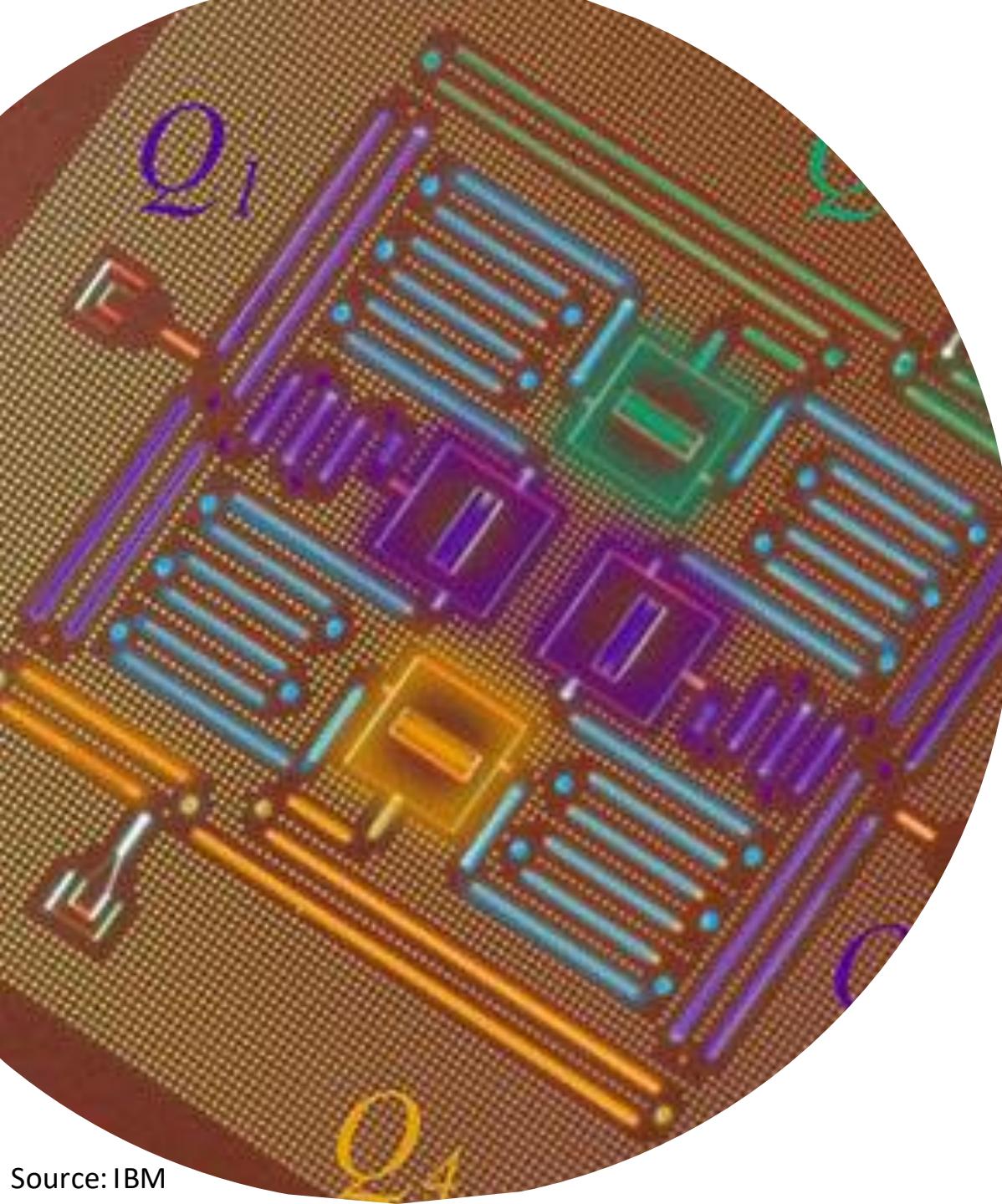


WELCOME EVERYONE!



Skill Surf



University of British Columbia
QUANTUM CLUB



A GENTLE INTRODUCTION TO QUANTUM INFORMATION AND COMPUTING

WORKSHOP SESSION 1: January 21, 2023

Acknowledgements



University of British Columbia
QUANTUM CLUB

www.ubcquantum.com

PILLARS

Community

Access to Training

Opportunity

MEMBERS BASE (EST. 2021)

270+

(BC Universities & Beyond)

40+

(UBC Undergraduates)

Community
Members

Official
Members

About Myself

Kithmin Wickremasinghe



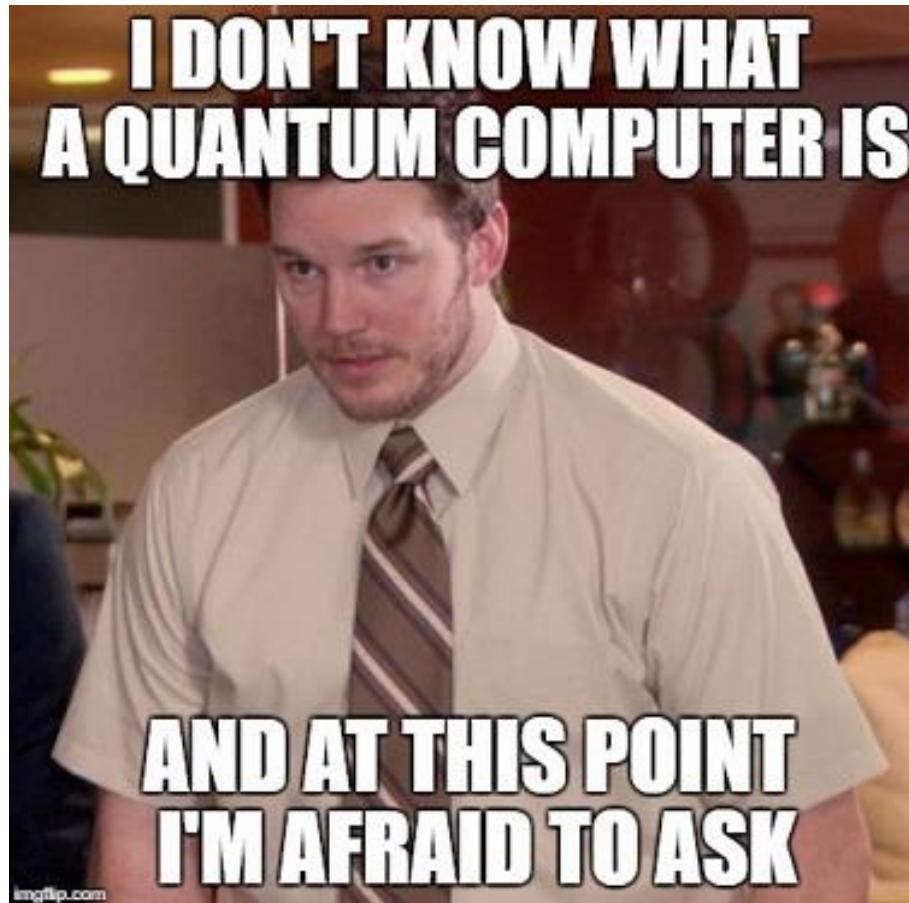
MASc Student in Electrical and
Computer Engineering
The University of British Columbia

ENTC Lecturer and Alumni (15' Batch)

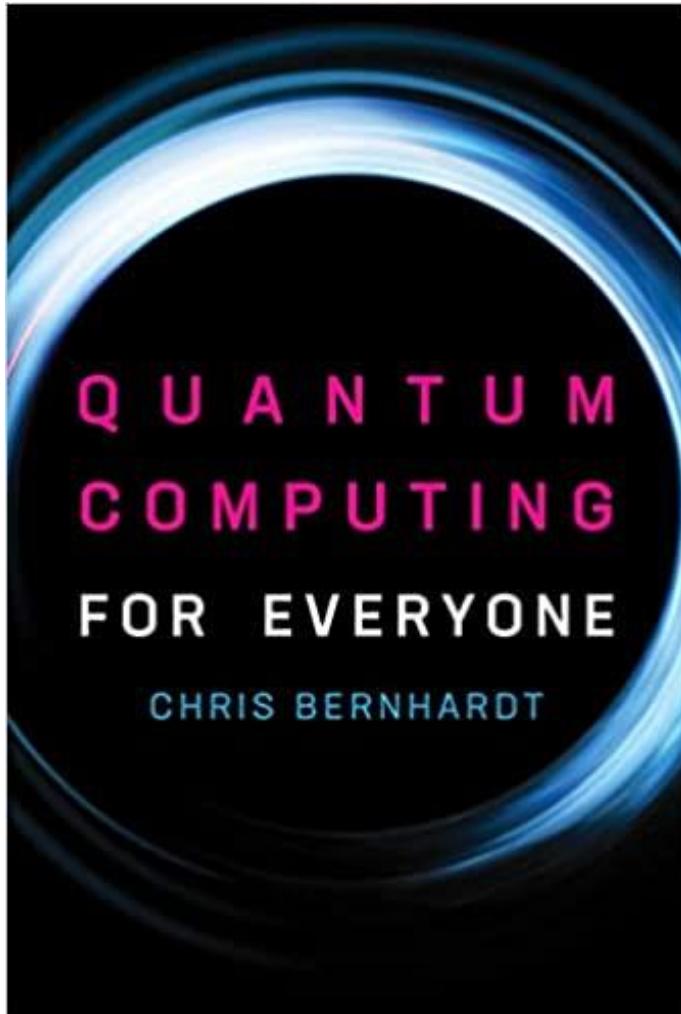


THE UNIVERSITY
OF BRITISH COLUMBIA

Please Ask Questions; We are also still learning about QC everyday! :D

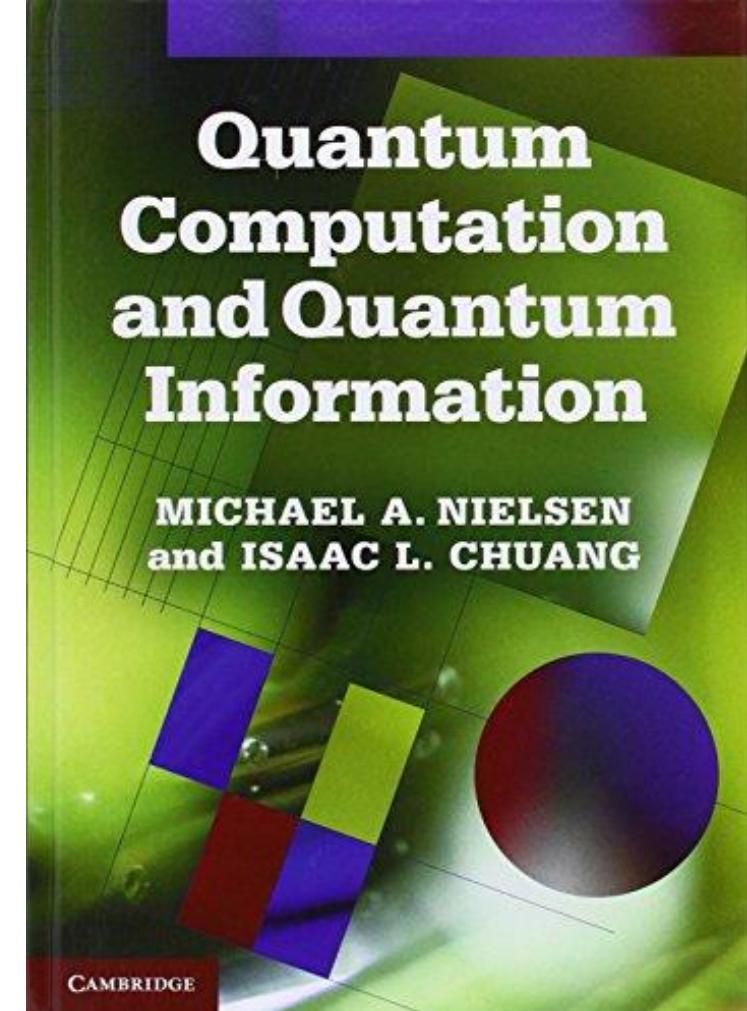


Interesting Resources



Many many more resources on this subject can be found on the Internet; Check the workshop registration email for some helpful links to study further!

Optional pre-requisites!



Optional Prerequisites

- Some basic knowledge in linear algebra is beneficial (but not required), a review can be found at
https://qiskit.org/textbook/ch-appendix/linear_algebra.html
(up to and including Matrices and Matrix Operations)
- Basic knowledge of programming in Python is beneficial and highly recommended (just the basics, like iterating through list, write a function, and understand what are attributes of Python class) - <https://learn.qiskit.org/summer-school/2020/qubits-states-circuits-measurements>

Workshop Agenda

SESSION 1

1. Introduction and Motivation for Quantum Computing
2. Diving into Quantum Bits: Polarization of Light
3. The mathematical background of Quantum Computing
4. Visualizing Qantum Gates Interactively

SESSION 2

1. Introduction to IBM QISKIT
2. Demonstration Session using Python Notebooks
3. Scientific Challenges of Quantum Computing

Instructors for the Workshop



Kithmin



Ravi

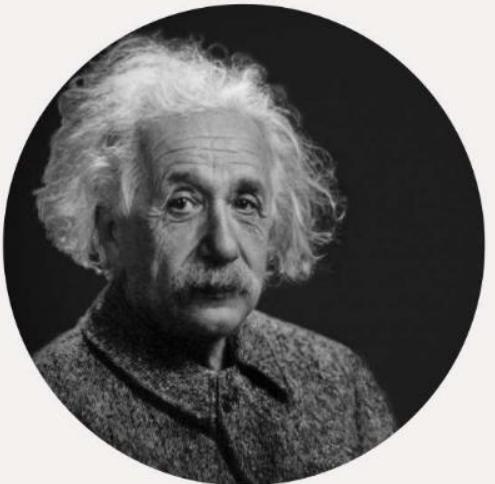


Theshani

SESSION 1

SESSION 2

The Story of Quantum Computing



Albert Einstein
1879 - 1955



Niels Bohr
1885 - 1962



Max Planck
1858 - 1947



Werner Heisenberg
1901 - 1976

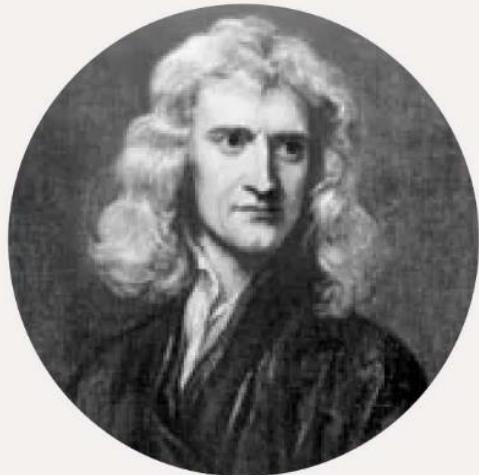


COPENHAGEN
1941

Classical Mechanics

force = mass x acceleration

$$\mathbf{F} = m\mathbf{a}$$



Issac Newton
1643 - 1727

Quantum Mechanics

change is proportional to energy

$$i\hbar \frac{\partial}{\partial t} |\Psi\rangle = \hat{H} |\Psi\rangle$$



Erwin Schrödinger
1887 - 1961

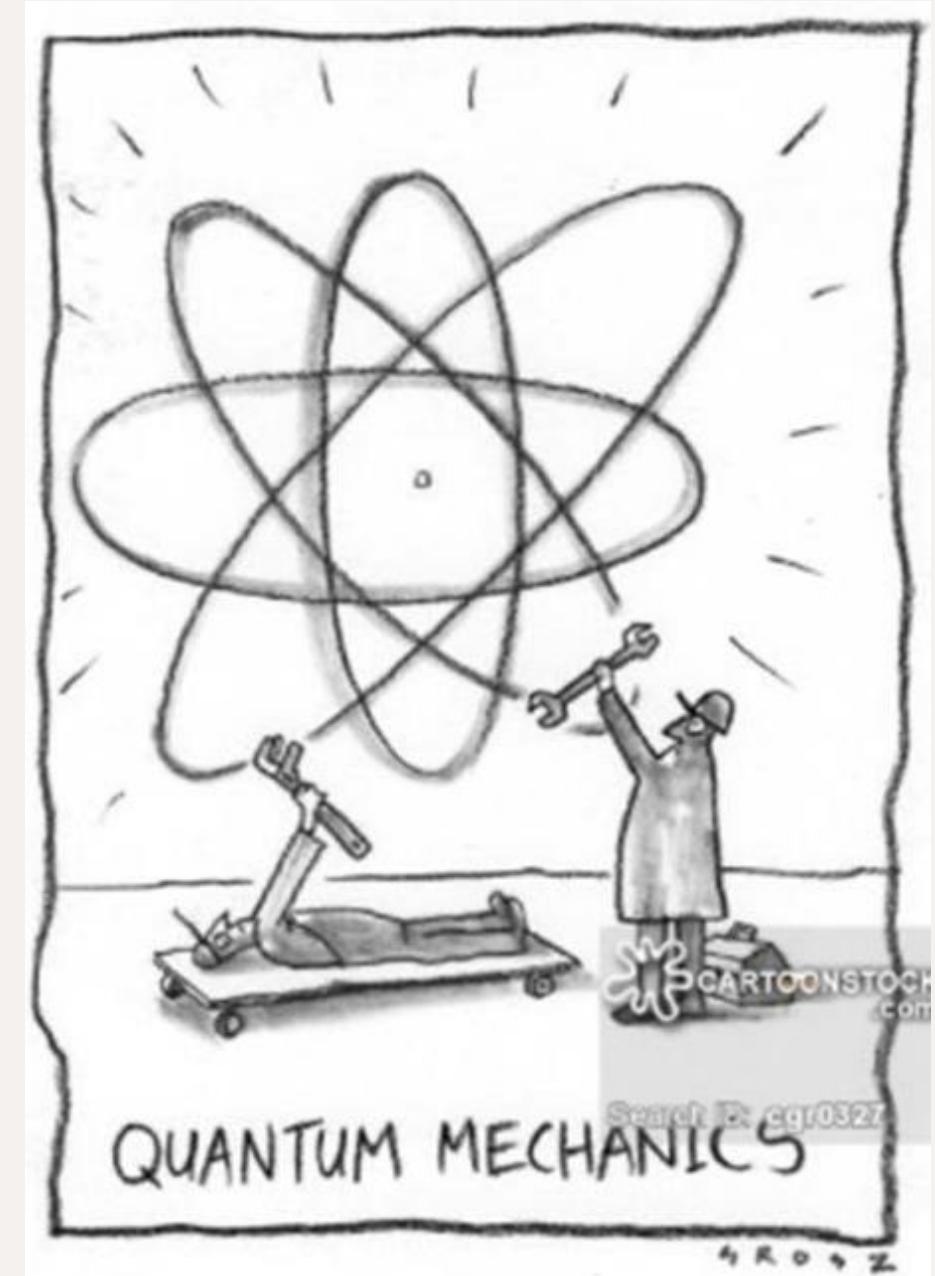
Postulates of Quantum Mechanics

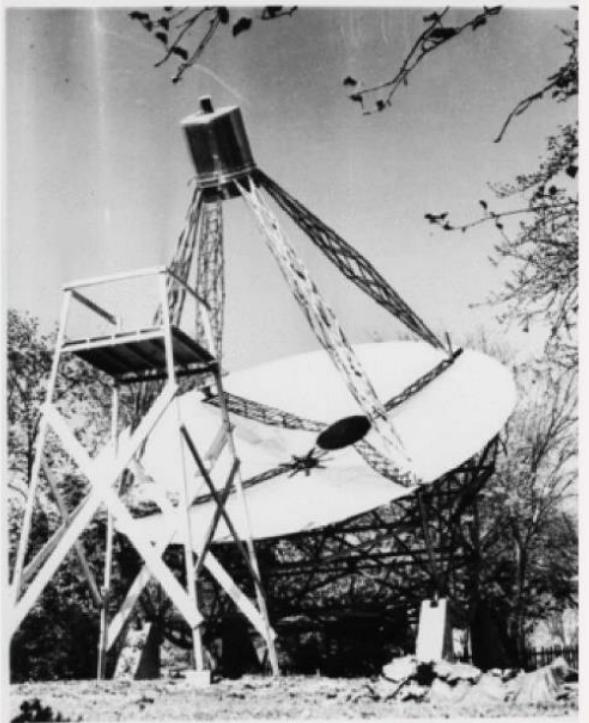
Quantum State?

**...is the status of something as described using
quantum mechanics**

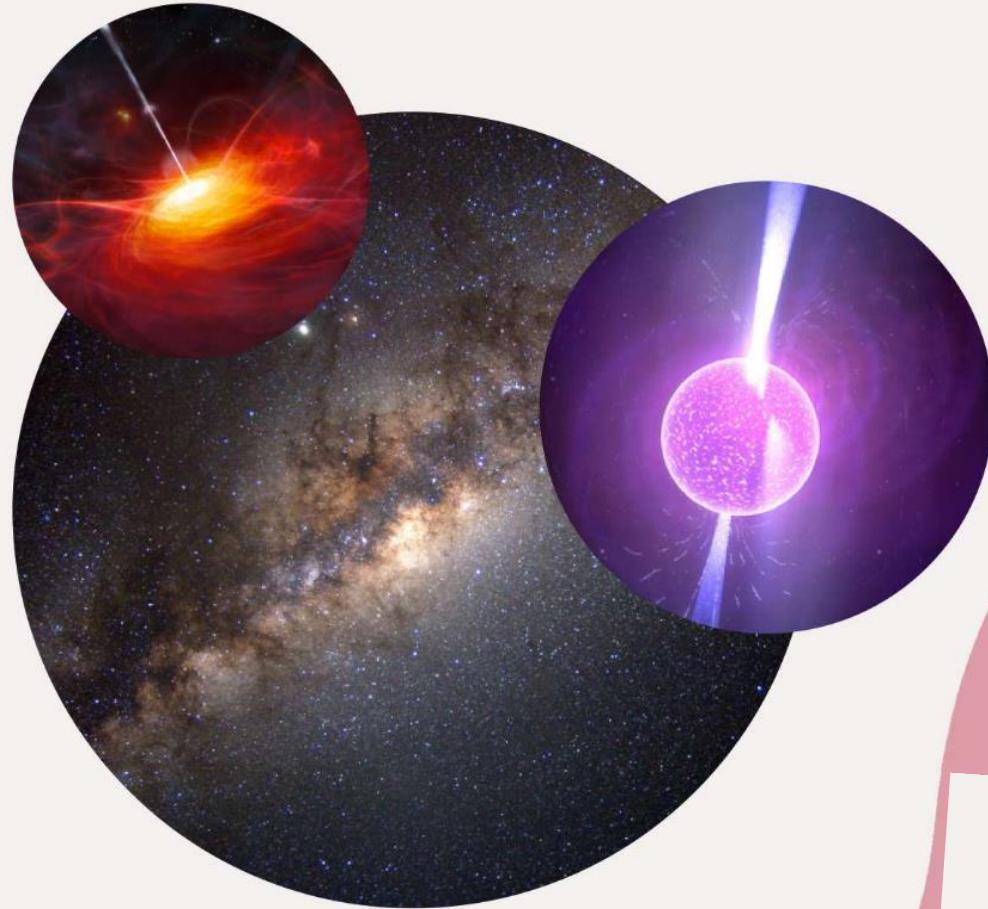
Quantum Theory

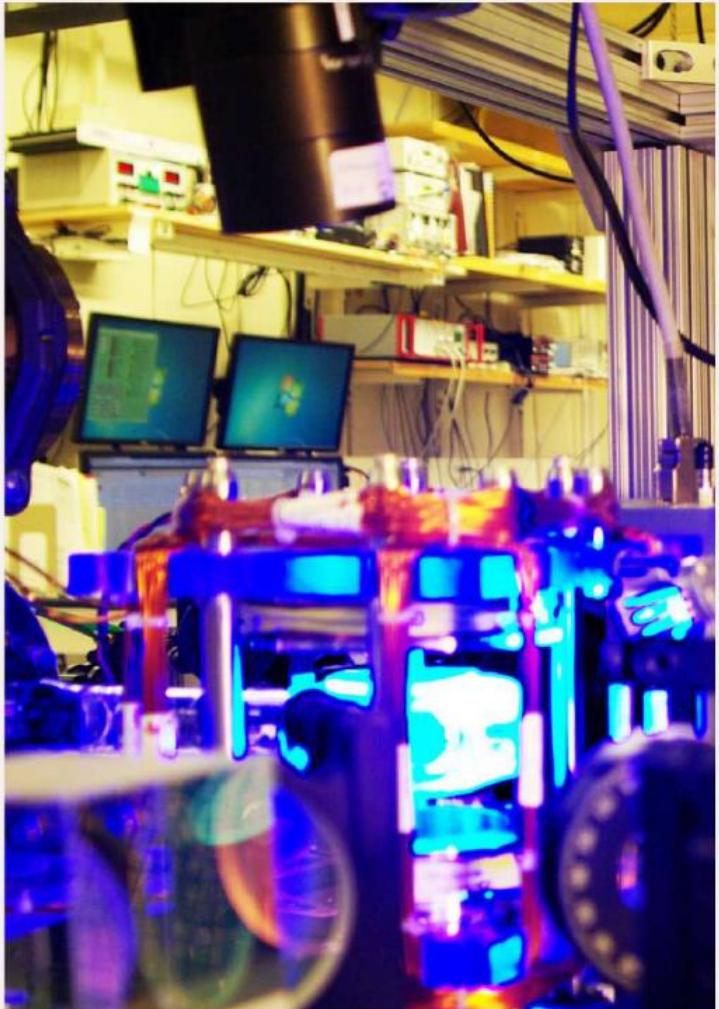
the foundation of everything





Radio Astronomy 1930-1940s





Control over single
quantum systems



?



1985

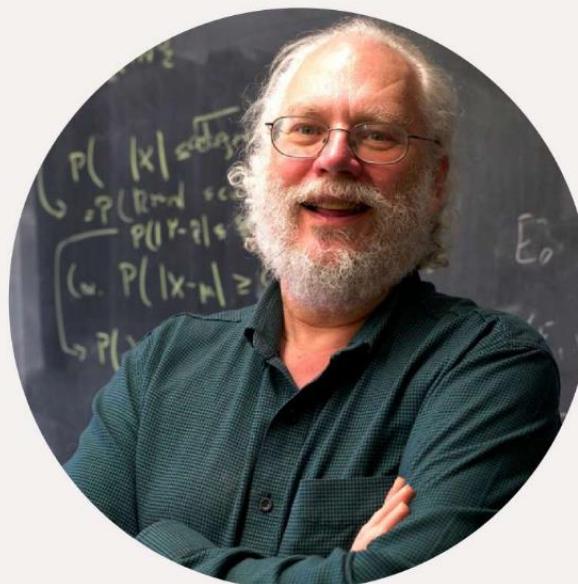
David Deutsch



Efficiently simulating an arbitrary physical system?

1994

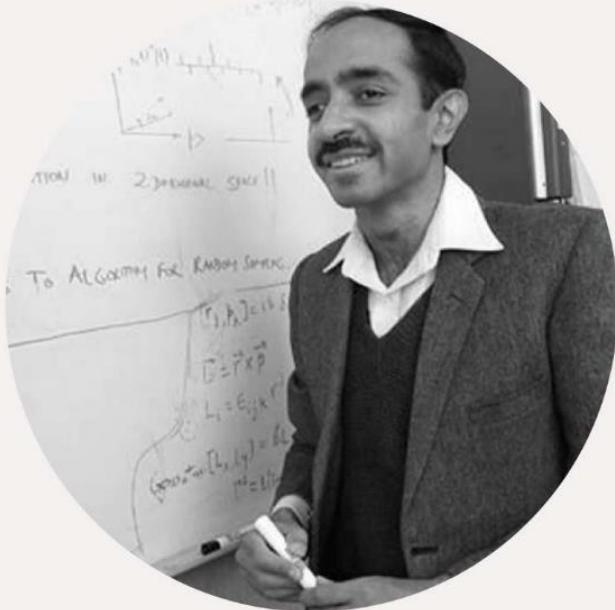
Peter Shor



Shor's algorithm for finding prime factors of an integer

1995

Lov Grover



Search algorithm in unstructured space

1990s

Various Groups

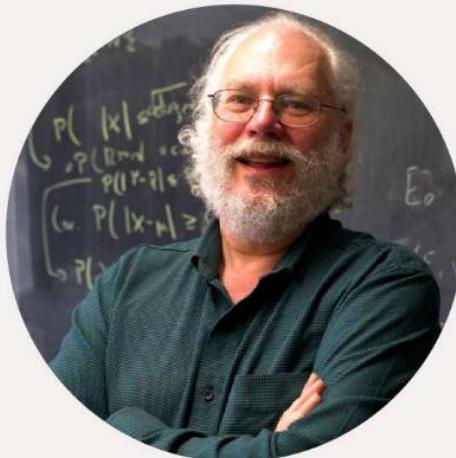


Simulation of quantum systems

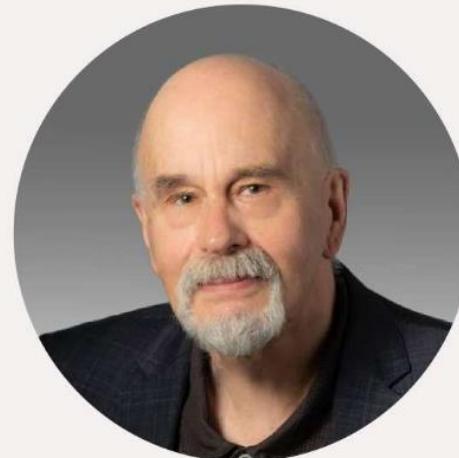
Error-correcting Code

Enables the modern quantum computers

1996



Peter Shor



Robert Calderbank



Andrew Steane



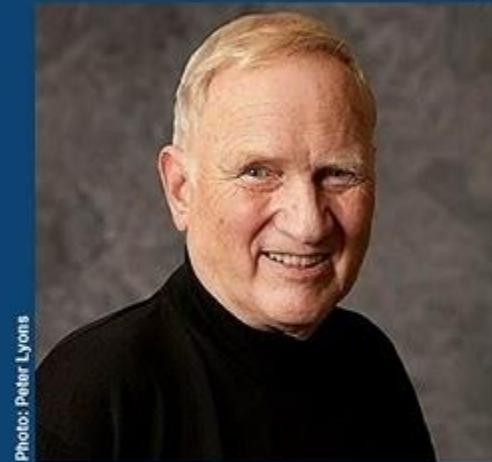
NOBELPRISET I FYSIK 2022

THE NOBEL PRIZE IN PHYSICS 2022



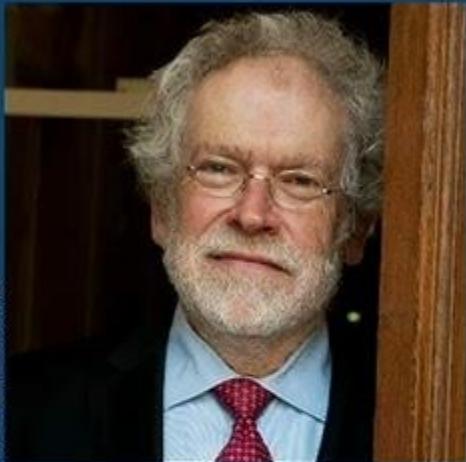
Alain Aspect

Université Paris-Saclay &
École Polytechnique, France



John F. Clauser

J.F. Clauser & Assoc.,
USA



Anton Zeilinger

University of Vienna,
Austria

*"för experiment med sammanflätade fotoner som påvisat brott mot Bell-olikheter och
banat väg för kvantinformationsvetenskap"*

*"for experiments with entangled photons, establishing the violation of Bell inequalities and
pioneering quantum information science"*

#nobelprize

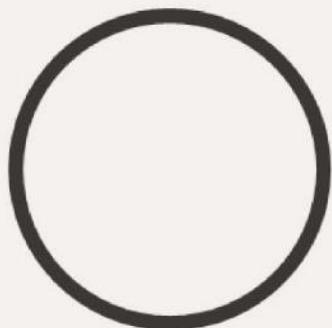
THE
NOBEL
PRIZE

Explaining Qubits: In Brief

Unit of Computation

Classical

OFF



ON



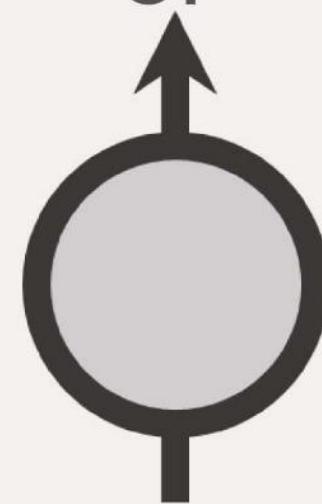
1 **X** 0

Quantum

DOWN

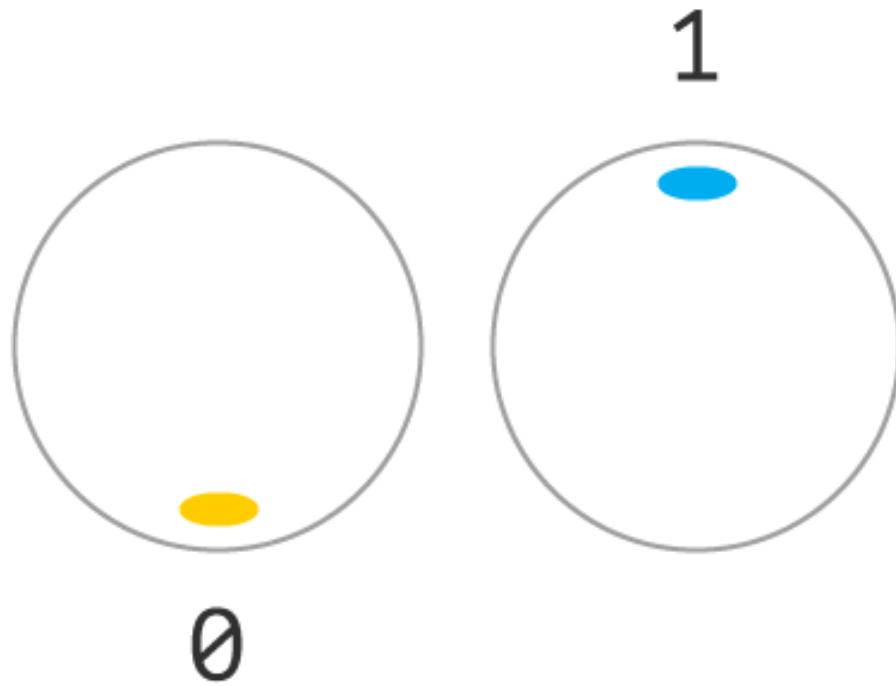


UP

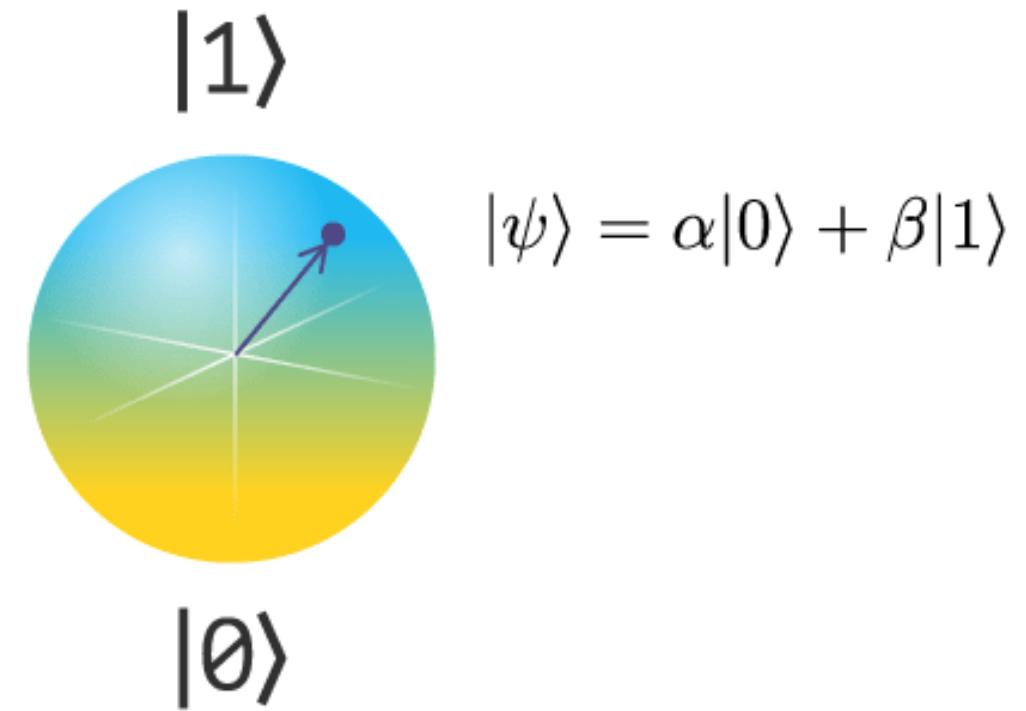


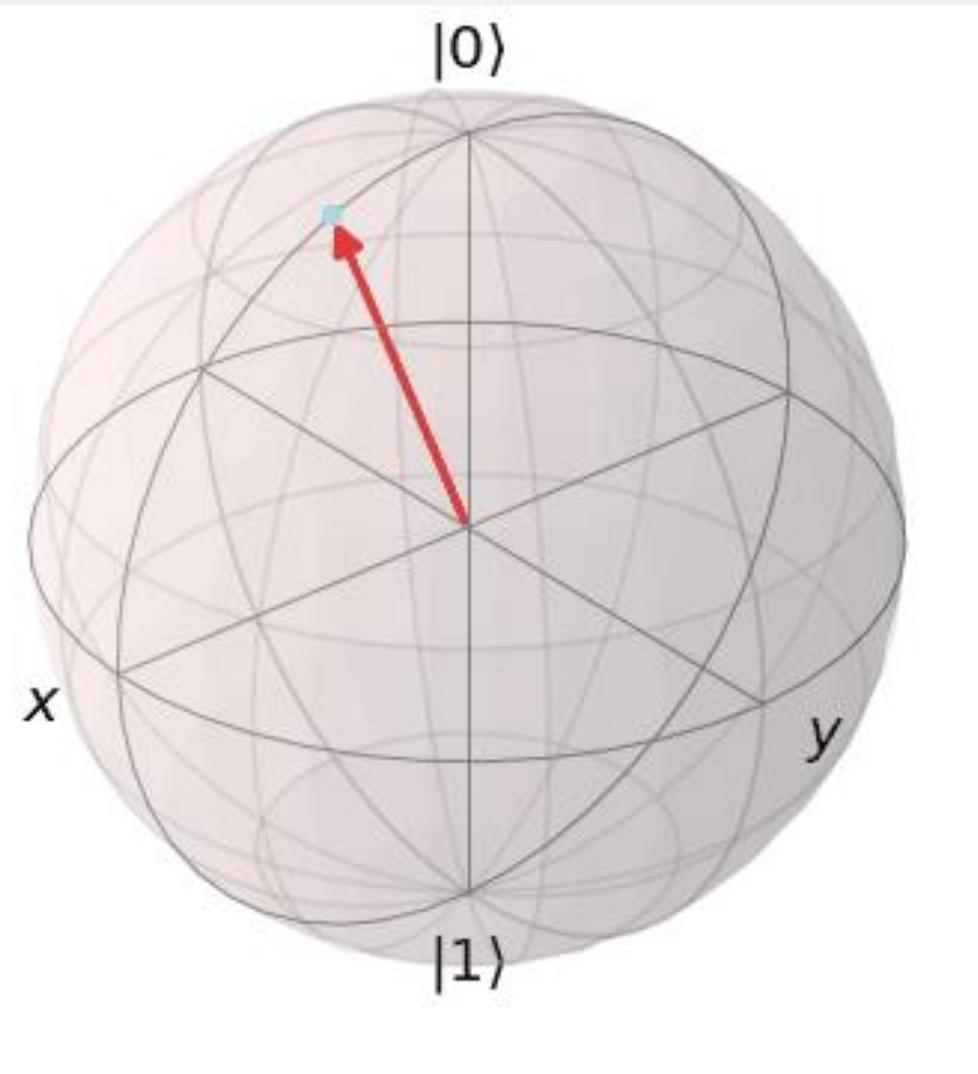
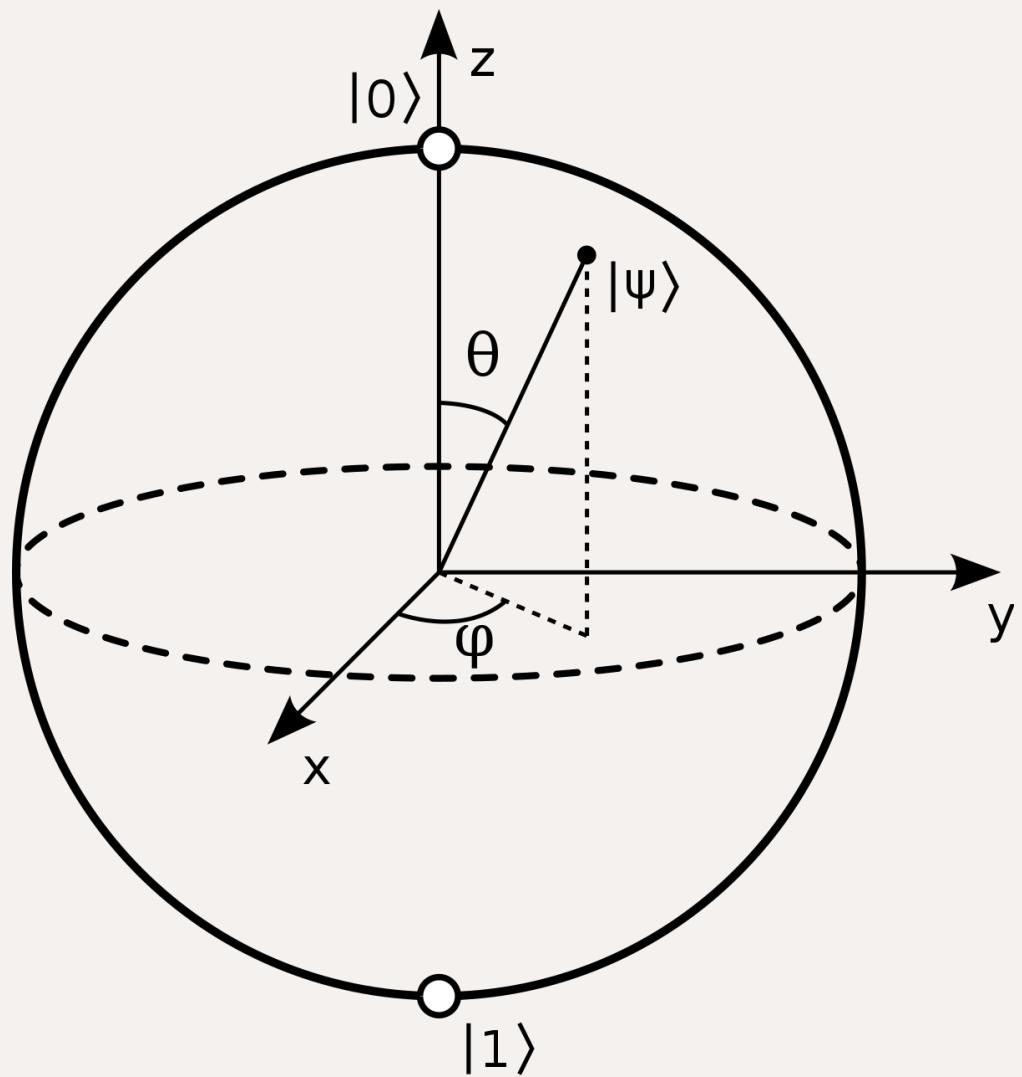
1 **•** 0

Bit

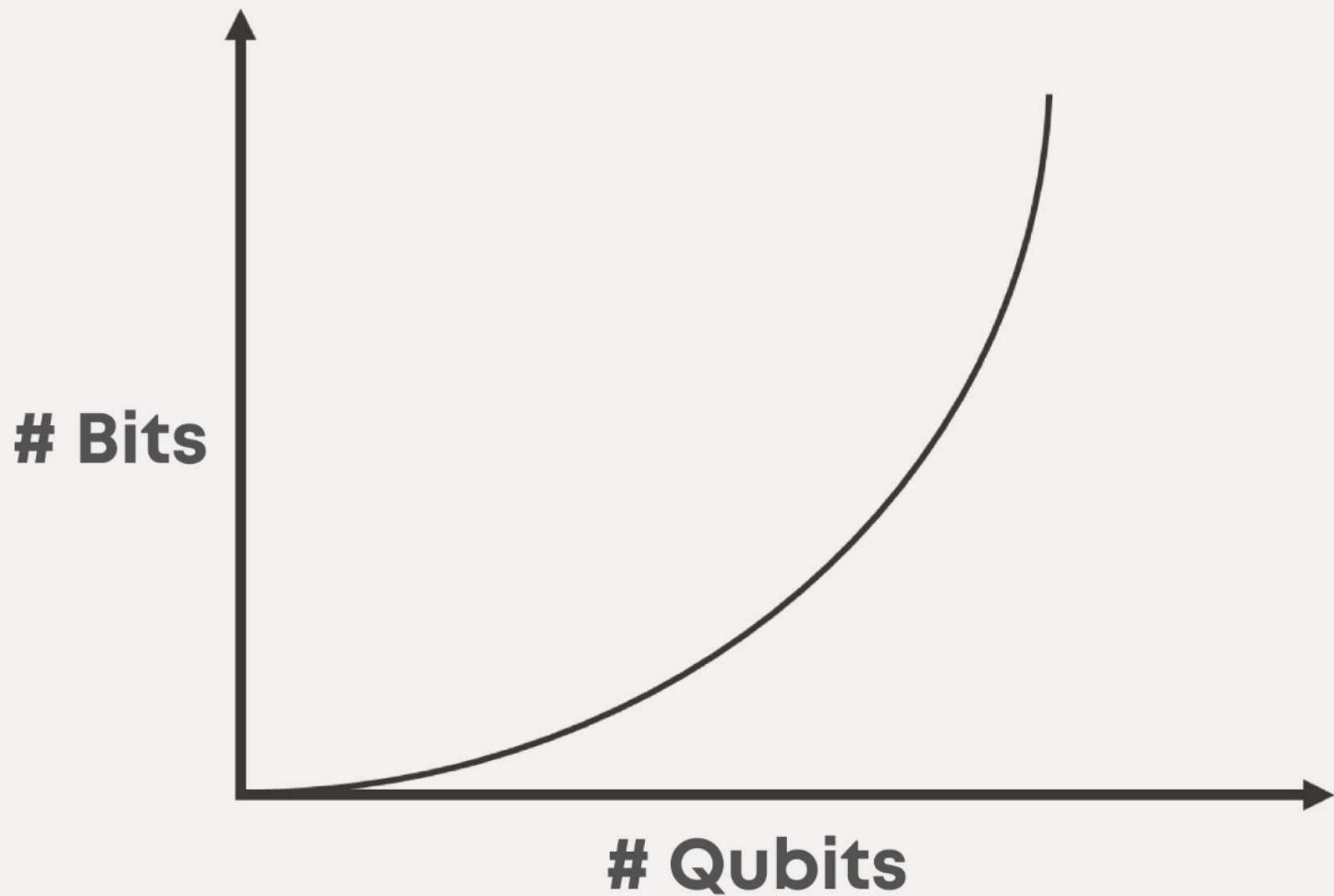


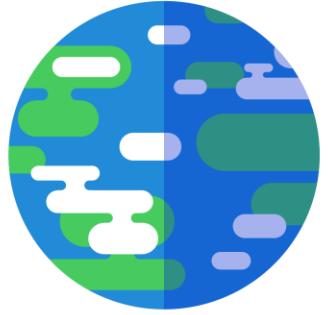
Qubit





Exponential Information Resources Initially Motivates QC

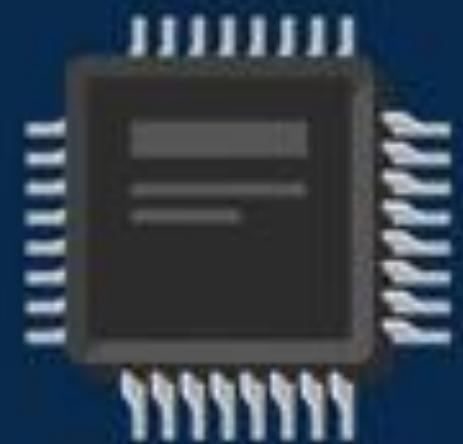




kurzgesagt
in a nutshell



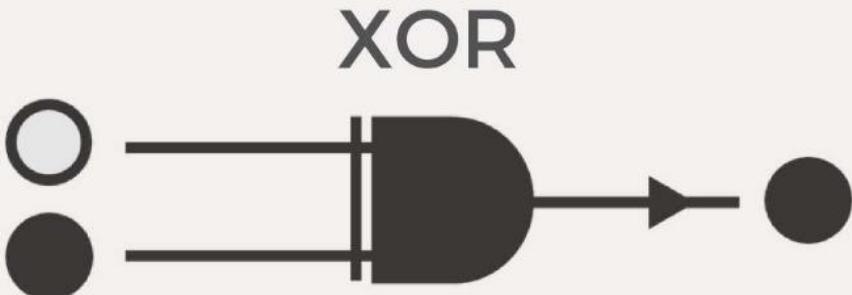
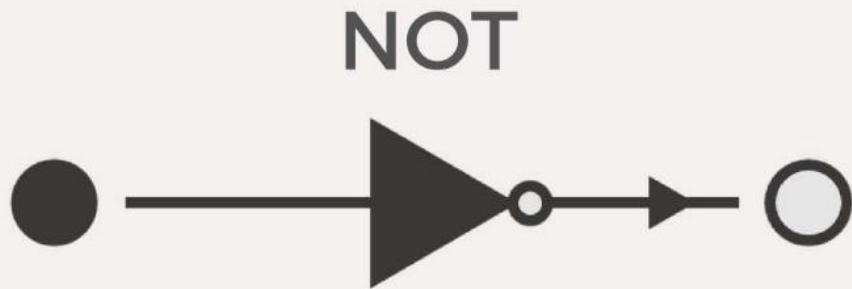
<https://www.youtube.com/watch?v=JhHMJCUmq28>



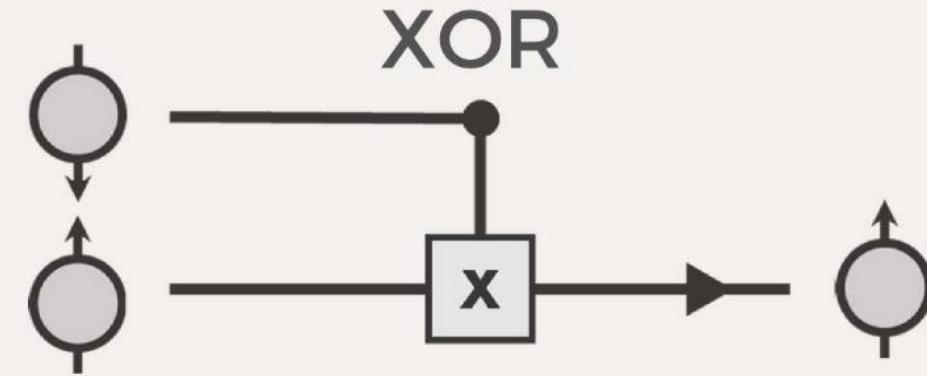
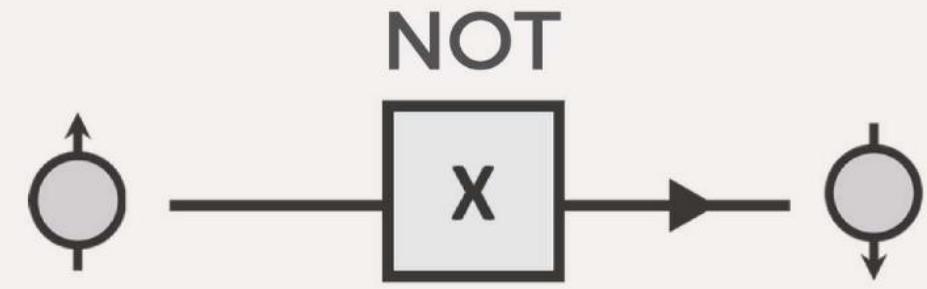
circuit chip

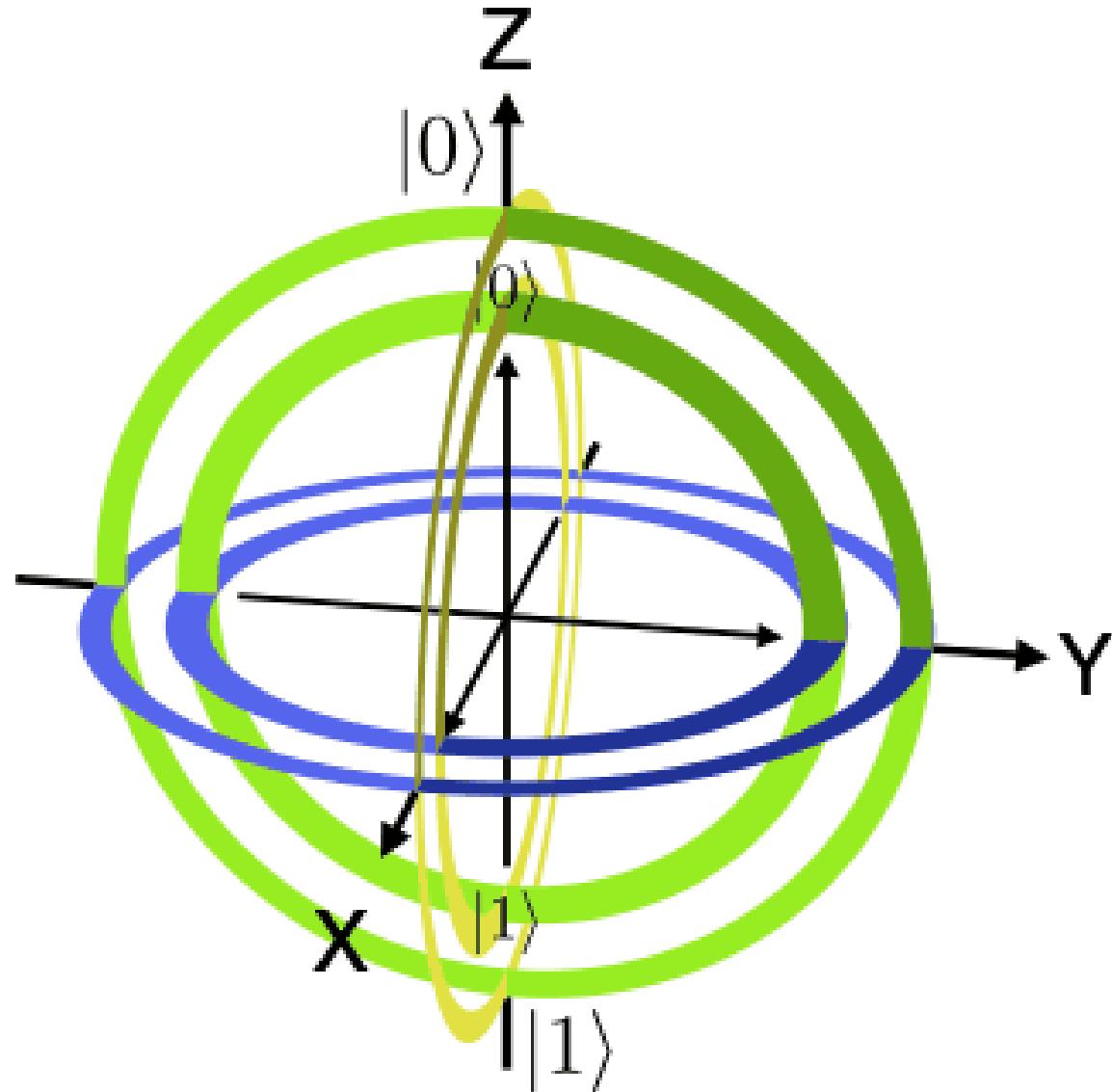
Operations on Qubits

Classical



Quantum

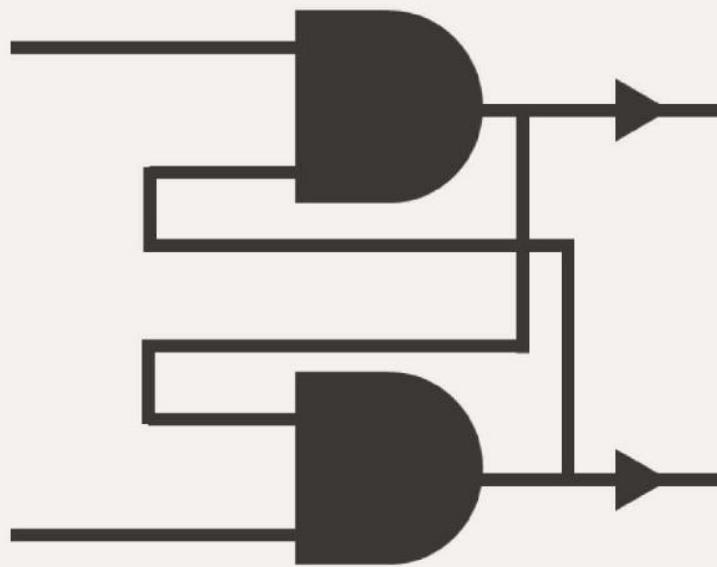




Algorithm: Combination of operations

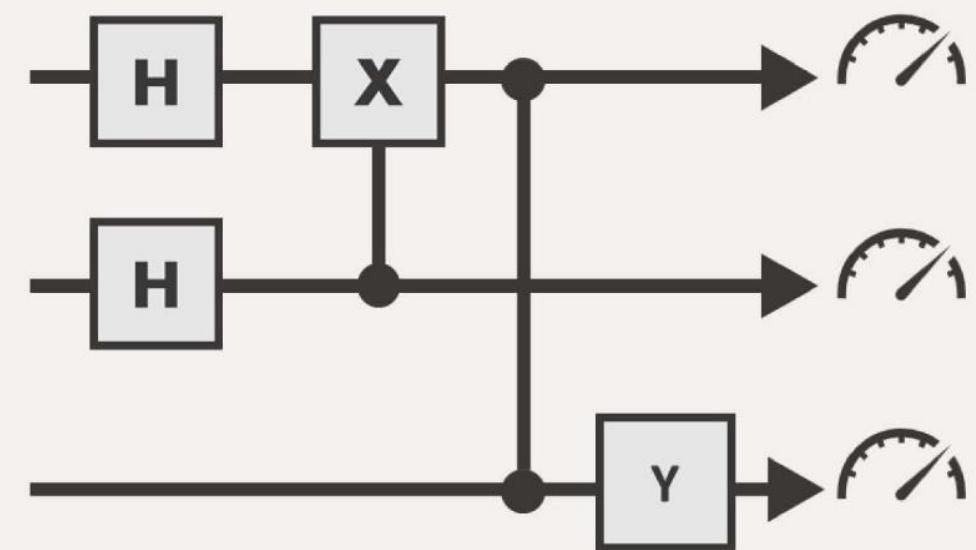
Classical

"Circuit"



Quantum

"Quantum Circuit"







Quantum Computing

- Operates with qubits that can represent 0 and 1 or both simultaneously
- Power increments dramatically with the number of qubits
- High error rates and need to be stored at ultracold temperature
- Best for complex tasks like optimization, data analysis and simulation



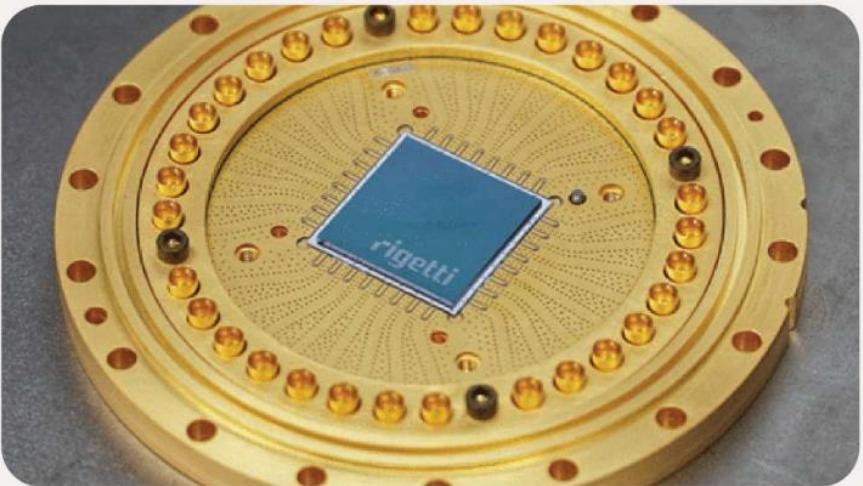
Classical computing

- Operate transistors that can only depict either 0 or 1
- Power increments in 1:1 ratio with the number of transistors
- Low error rates and can perform at room temperature
- Best at performing everyday tasks



Vs.

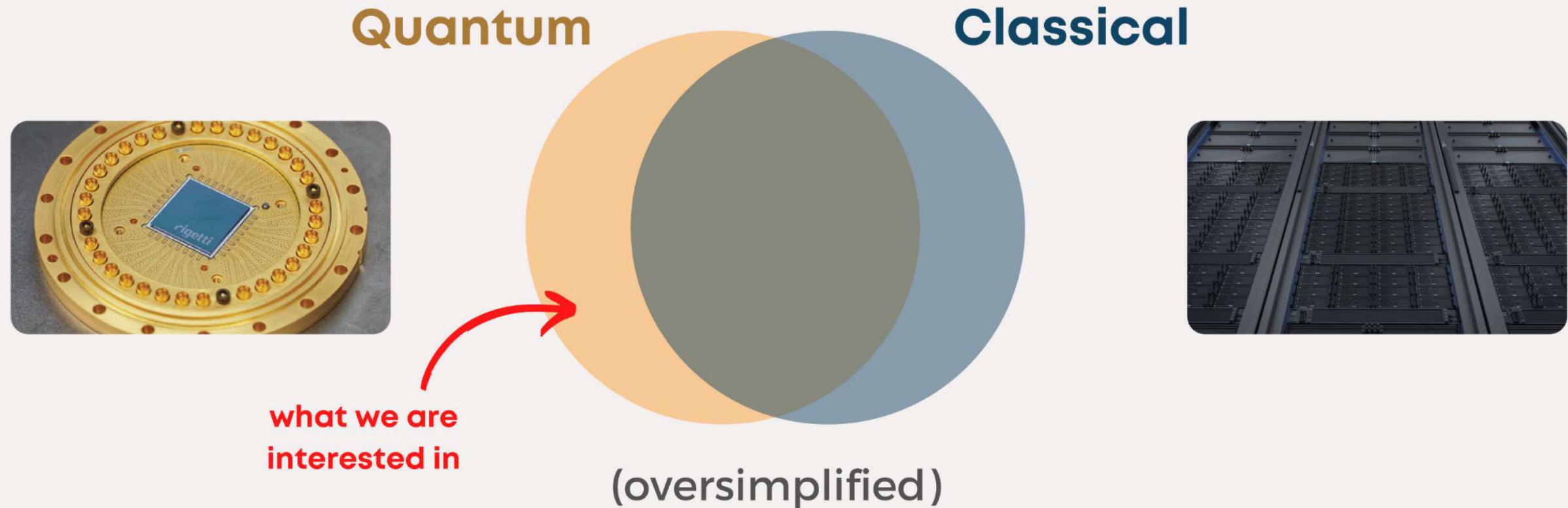
Quantum Computers are NOT to replace classical computers (even if they want to)



Ref:

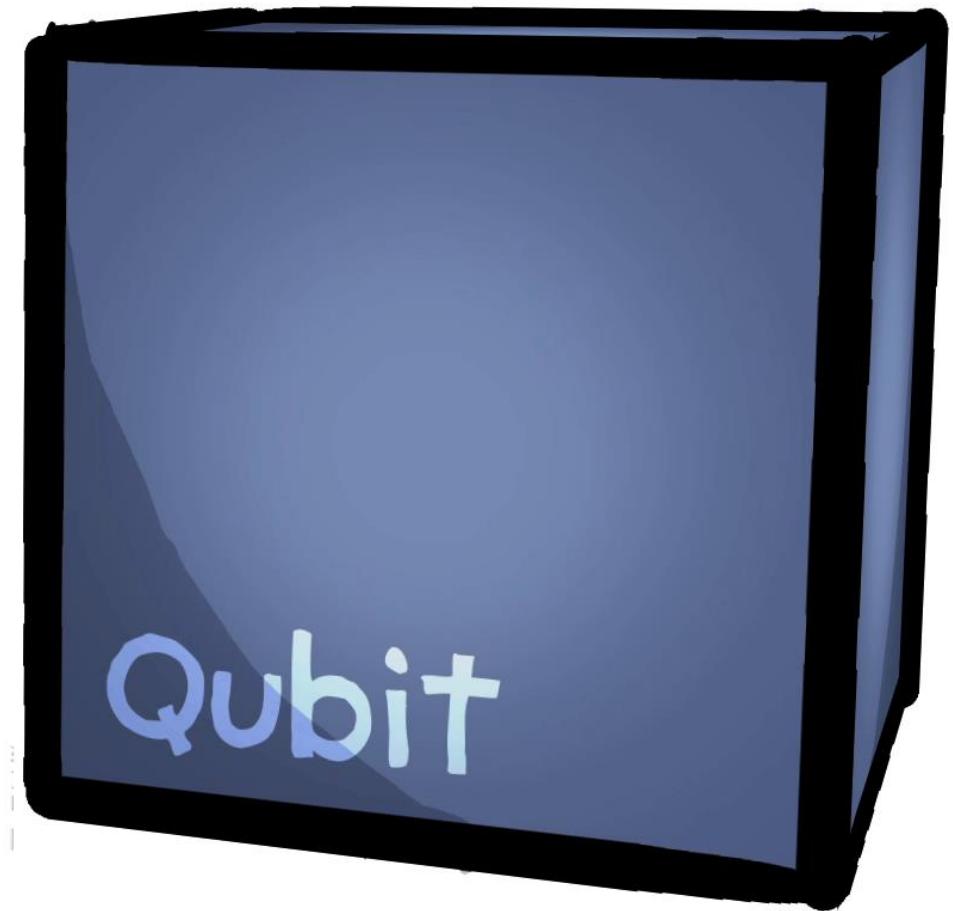
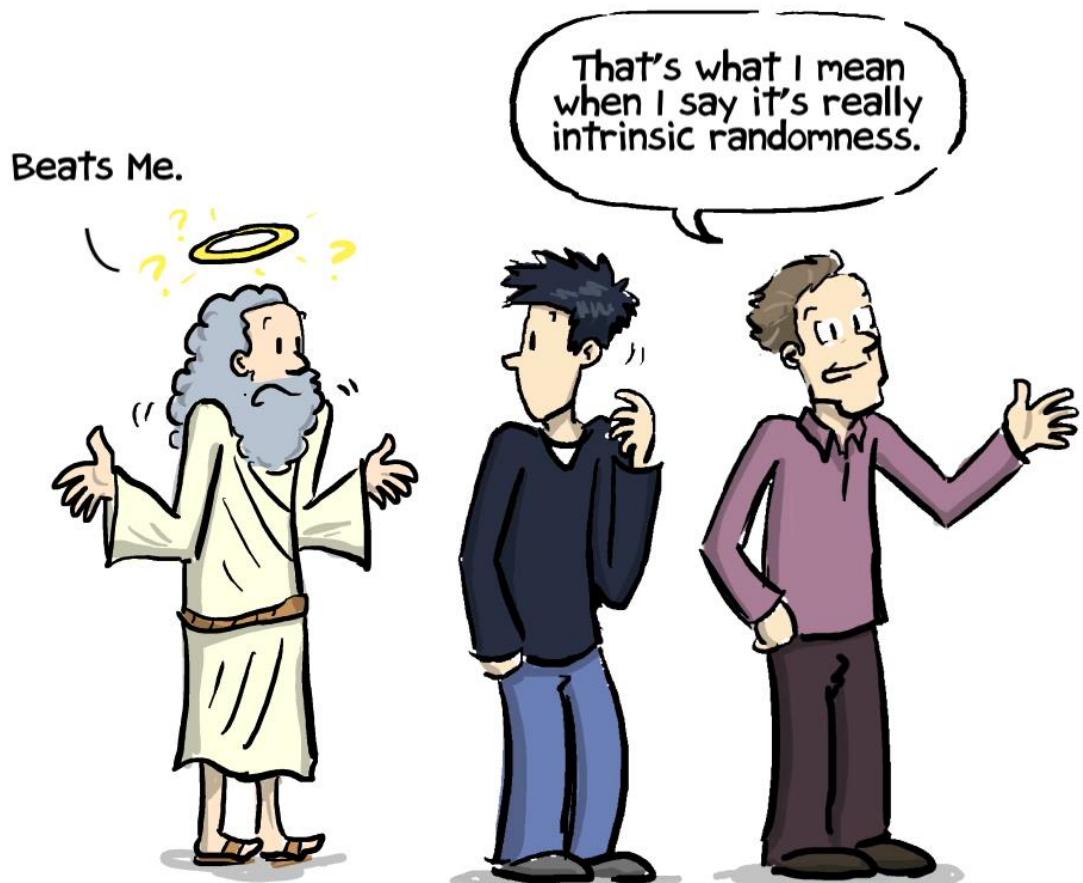
L. Gomes, "Quantum computing: Both here and not here," in IEEE Spectrum, vol. 55, no. 4, pp. 42-47, April 2018, doi: 10.1109/MSPEC.2018.8322045.

Quantum Computers are special-purpose machines

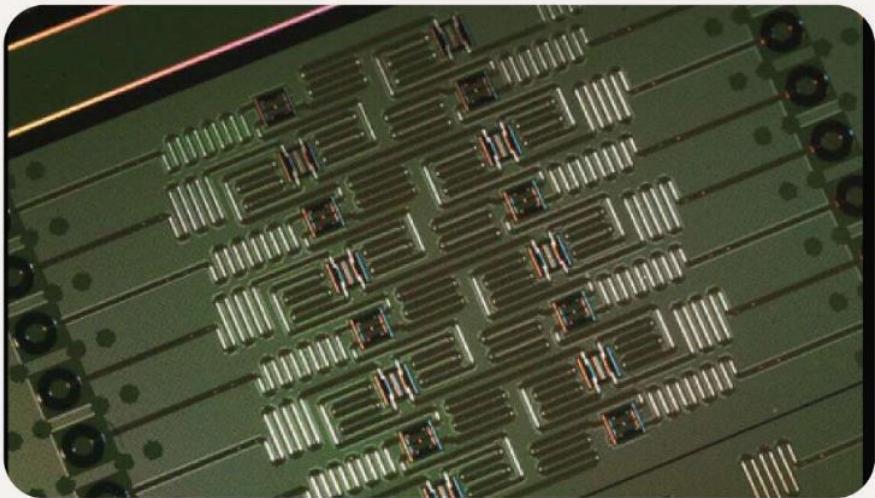


Ref:

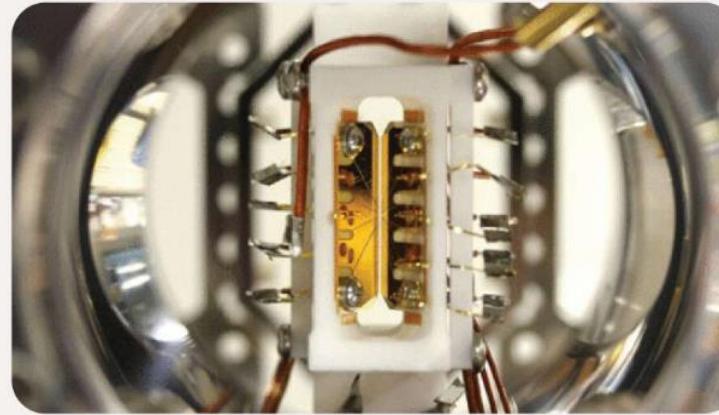
L. Gomes, "Quantum computing: Both here and not here," in IEEE Spectrum, vol. 55, no. 4, pp. 42-47, April 2018, doi: 10.1109/MSPEC.2018.8322045.



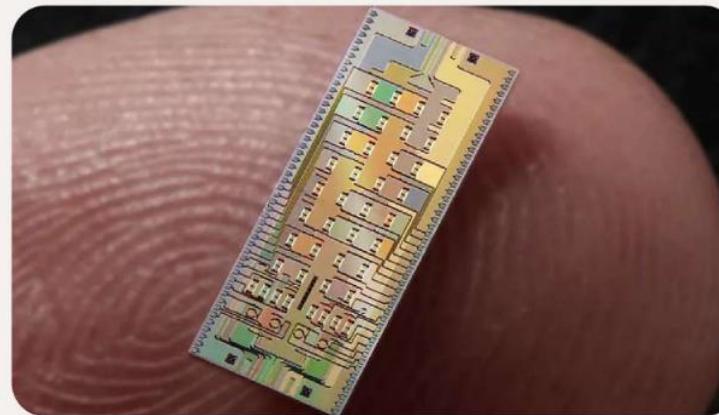
How does quantum computer chip look like?



Google (Superconducting)



**IonQ
(Ions Trap)**



**Xanadu
(Photonics)**

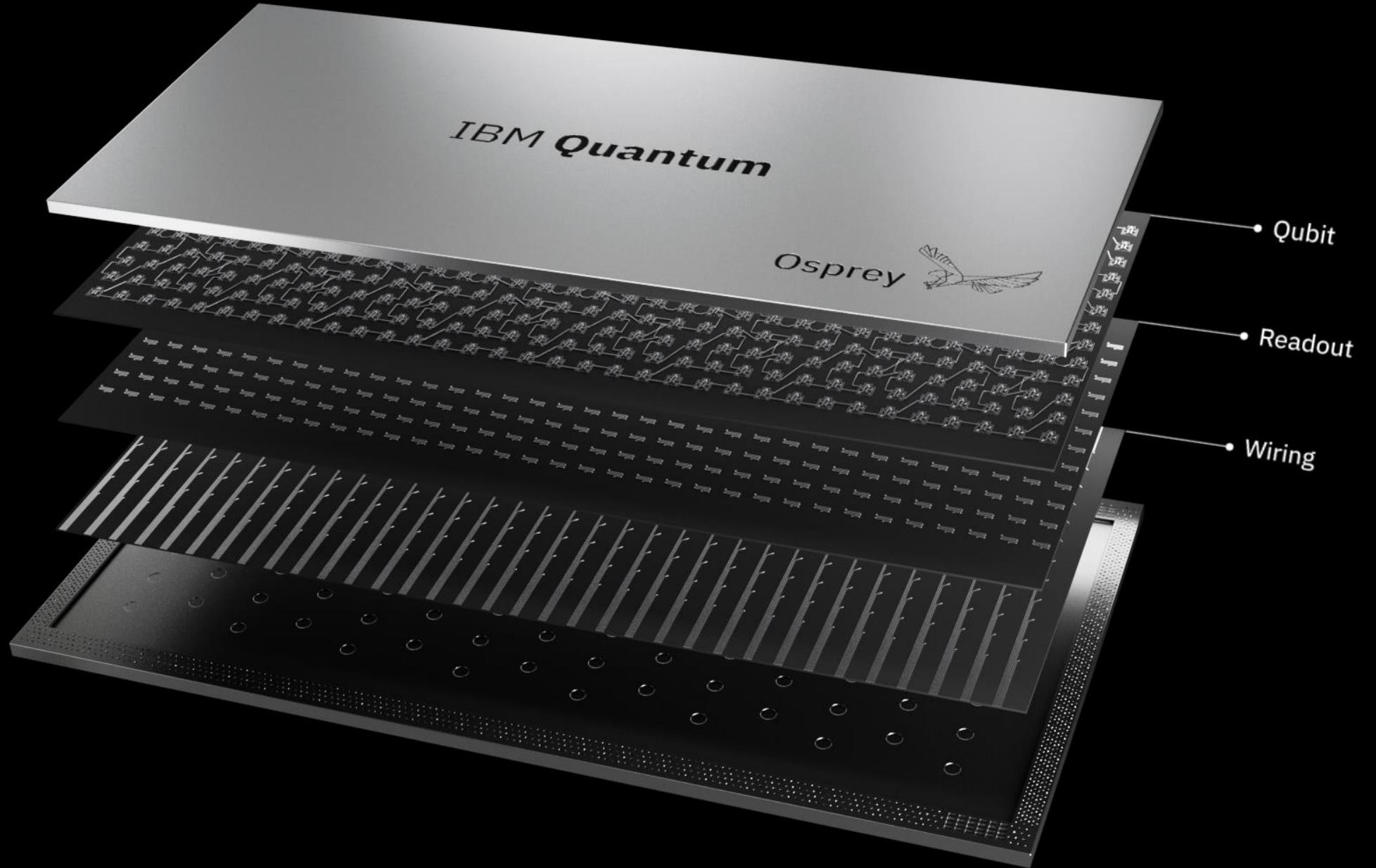
Ref:

L. Gomes, "Quantum computing: Both here and not here," in IEEE Spectrum, vol. 55, no. 4, pp. 42-47, April 2018, doi: 10.1109/MSPEC.2018.8322045.

Qubit Scaling on Quantum Processors



NO. OF QUBITS



Development Roadmap

Executed by IBM ✓
On target ✅

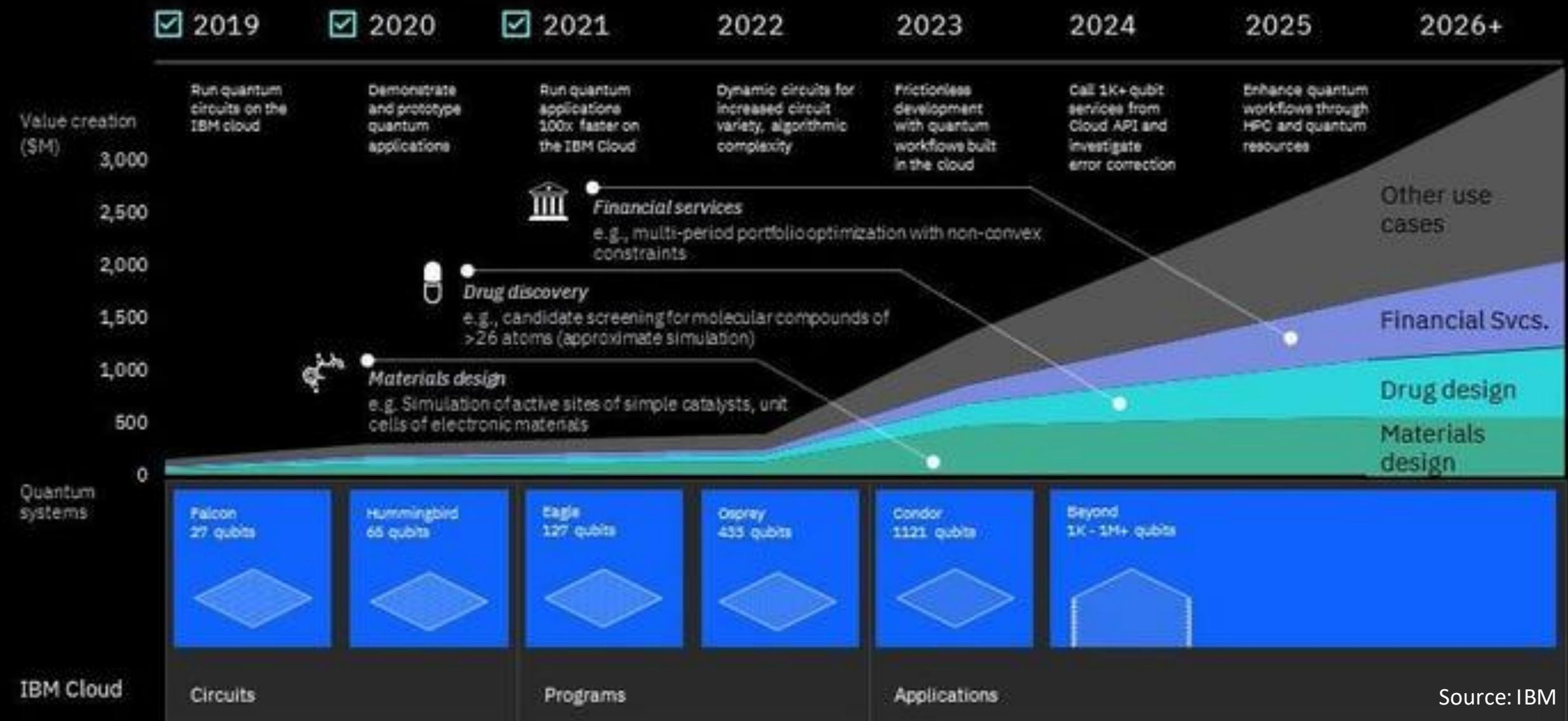
IBM Quantum

2019 ✓	2020 ✓	2021 ✓	2022	2023	2024	2025	Beyond 2026	
Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime	
Model Developers				Prototype quantum software applications →	Quantum software applications			
Algorithm Developers		Quantum algorithm and application modules ✓	Machine learning Natural science Optimization	Quantum Serverless	Intelligent orchestration	Circuit Knitting Toolbox	Circuit libraries	
Kernel Developers	Circuits	Qiskit Runtime	Dynamic circuits ↗	Threaded primitives	Error suppression and mitigation		Error correction	
System Modularity	Falcon 27 qubits ✓	Hummingbird 65 qubits ✓	Eagle 127 qubits ✓	Osprey 433 qubits ↗	Condor 1,121 qubits	Flamingo 1,386+ qubits	Kookaburra 4,158+ qubits	Scaling to 10K-100K qubits with classical and quantum communication
				Heron 133 qubits x p	Crossbill 408 qubits			

Market Analysis by Boston Consulting Group

BCG predicts Quantum computing's inflection point around the corner

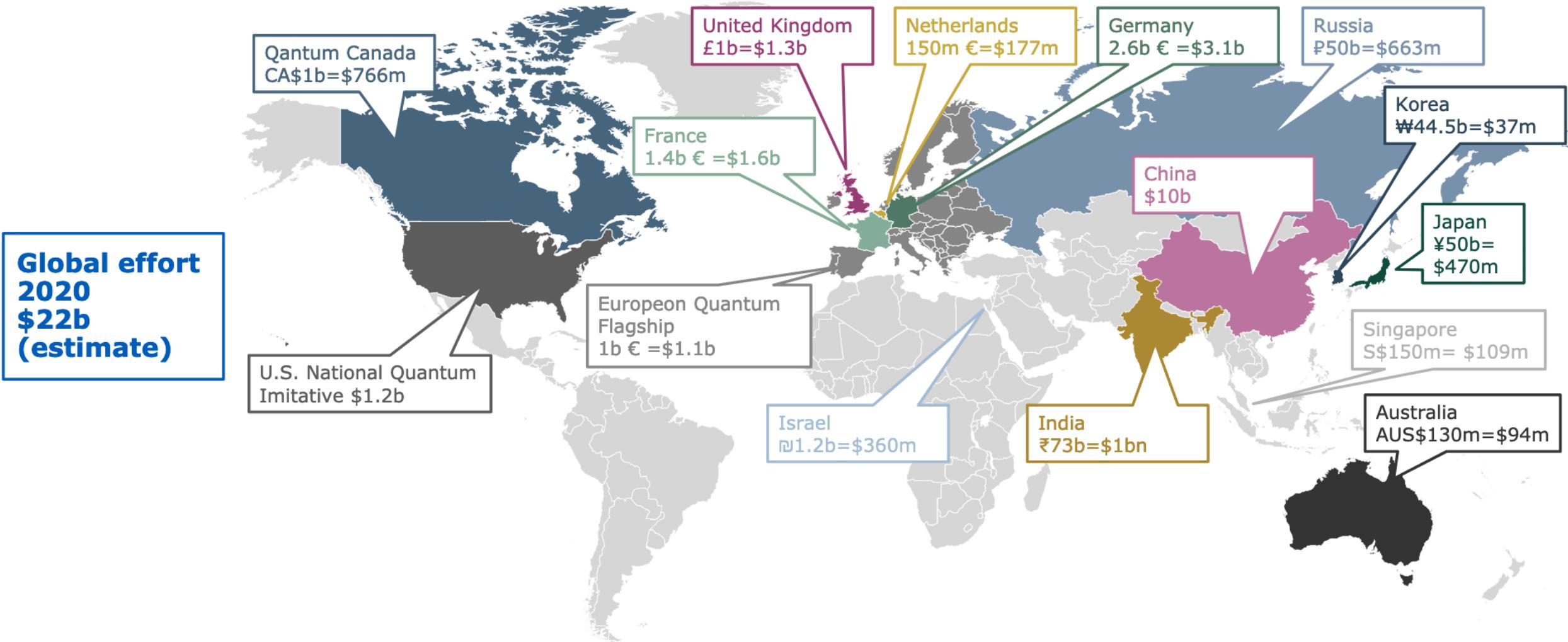
→ poised to create \$3B+ value by 2024



Quantum Computing Ecosystem

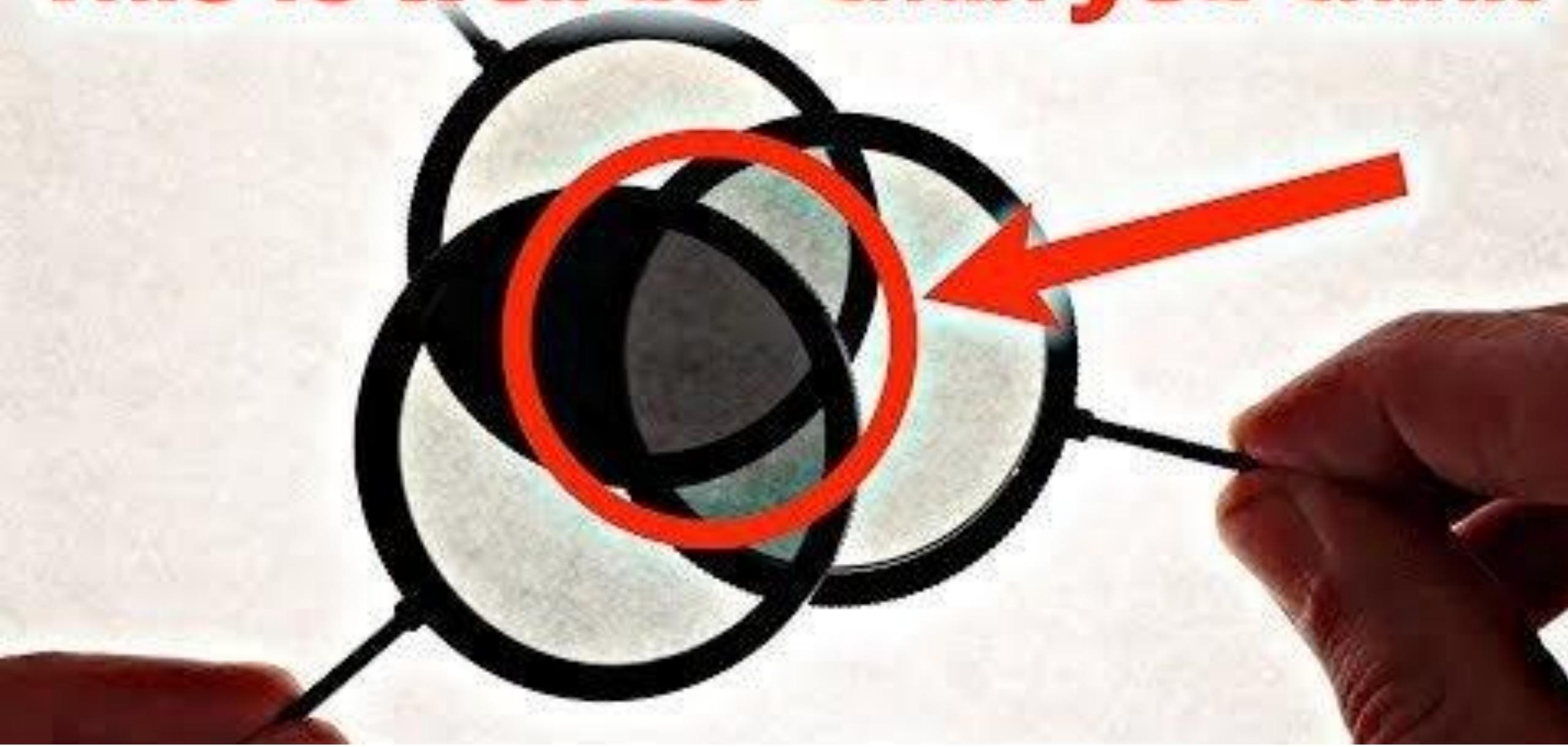


Quantum Computing Efforts Worldwide



What to look forward to in
the workshop?

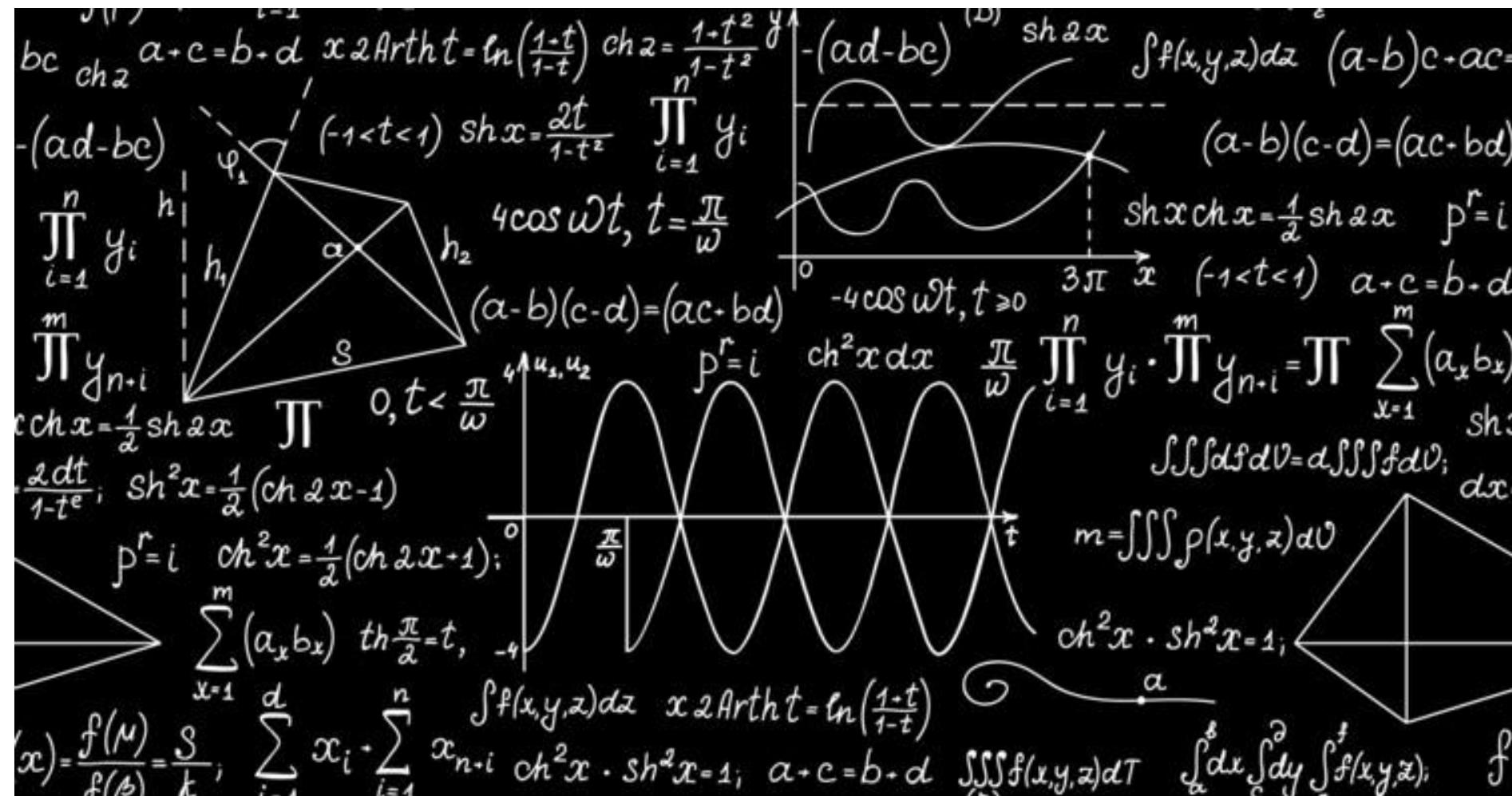
This is weirder than you think



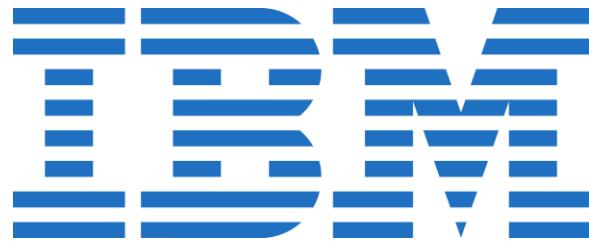
DON'T BE OVERWHELMED!

LOOK AT HARD CONCEPTS IN SIMPLE TERMS

<https://www.linkedin.com/pulse/math-quantum-computing-hard-concept-simple-terms-teddy-porfiris/>



Open-source python-based frameworks for quantum computing



<https://qiskit.org/>



PENNYLANE

<https://pennylane.ai/>



<https://quantumai.google/cirq>

The Journey of a Quantum Algorithm



IQM

IQM Quantum Computers

IQM is the European leader in superconducting quantum computers. We build quantum computers.

Computer Hardware Manufacturing · Espoo, Southern Finland · 22,876 followers

See all 194 employees on LinkedIn

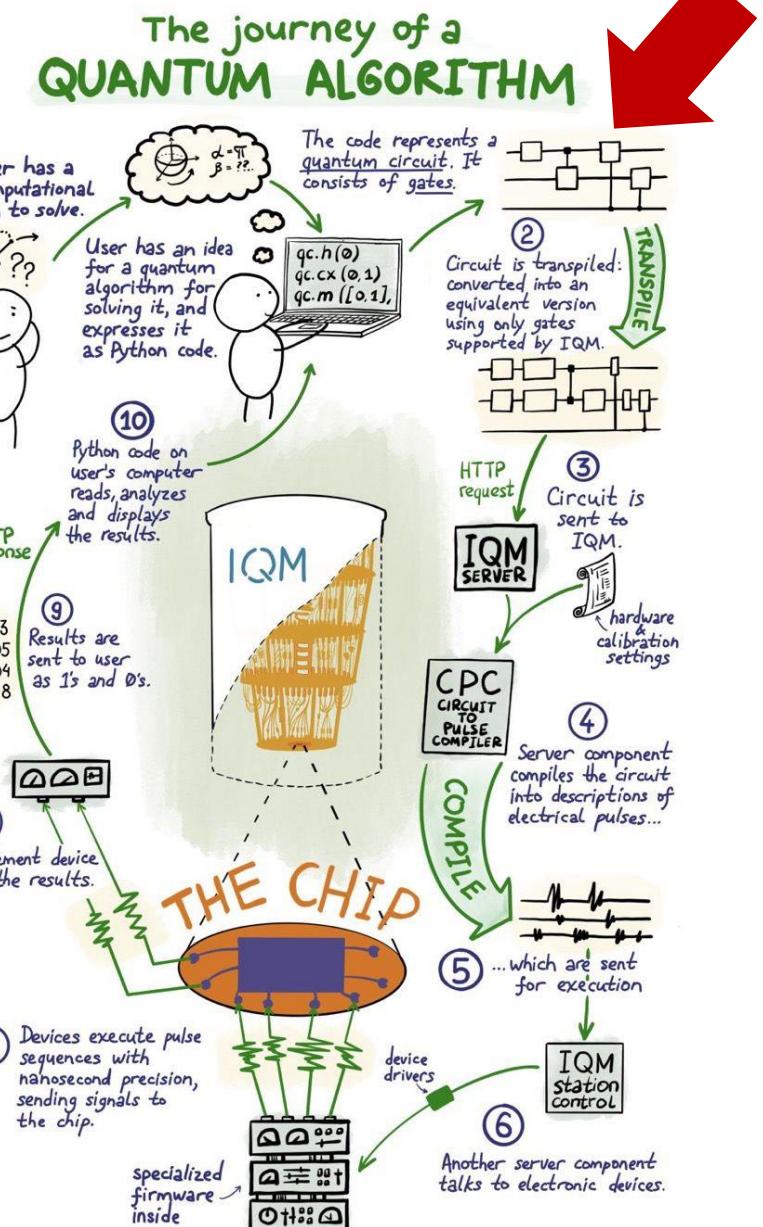
✓ Following **Visit website** **More**

IQM Quantum Computers @meetIQM

IQM is the Pan-European category leader in quantum computers.

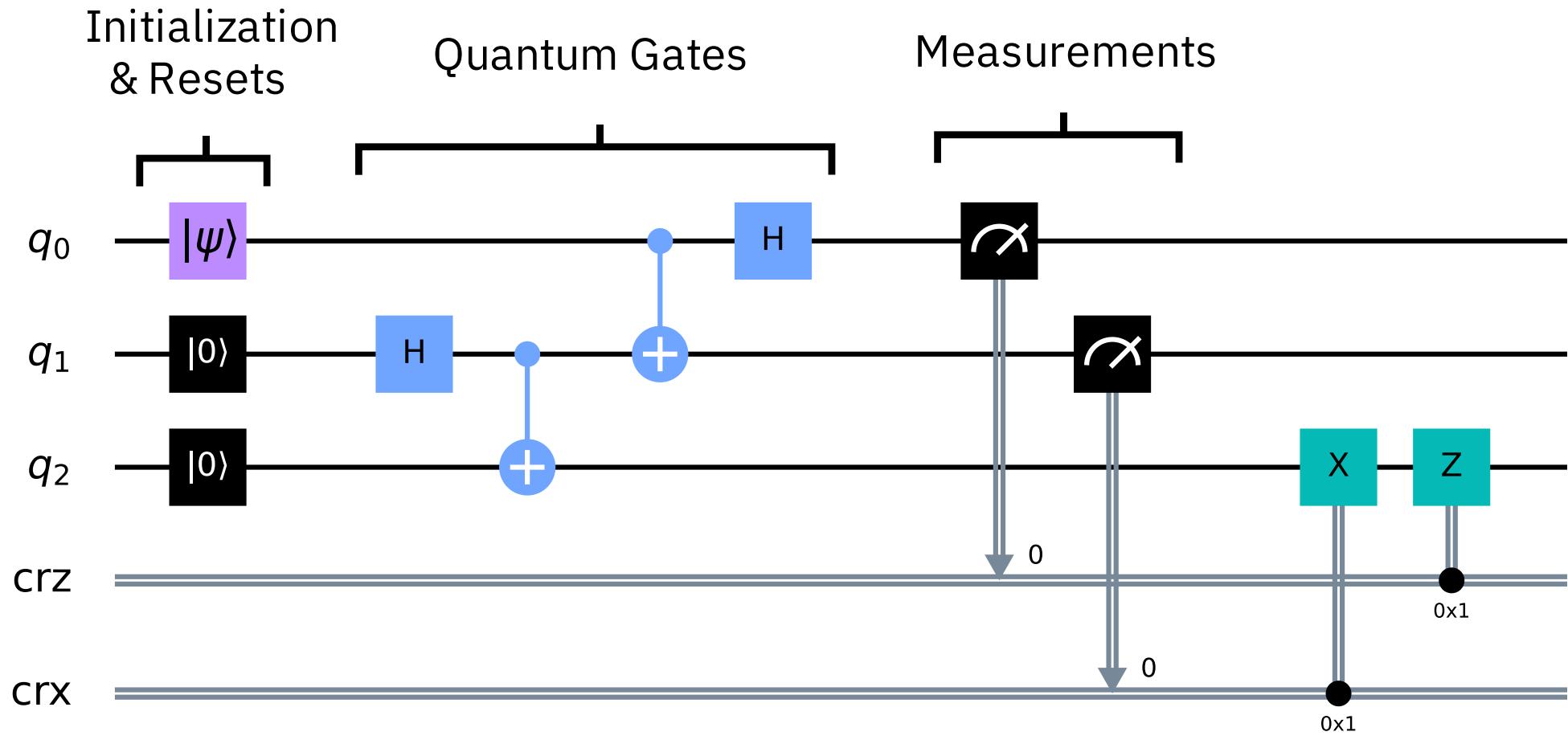
We build quantum computers.

Source:
www.meetiqm.com

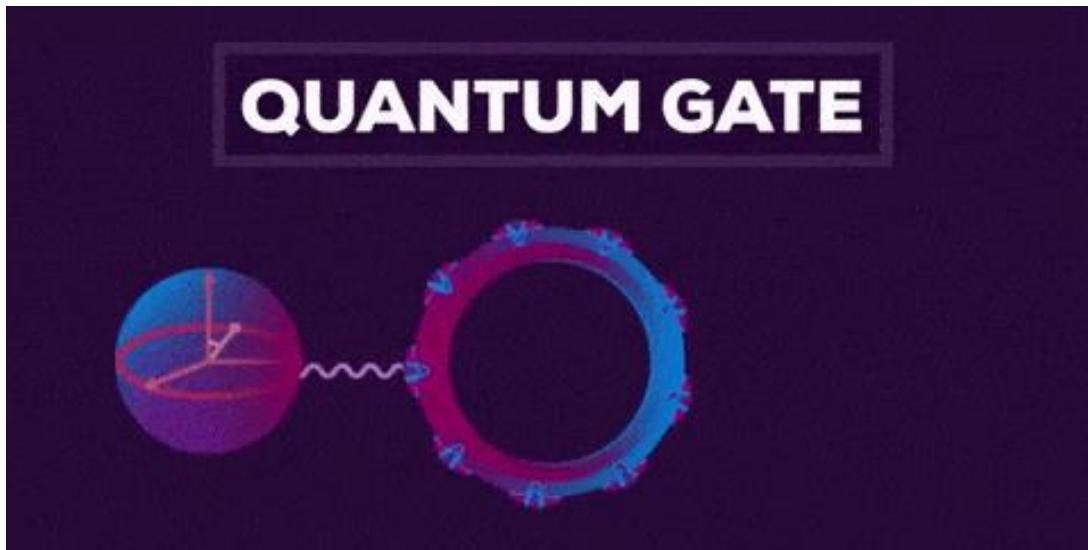
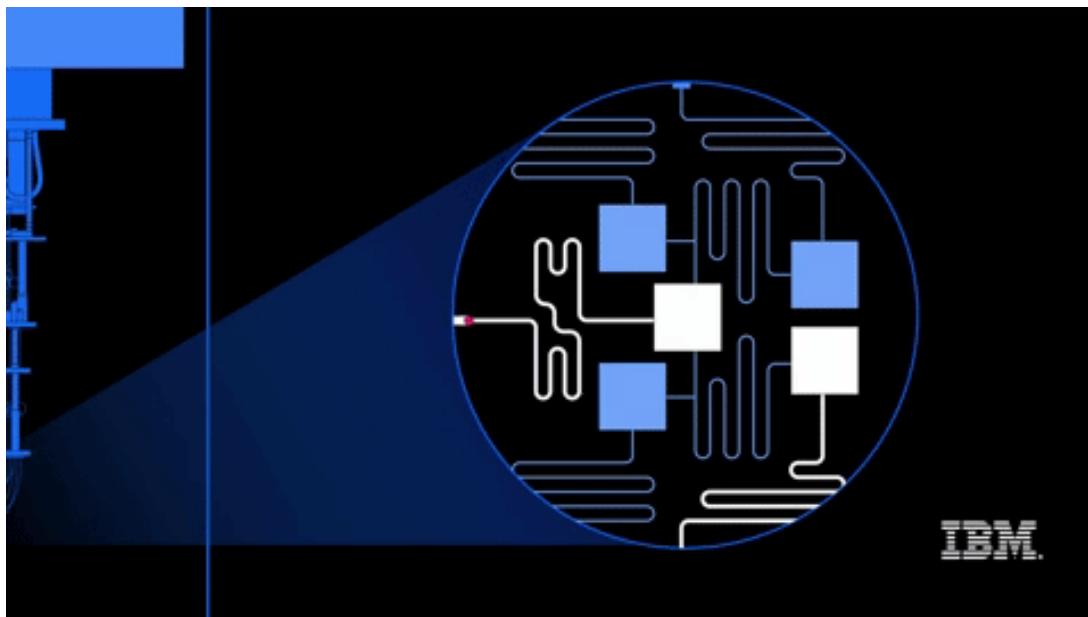


IQM

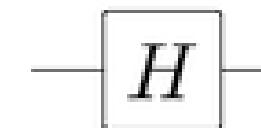
Copyright © 2022 IQM Quantum Computers. All rights reserved.



Classically Controlled
Quantum Gates

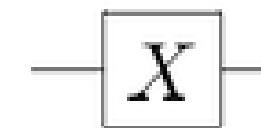


Hadamard



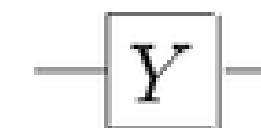
$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Pauli-X



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

Pauli-Y



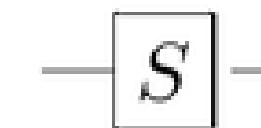
$$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

Pauli-Z



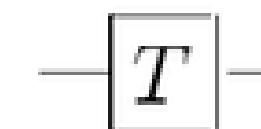
$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Phase

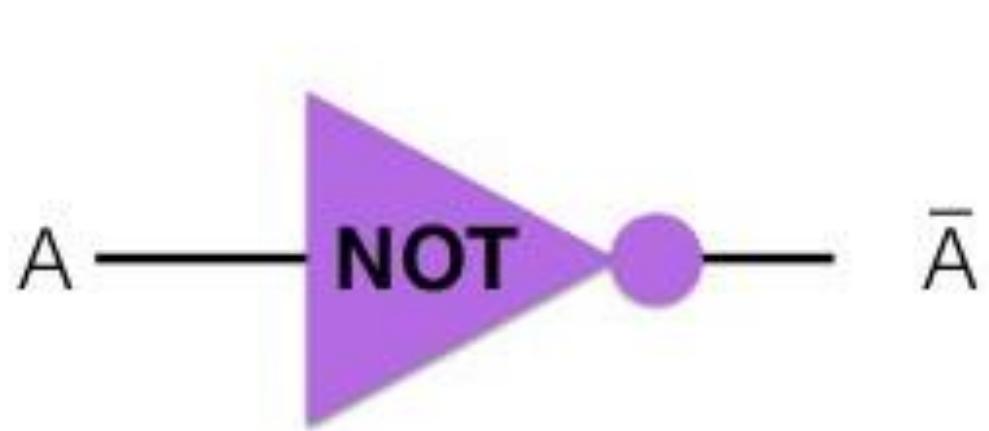


$$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$$

$\pi/8$

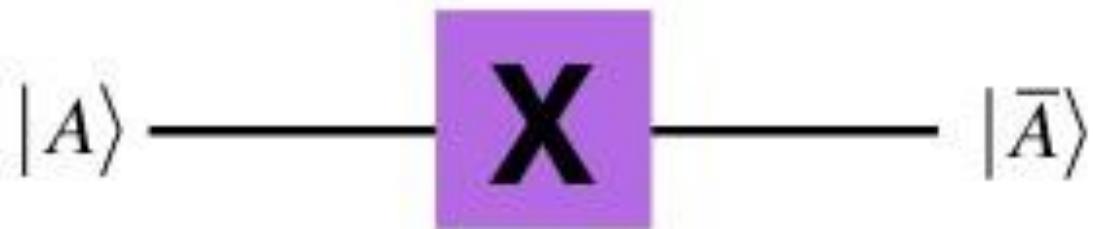


$$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$$



A	\bar{A}
0	1
1	0

PAULI X GATE



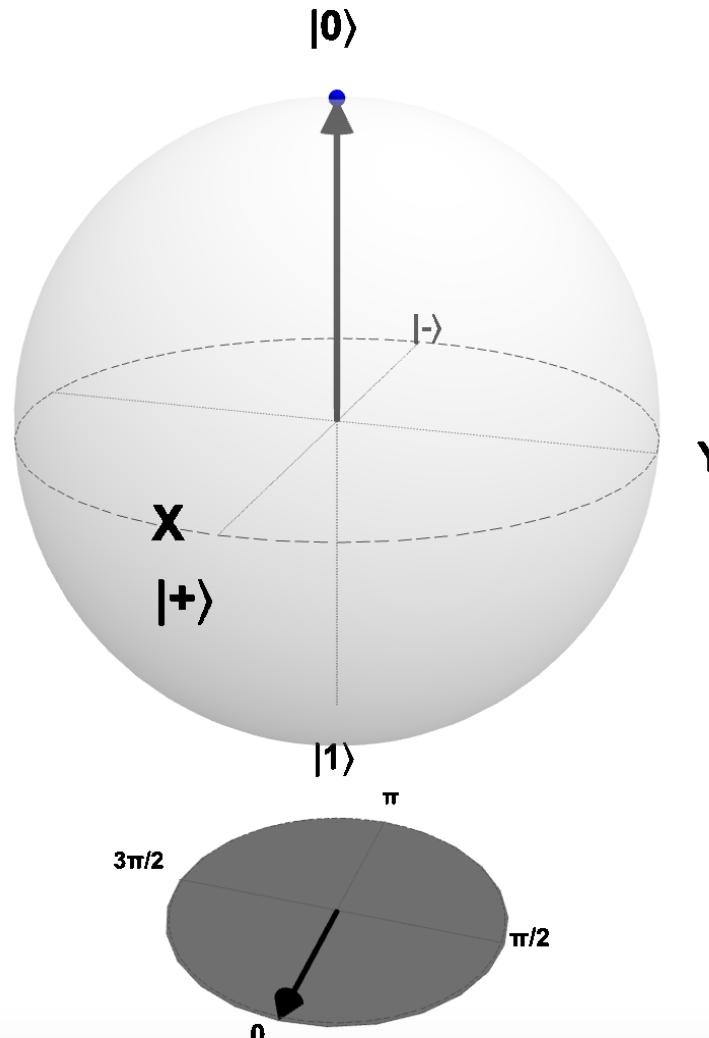
$ A\rangle$	$ \bar{A}\rangle$
0	1
1	0

$$|\psi\rangle = \sqrt{1.00}|0\rangle + (\sqrt{0.00})e^{i\theta}|1\rangle$$

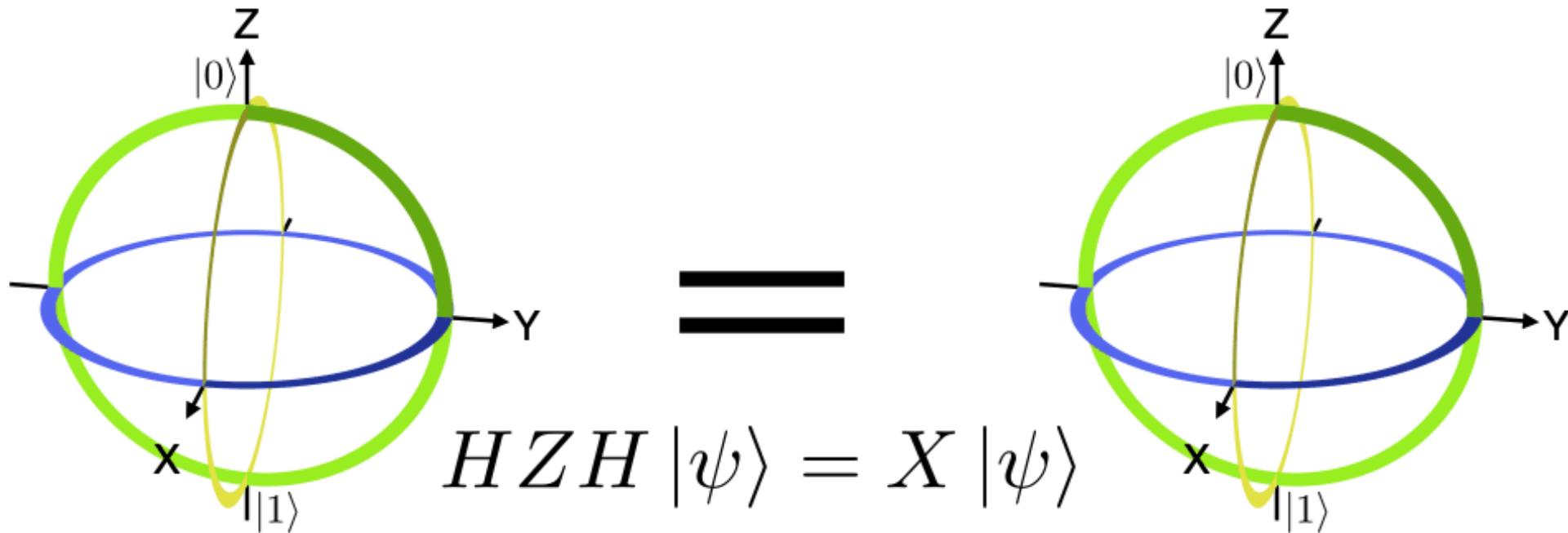
Prob of $|0\rangle$

1

0

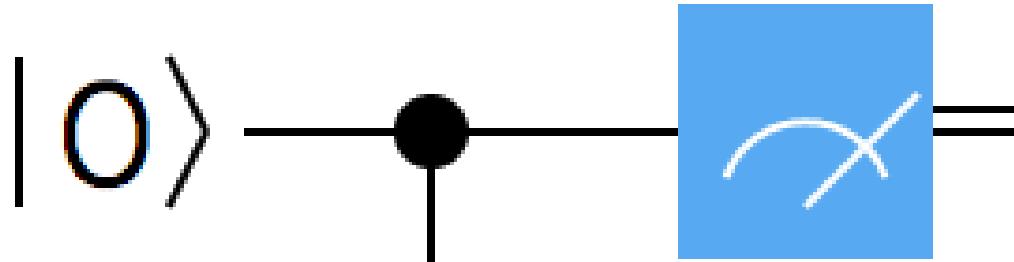


$ 0\rangle$	$ 1\rangle$
X	S
Y	S^\dagger
Z	T
H	T^\dagger
\bullet $\theta=\pi/8$	\circ $\theta=\pi/12$
Rx +θ	Rx -θ
Ry +θ	Ry -θ
Rz +θ	Rz -θ

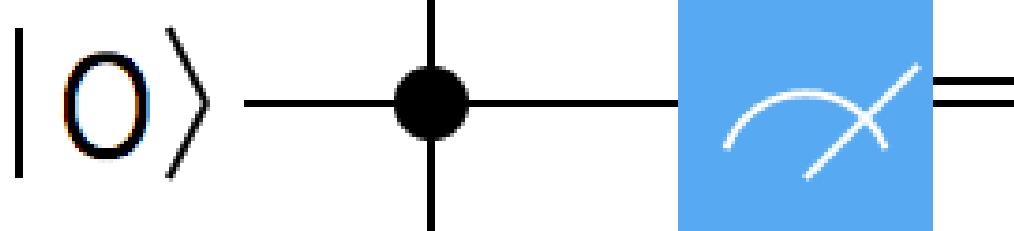


Two-Qubit and Multi Qubit Gates

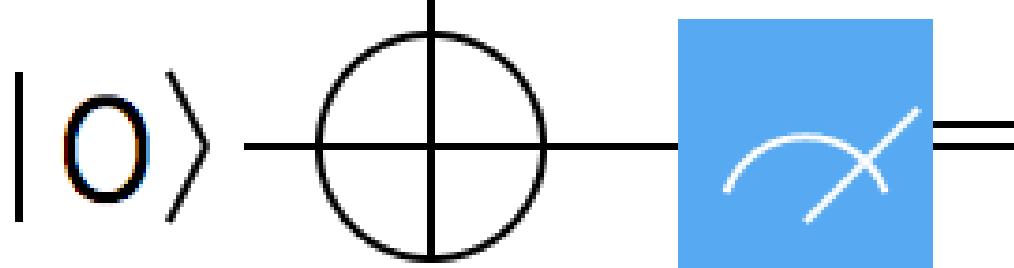
qubit1



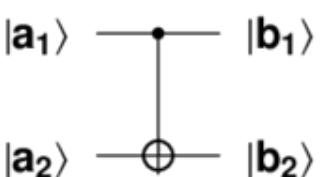
qubit2



qubit3

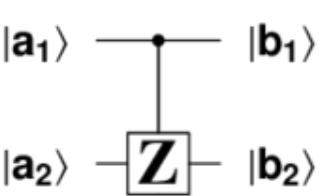


CNOT gate



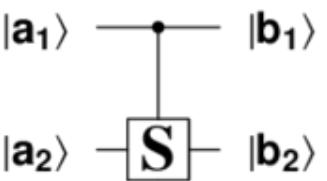
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Controlled - Z



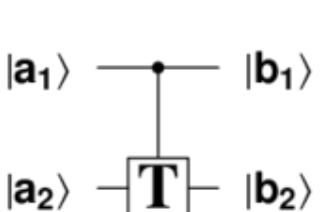
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Controlled - S



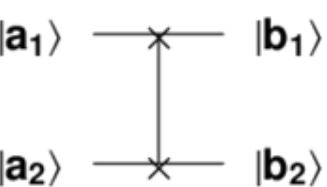
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & i \end{pmatrix}$$

Controlled - T

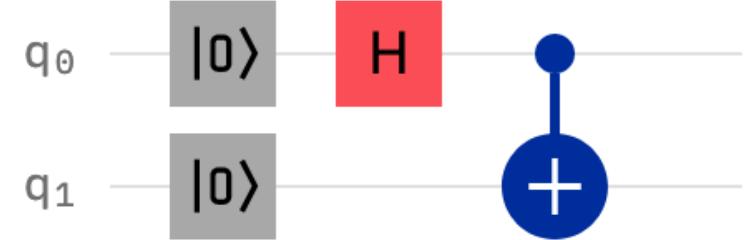


$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$$

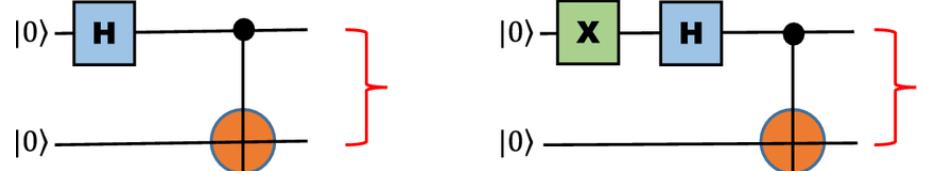
SWAP gate



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

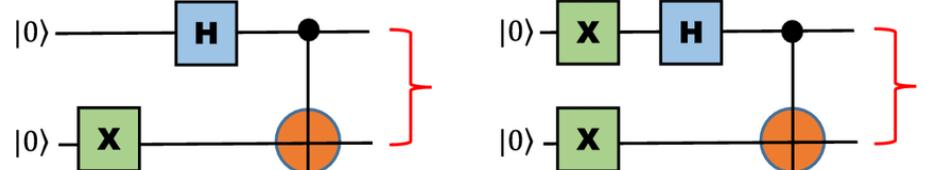


c_2



$$|\psi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

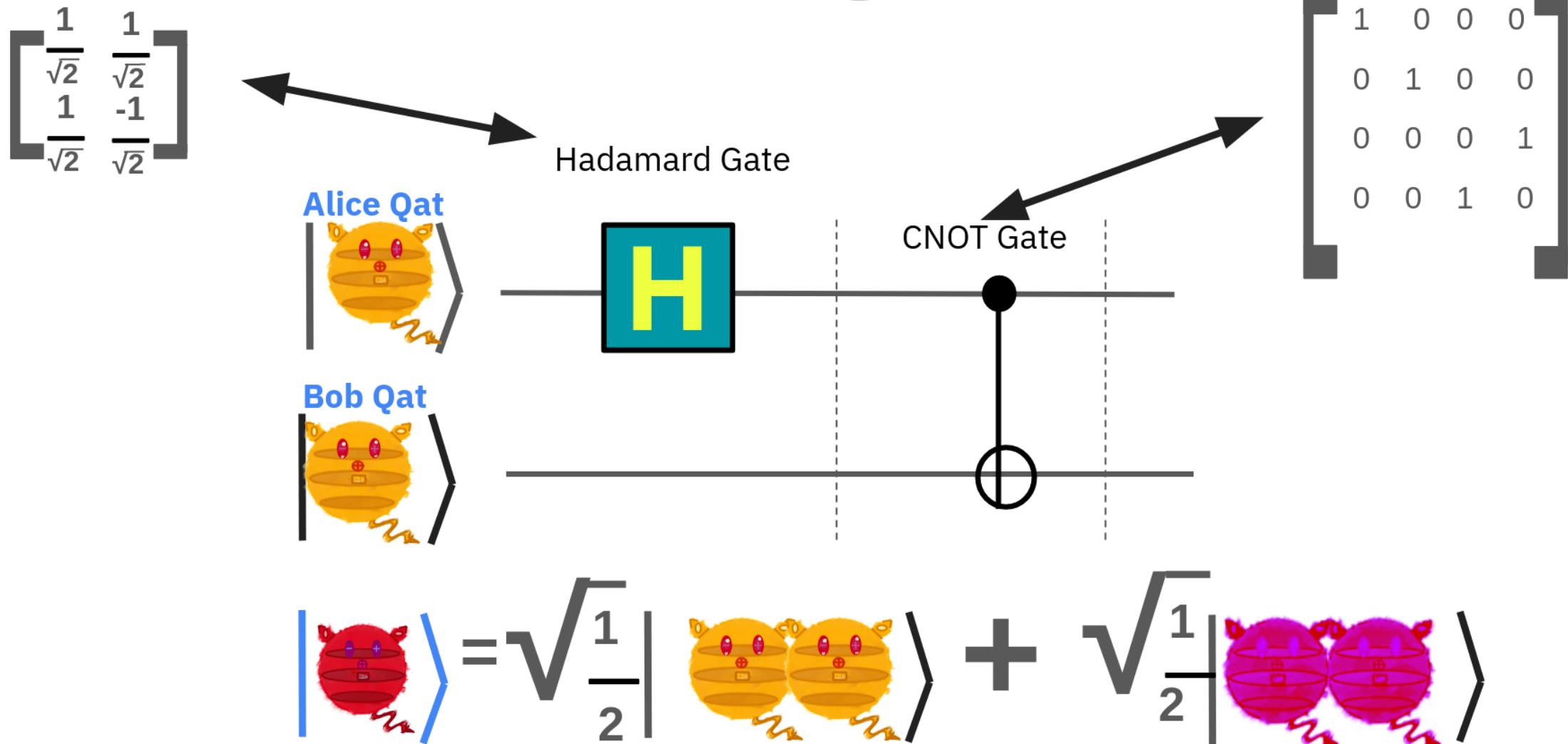
$$|\psi^-\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$



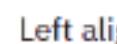
$$|\phi^+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

$$|\phi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

quantum entanglement



Operations



Left alignment



Inspect



Search



H

T

S

RZ

|



q[0]

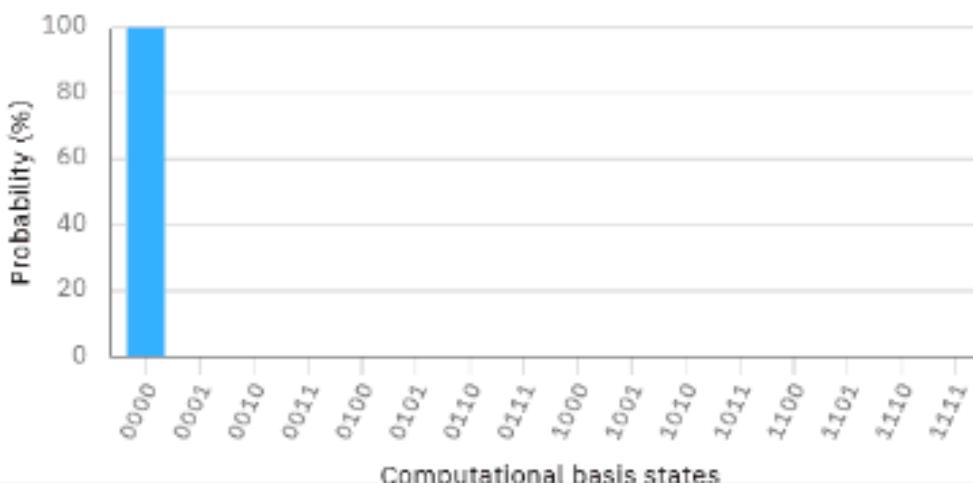
q[1]

q[2]

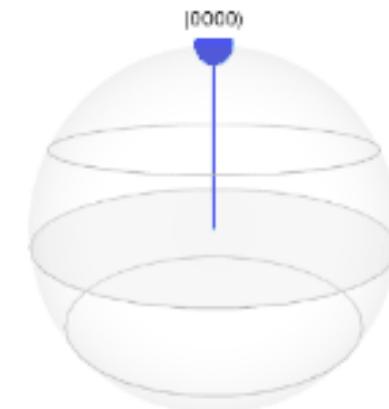
q[3]

c4

Probabilities



Q-sphere

 State Phase angle

Toolbox

Probes	Displays	Half Turns	Quarter Turns	Eighth Turns	Spinning	Formulaic	Parametrized	Sampling	Parity
		Z Swap	S S ⁻¹	T T ⁻¹	Z ^t Z ^{-t}	Z ^{f(t)} Rz(f(t))	Z ^{A/2^n} Z ^{-A/2^n}		[Z] par
0><0 1><1	Density Bloch	Y	Y ^{1/2} Y ^{-1/2}	Y ^{1/4} Y ^{-1/4}	Y ^t Y ^{-t}	Y ^{f(t)} Ry(f(t))	Y ^{A/2^n} Y ^{-A/2^n}		[Y] par
○ ●	Chance Amps		X ^{1/2} X ^{-1/2}	X ^{1/4} X ^{-1/4}	X ^t X ^{-t}	X ^{f(t)} Rx(f(t))	X ^{A/2^n} X ^{-A/2^n}		[X] par

use controls

drag gates onto circuit

outputs change

Local wire states (Chance/Bloch)

Final amplitudes

Toolbox₂

⊕ ⊕	+[t] -[t]	QFT QFT [†]	input A	A=# default	+1 -1	⊕A<B ⊕A>B	+1 mod R -1 mod R	...	0
∅ ⊗	Reverse		input B	B=# default	+A -A	⊕A≤B ⊕A≥B	+A mod R -A mod R	-	
+><+ -><-		Grad ^{1/2} Grad ^{-1/2}	input R	R=# default	+AB -AB	⊕A=B ⊕A≠B	xA mod R xA ⁻¹ mod R	i	-i
i><i i-i><-i		Grad ^t Grad ^{-t}			xA xA ⁻¹		xB ^A mod R xB ^{-A} mod R	√i	√-i
X/Y Probes	Order	Frequency	Inputs	Arithmetic	Compare	Modular	Scalar	Custom Gates	

Universal Quantum

The universal quantum computer is the most powerful, the most general, and the hardest to build, posing a number of difficult technical challenges. Current estimates indicate that this machine will comprise more than 100,000 physical qubits.

APPLICATIONS

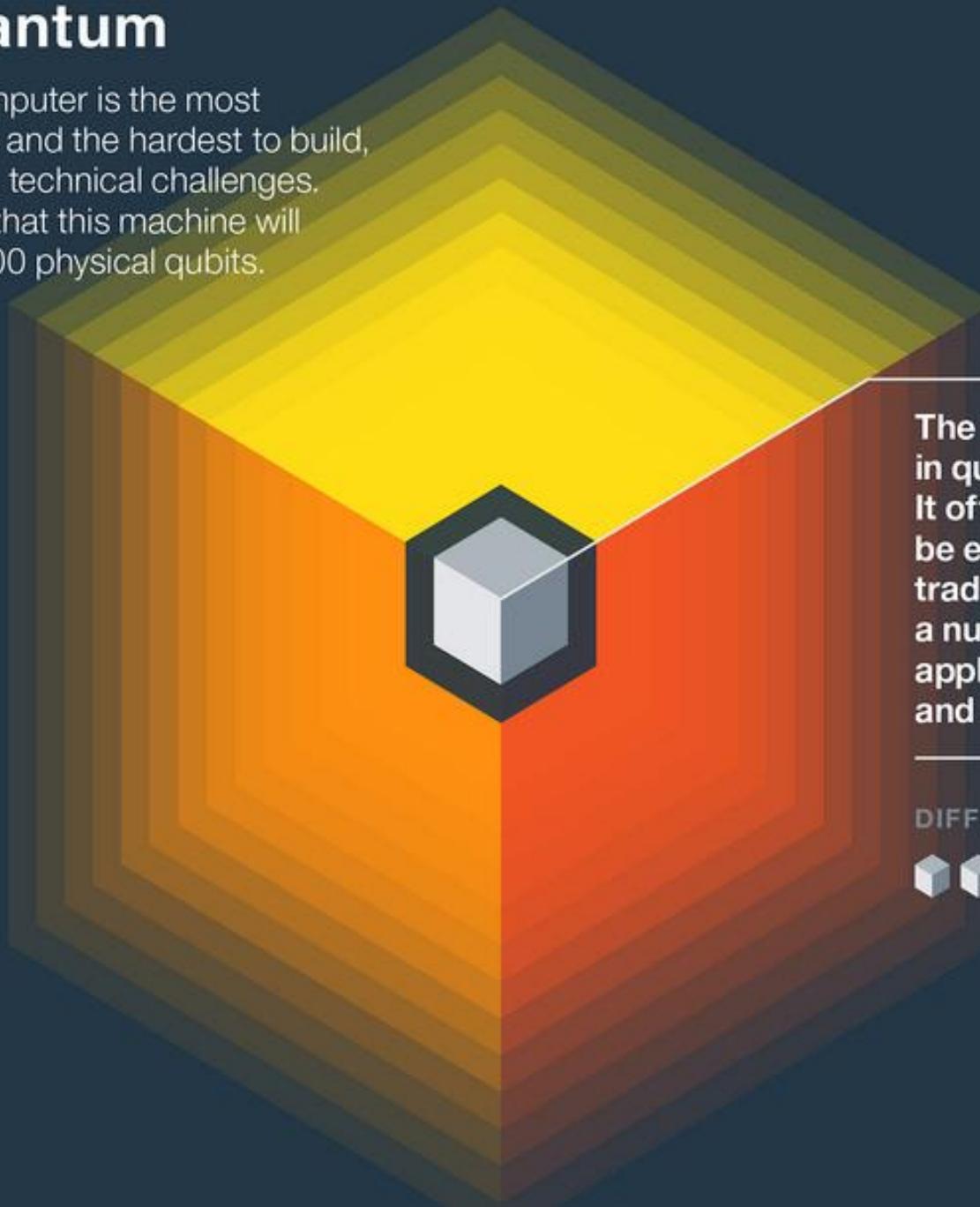
Secure computing
Machine Learning
Cryptography
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics
Searching

GENERALITY

Complete with known speed up

COMPUTATIONAL POWER

Very High

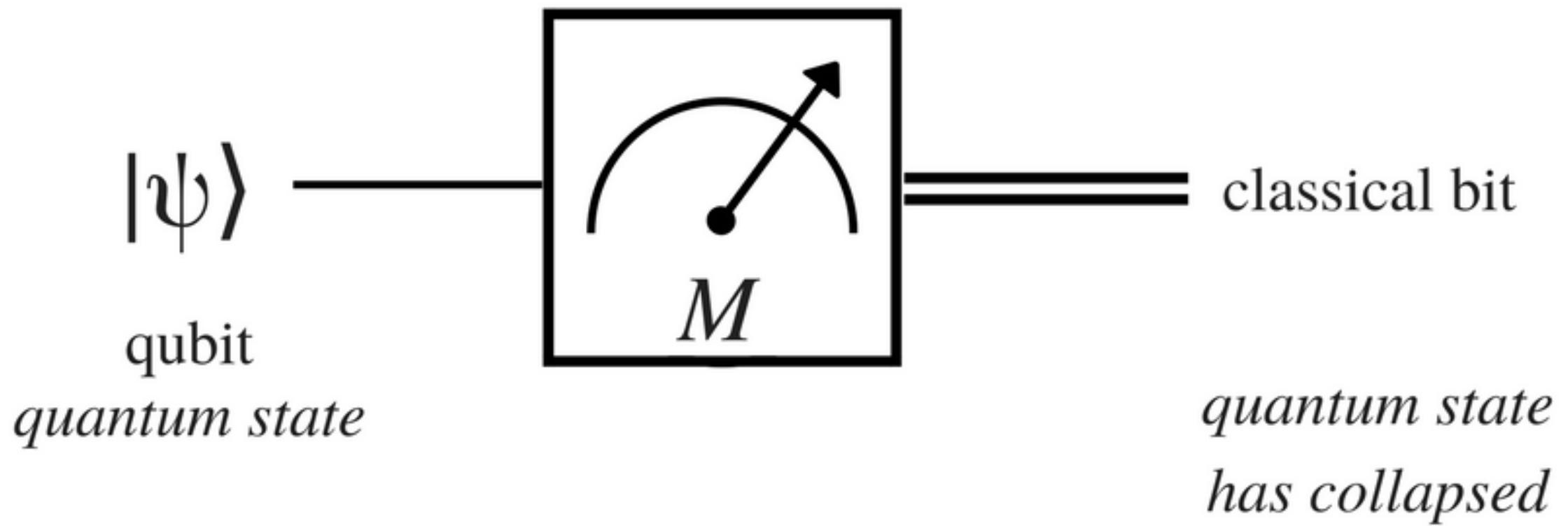


The true grand challenge in quantum computing. It offers the potential to be exponentially faster than traditional computers for a number of important applications for science and businesses.

DIFFICULTY LEVEL



Quantum Measurements



Noise is the big challenge

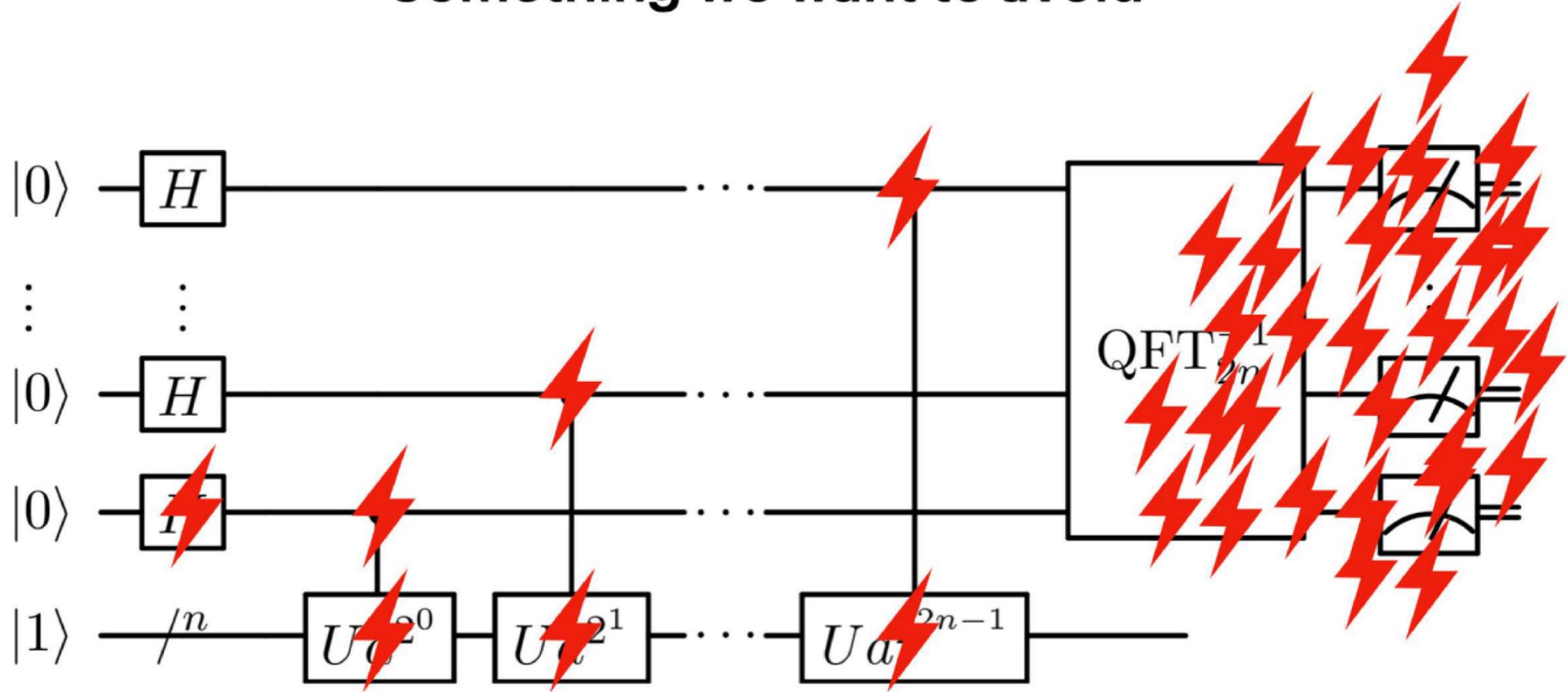
Protect the qubits! 🛡️⚔️



The avalanche of errors



Something we want to avoid



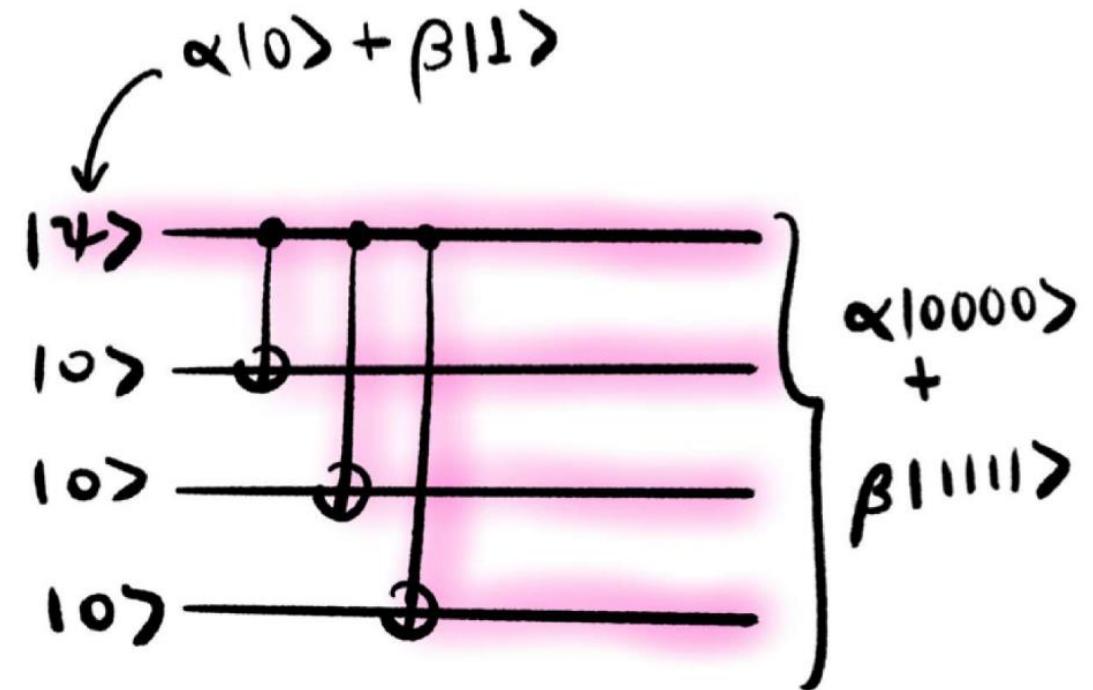
Quantum error correction

Needs to correct infinite types of errors

$[[n, k, d]]$



$\alpha |000\rangle + \beta |111\rangle$



Go below threshold

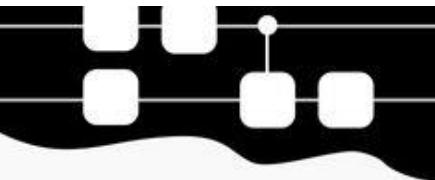
The holy grail of fault tolerance

If **hardware** is below threshold, then **software** can kick in to fix errors.



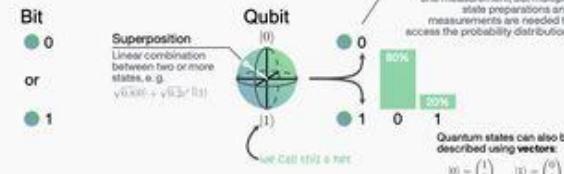
Quantum Computing CHEAT SHEET

for circuit magicians



Bits and Qubits

Instead of classical bits, quantum computers use quantum bits (or qubits for short).

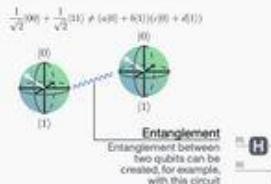


One way to picture quantum states is the circle notation:
the inner circle represents the amplitude
the brace she indicates the phase
 $\sqrt{0.8}|0\rangle + \sqrt{0.2}e^{i\frac{\pi}{2}}|1\rangle$

Multiple qubits form a register. The number of computational states doubles with each new qubit. A state with multiple qubits involved is often denoted like $|00\rangle = |0\rangle \otimes |0\rangle$.

# qubits	# basis states	example
1	2	$ 0\rangle, 1\rangle, \frac{1}{\sqrt{2}} 0\rangle - \frac{1}{\sqrt{2}} 1\rangle$
2	4	$ 00\rangle, 01\rangle, 10\rangle, 11\rangle, \frac{1}{\sqrt{2}} 00\rangle + \frac{1}{\sqrt{2}} 10\rangle + \frac{1}{\sqrt{2}} 01\rangle + \frac{1}{\sqrt{2}} 11\rangle$ possible linear combination of two-qubit states
3	8	$ 000\rangle, 001\rangle, 010\rangle, 011\rangle, 100\rangle, 101\rangle, 110\rangle, 111\rangle$

Two or more qubits can be entangled, meaning that the state cannot be factorized as a product of states:



One-Qubit Gates

X Pauli-X is a 180° rotation around the x-axis; also known as the quantum NOT gate

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

Ket and circle notation
 $a|0\rangle + b|1\rangle$ $b|0\rangle + a|1\rangle$

Y Pauli-Y is a 180° rotation around the y-axis

Matrix
 $\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$

Ket and circle notation
 $a|0\rangle + b|1\rangle$ $-ib|0\rangle + ia|1\rangle$

Z Pauli-Z is a 180° rotation around the z-axis

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

Ket and circle notation
 $a|0\rangle + b|1\rangle$ $a|0\rangle - b|1\rangle$

H Hadamard maps $|0\rangle$ to $|+\rangle$ and $|1\rangle$ to $|-\rangle$ used to create an equal superposition

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

Ket and circle notation
 $|0\rangle$ $|+\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$
 $|1\rangle$ $|-\rangle = \frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle$

S is a 90° rotation around the z-axis; The inverse S^\dagger rotates in the opposite direction

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

Ket and circle notation
 $a|0\rangle + b|1\rangle$ $a|0\rangle + bi^{\frac{1}{2}}|1\rangle$

T is a 45° rotation around the z-axis; The inverse T^\dagger rotates in the opposite direction

Matrix
 $\begin{pmatrix} 1 & 0 \\ 0 & e^{\frac{i\pi}{4}} \end{pmatrix}$

Ket and circle notation
 $a|0\rangle + b|1\rangle$ $a|0\rangle + be^{\frac{i\pi}{4}}|1\rangle$

Quantum circuits are a model to visualize operations on qubits.



Binary and decimal: You will find both the use of the binary representation of qubit states as well as the decimal representation.

Decimal	Binary	means that the digits 1, 2, ..., n are the 1st, 2nd, ..., n-th qubit in the register	Decimal	Binary
0	000		4	100
1	001	first 1 and the second	5	101
2	010	first 1 and the third	6	110
3	011		7	111

Multi-Qubit Gates

Gate

CNOT applies a Pauli-X gate to the target qubit if the state of the control qubit is $|1\rangle$.

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

Ket and circle notation

Gate

CZ applies a Pauli-Z gate to the target qubit if the state of the control qubit is $|1\rangle$.

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

Ket and circle notation

Gate

SWAP swaps the state of 2 qubits; can be implemented using 3 alternating CNOTs.

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

Ket and circle notation

Gate

Toffoli applies a Pauli-X gate to the target qubit if both control qubits are in state $|1\rangle$; can be used to construct a reversible version of the classical AND-gate

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

Ket and circle notation

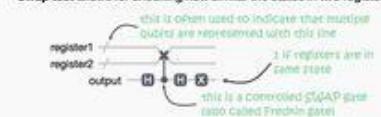
Building Blocks for Quantum Algorithms

There are many clever ways to arrange quantum circuits. A couple of them are depicted below.

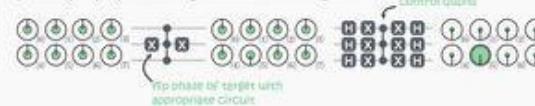
Increment & **decrement** are used to add or subtract one from a register and are an example of how to do arithmetic with quantum gates.



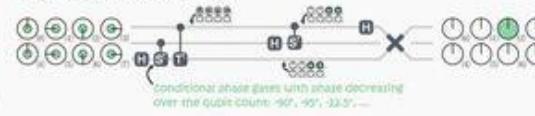
Swap test allows for checking how similar the states in two registers are.

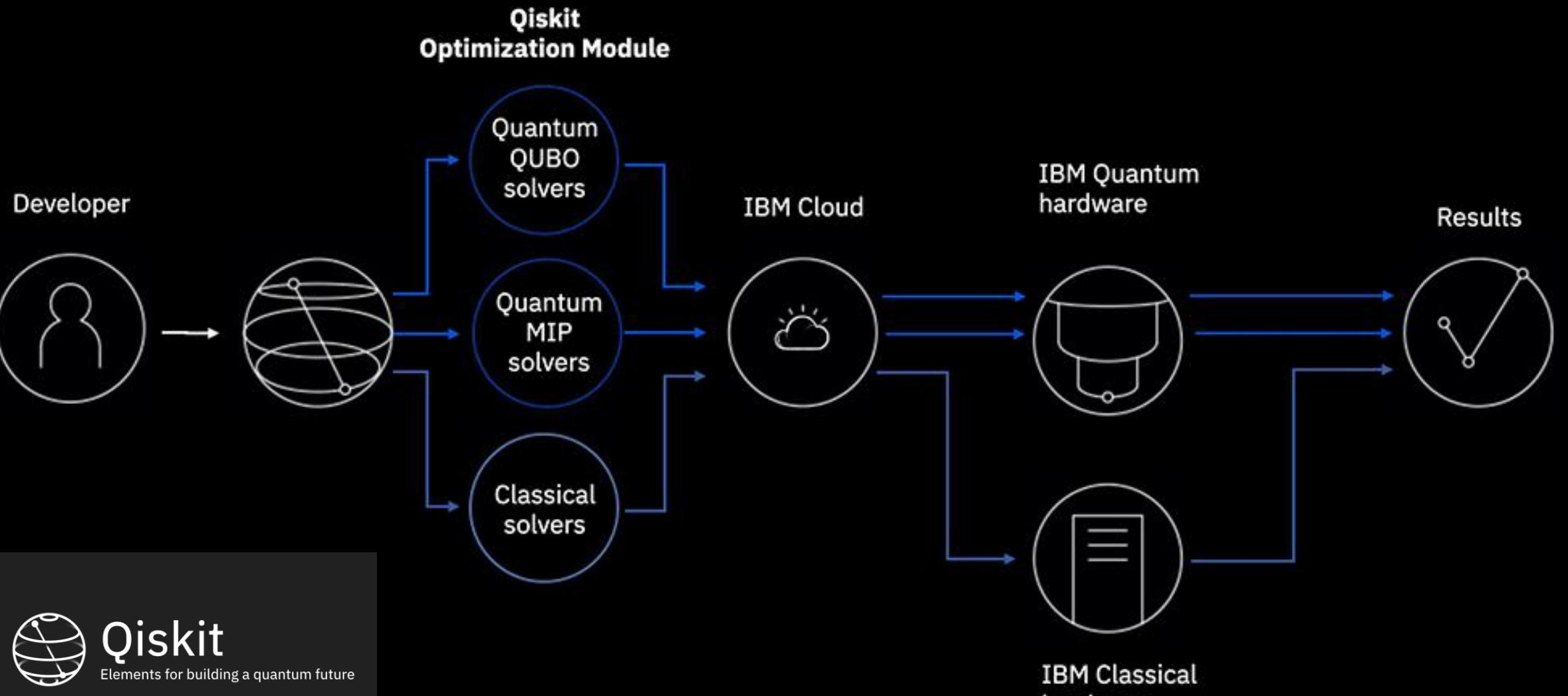


Amplitude Amplification converts phase differences into amplitude differences. It can be used (multiple times) to increase the success probability of query or search algorithms like Grover's algorithm.



Quantum Fourier Transform can reveal the signal frequency in a register. Among other algorithms, it is used in Shor's algorithm for factoring numbers and computing the discrete logarithm.





Source: IBM

THANK YOU!