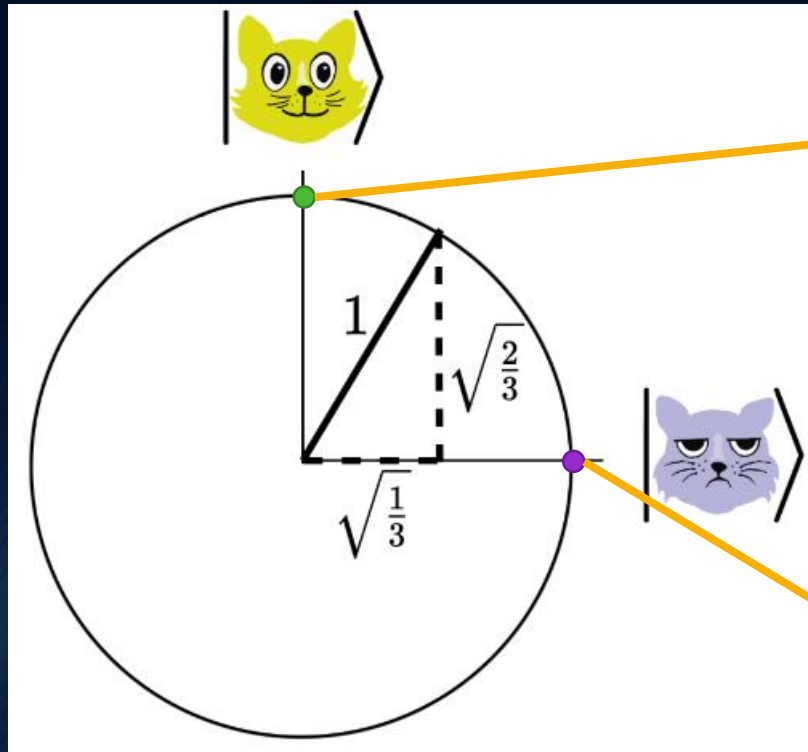
Vector notation



$$\left| \text{Yellow Cat} \right\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \left| \text{Purple Cat} \right\rangle + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \left| \text{Yellow Cat} \right\rangle$$

Quantum States

Vector notation

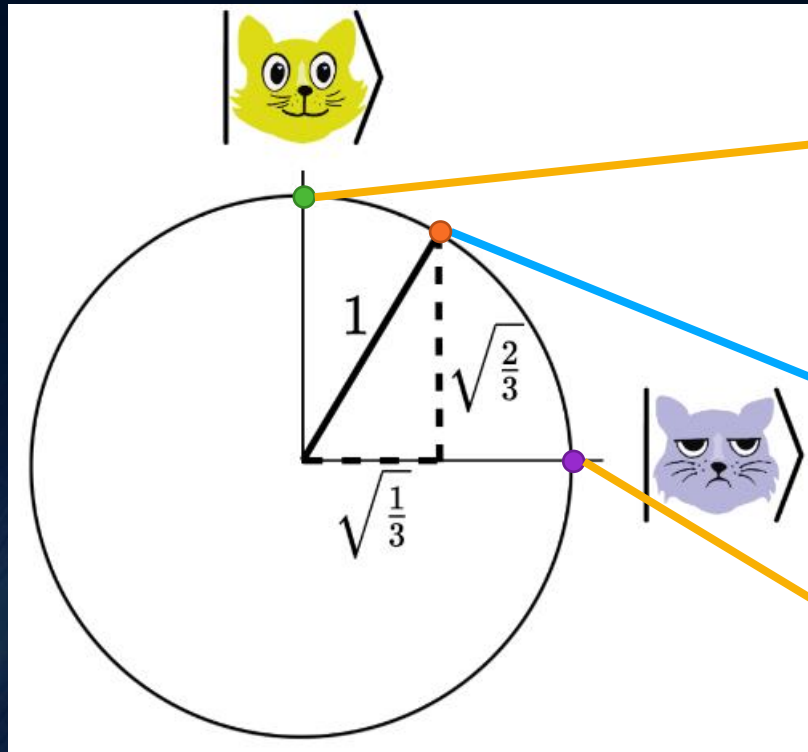


$$\left| \text{Yellow Cat} \right\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} \left| \text{Purple Cat} \right\rangle \\ \left| \text{Yellow Cat} \right\rangle \end{bmatrix}$$

$$\left| \text{Purple Cat} \right\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} \left| \text{Purple Cat} \right\rangle \\ \left| \text{Yellow Cat} \right\rangle \end{bmatrix}$$

Quantum States

Vector notation



$$|\text{cat smiley}\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{matrix} |\text{cat frowny}\rangle \\ |\text{cat smiley}\rangle \end{matrix}$$

$$\sqrt{\frac{1}{3}} |\text{cat frowny}\rangle + \sqrt{\frac{2}{3}} |\text{cat smiley}\rangle = \begin{bmatrix} \sqrt{\frac{1}{3}} \\ \sqrt{\frac{2}{3}} \end{bmatrix} \begin{matrix} |\text{cat frowny}\rangle \\ |\text{cat smiley}\rangle \end{matrix}$$

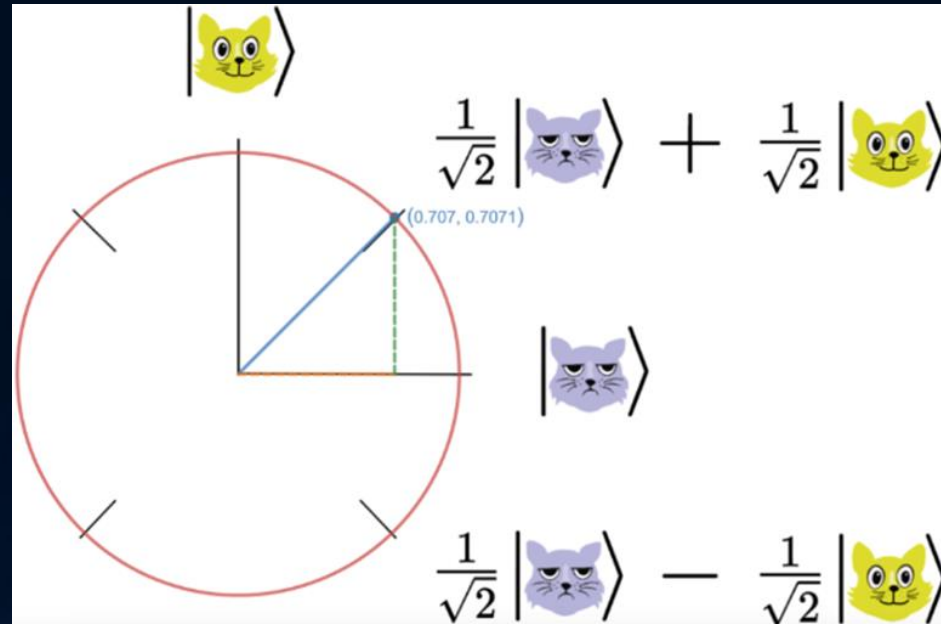
$$|\text{cat frowny}\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{matrix} |\text{cat frowny}\rangle \\ |\text{cat smiley}\rangle \end{matrix}$$

Superposition

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

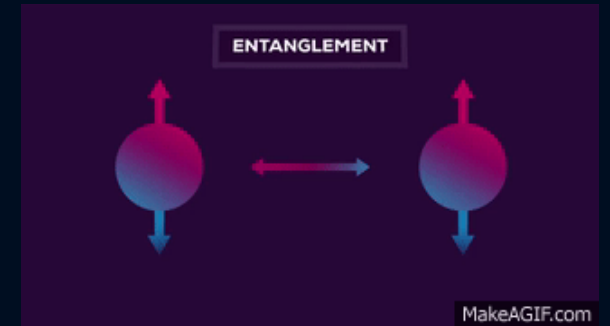
Superposition

- 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.

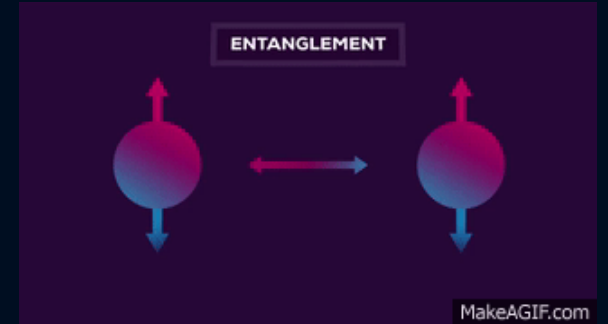


Entanglement

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- Suppose we have two qubits:

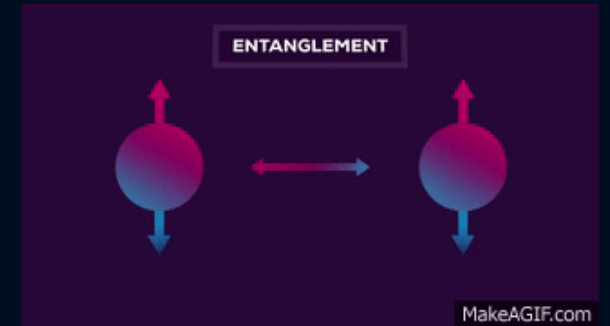
q_0

q_1



Entanglement

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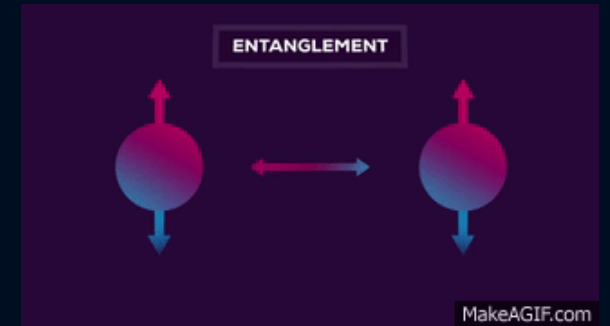
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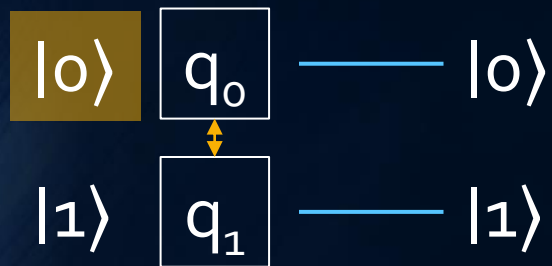
Entanglement Rule:

$ 0\rangle$	\longleftrightarrow	Leave the state as it is
$ 1\rangle$	\longleftrightarrow	Flip the state



Entanglement

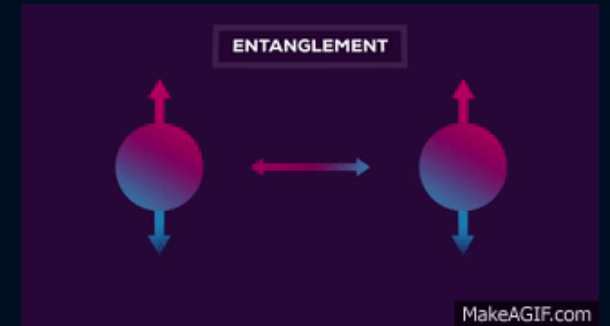
- When the states of two quantum particles are linked (or correlated) to each other, such that the state of one particle controls the state of other particle, the phenomena is called Entanglement.
- Let's see an example:



Initial
state

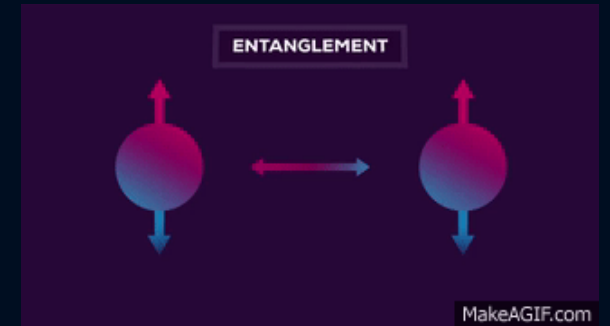
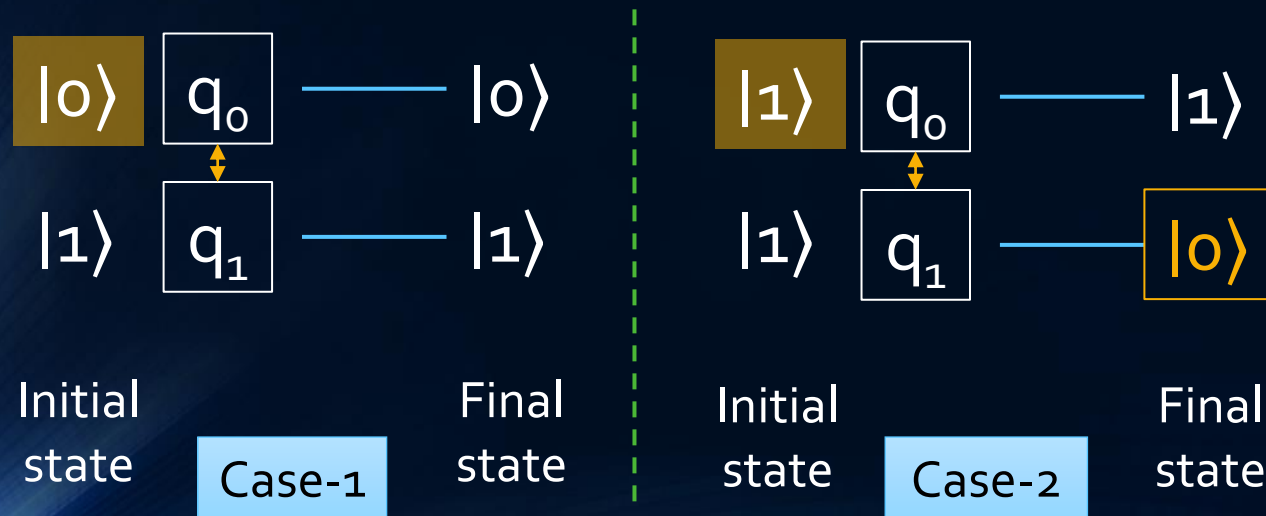
Case-1

Final
state



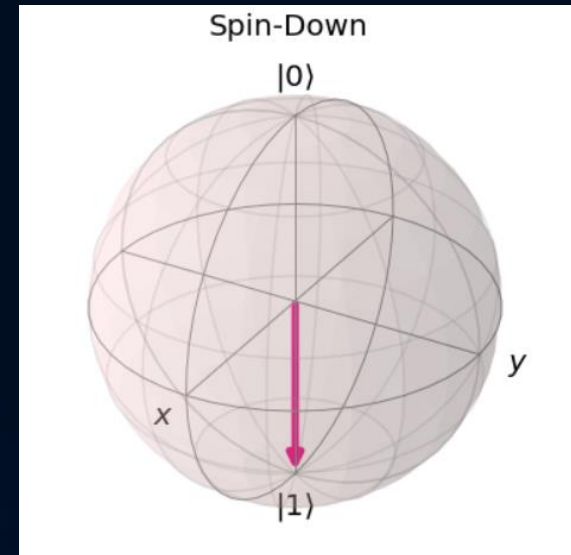
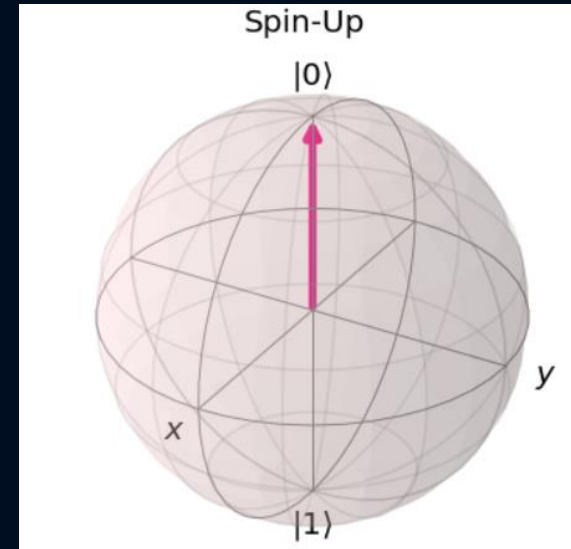
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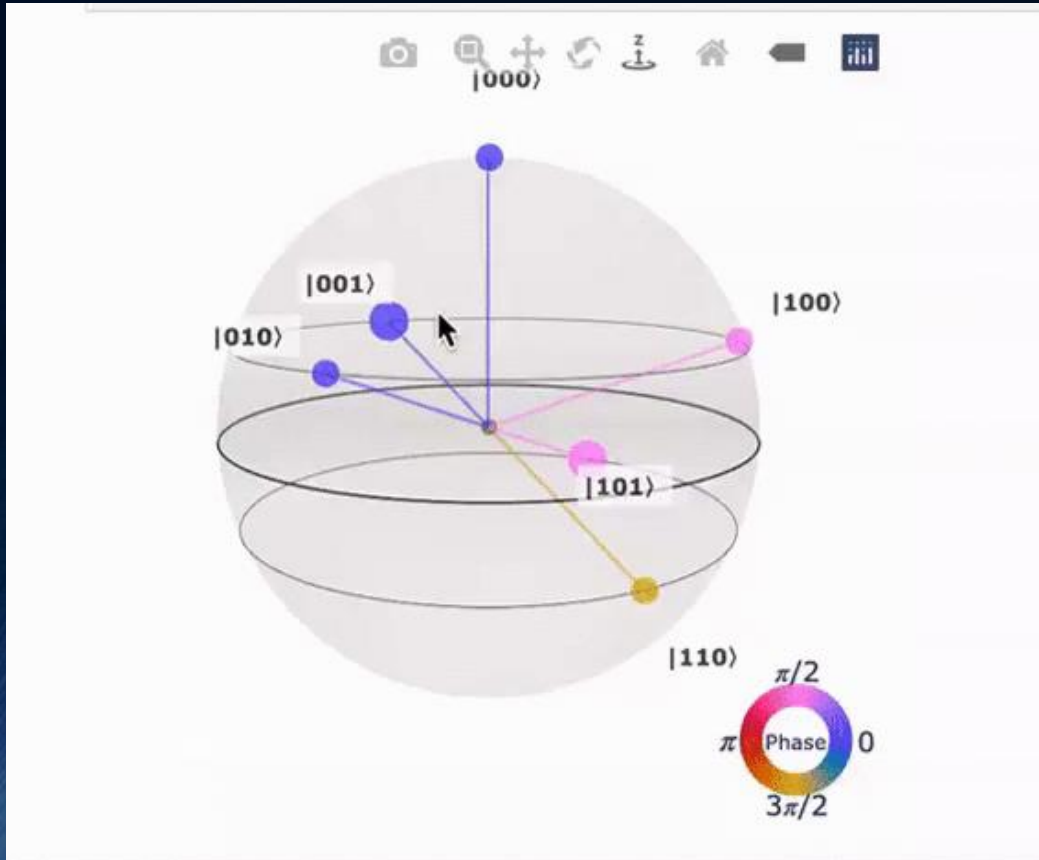


Bloch Sphere and Q-sphere

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

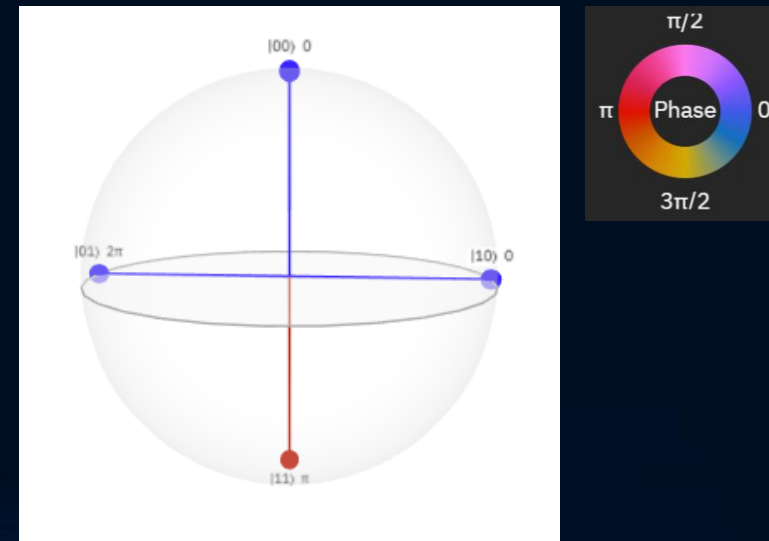


Bloch Sphere and Q-sphere

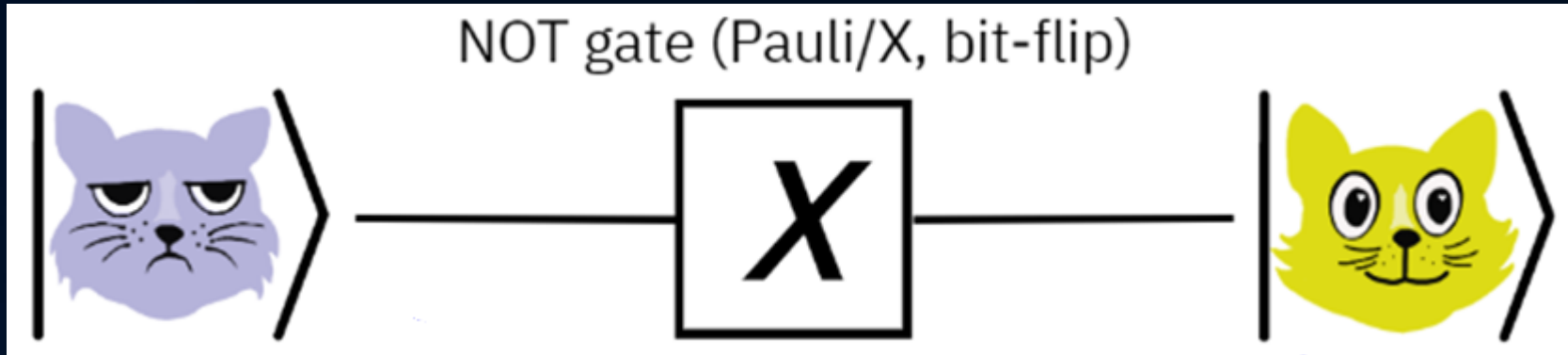


A Q-sphere is used to visualize quantum state for individual as well as multiple qubits.

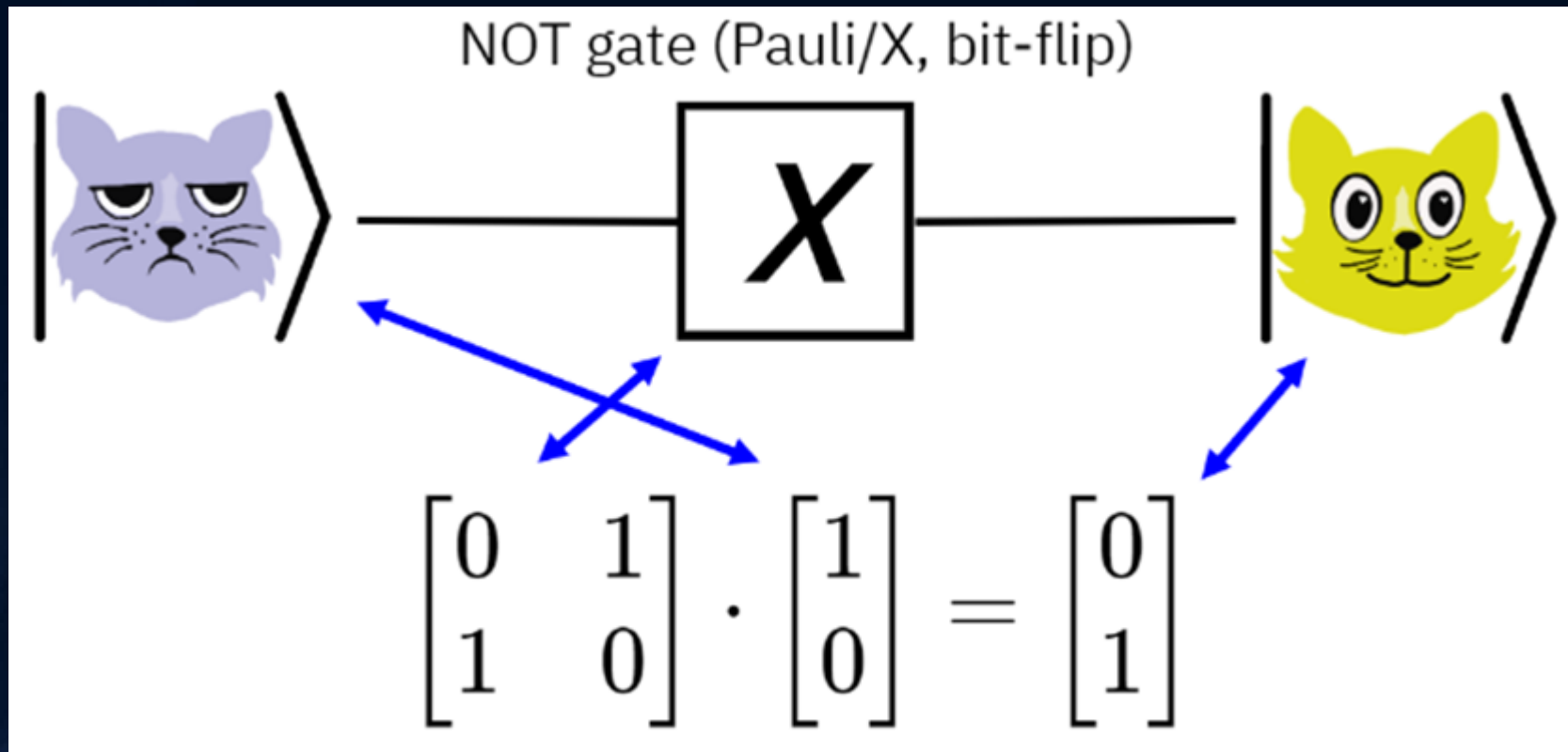
The adj. picture has been downloaded from IBM Quantum Experience which shows different states in different phases for multiple qubits.



Few Quantum Gates



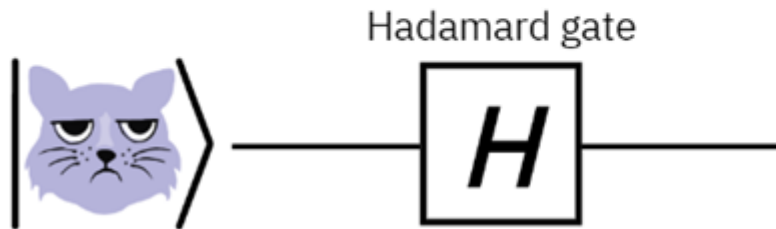
Few Quantum Gates



Few Quantum Gates

Hadamard gate

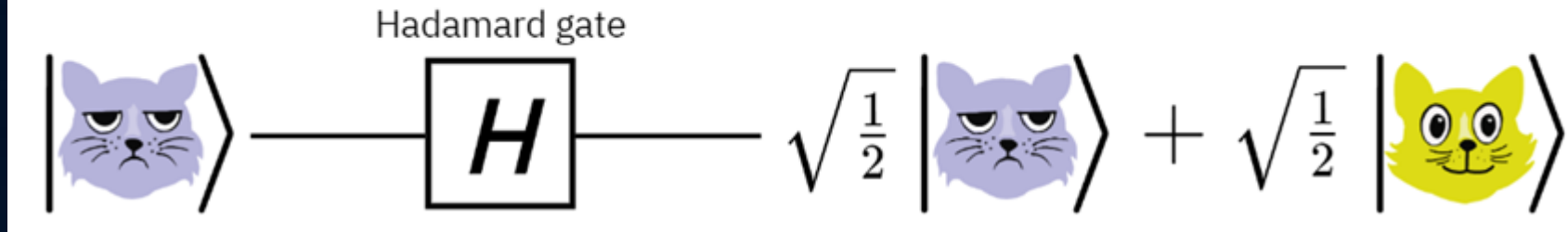
great for putting cats in equal superpositions



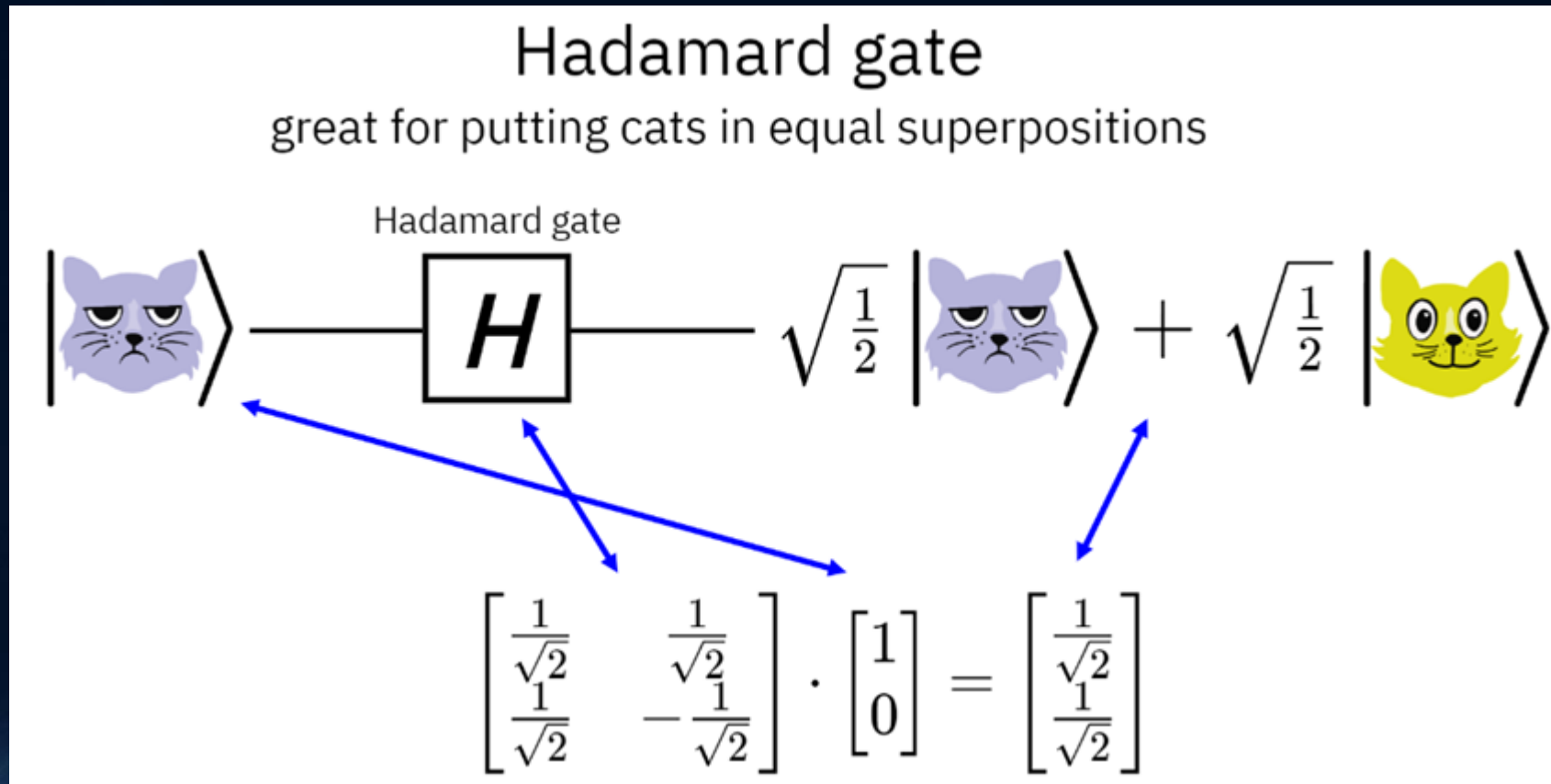
Few Quantum Gates

Hadamard gate

great for putting cats in equal superpositions



Few Quantum Gates



Multiple Qubits

$$\left| \begin{array}{cc} \text{purple cat} & \text{purple cat} \end{array} \right\rangle = \left| \text{purple cat} \right\rangle \left| \text{purple cat} \right\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \otimes \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \left| \begin{array}{cc} \text{purple cat} & \text{purple cat} \\ \text{purple cat} & \text{yellow cat} \\ \text{yellow cat} & \text{purple cat} \\ \text{yellow cat} & \text{yellow cat} \end{array} \right\rangle$$

$$\left| \begin{array}{cc} \text{purple cat} & \text{yellow cat} \end{array} \right\rangle = \left| \text{purple cat} \right\rangle \left| \text{yellow cat} \right\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \otimes \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \left| \begin{array}{cc} \text{purple cat} & \text{purple cat} \\ \text{purple cat} & \text{yellow cat} \\ \text{yellow cat} & \text{purple cat} \\ \text{yellow cat} & \text{yellow cat} \end{array} \right\rangle$$

Quantum Circuits

IBM Quantum Experience

File Edit Inspect View Help Run Settings Run on ibmq_ourense

Circuits / Demo Saved

</> Code Docs Jobs

H \oplus \oplus \oplus \otimes \otimes T S Z S^\dagger T^\dagger U1 $|0\rangle$ if Z RX RY RZ U3 Y U2 CH CY CZ CRX CRY CRZ CU1 CU3 RXX RZZ + Add

q0 q1 c2

Measurement Probabilities

Q-sphere

Statevector

Output state

The screenshot displays the IBM Quantum Experience web application. At the top, there's a navigation bar with 'File', 'Edit', 'Inspect', 'View', and 'Help' menus, along with 'Run Settings' and a 'Run on ibmq_ourense' button. Below this is a breadcrumb 'Circuits / Demo' and icons for 'Code', 'Docs', and 'Jobs'. A toolbar contains various quantum gates: H, CNOT, Toffoli, CNOT, CNOT, CNOT, T, S, Z, S†, T†, U1, |0⟩, if, Z, RX, RY, RZ, U3, Y, U2, CH, CY, CZ, CRX, CRY, CRZ, CU1, CU3, RXX, RZZ, and an '+ Add' button. The main workspace shows a quantum circuit with three qubits: q0, q1, and c2. q0 has an H gate. q1 has a CNOT gate controlled by q0. c2 has a CNOT gate controlled by q1, followed by a measurement gate. The results section at the bottom contains three panels: 'Measurement Probabilities' showing a bar chart for computational basis states 00 and 11; 'Q-sphere' showing a Bloch sphere with points for |00⟩ and |11⟩; and 'Statevector' showing a bar chart for computational basis states 00 and 11. An 'Output state' panel at the bottom right displays the state vector [0.707+0j, 0+0j, 0+0j, 0.707+0j].

Computational basis states	Measurement probability (%)
00	50
11	50

Computational basis states	Amplitude
00	0.707
01	0
10	0
11	0.707

Output state: [0.707+0j, 0+0j, 0+0j, 0.707+0j]

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

<https://doi.org/10.1038/s41586-019-1666-5>

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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 processor¹. 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.

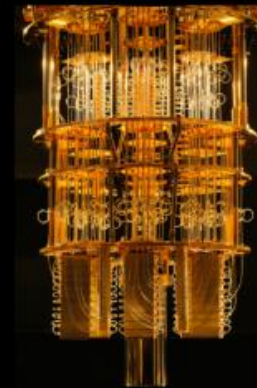
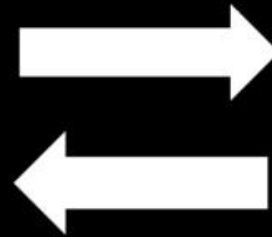
Conclusion

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



Modern Infrastructure for Big Data & AI

Store, manage and process huge quantities of data to extract insights and take business action.



Quantum Computers

Explore large set of possibilities and identify optimal answer to drive business value.

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

THANK $Y|0\rangle U!$

FEEL FREE TO ASK QUESTIONS / GIVE FEEDBACK.