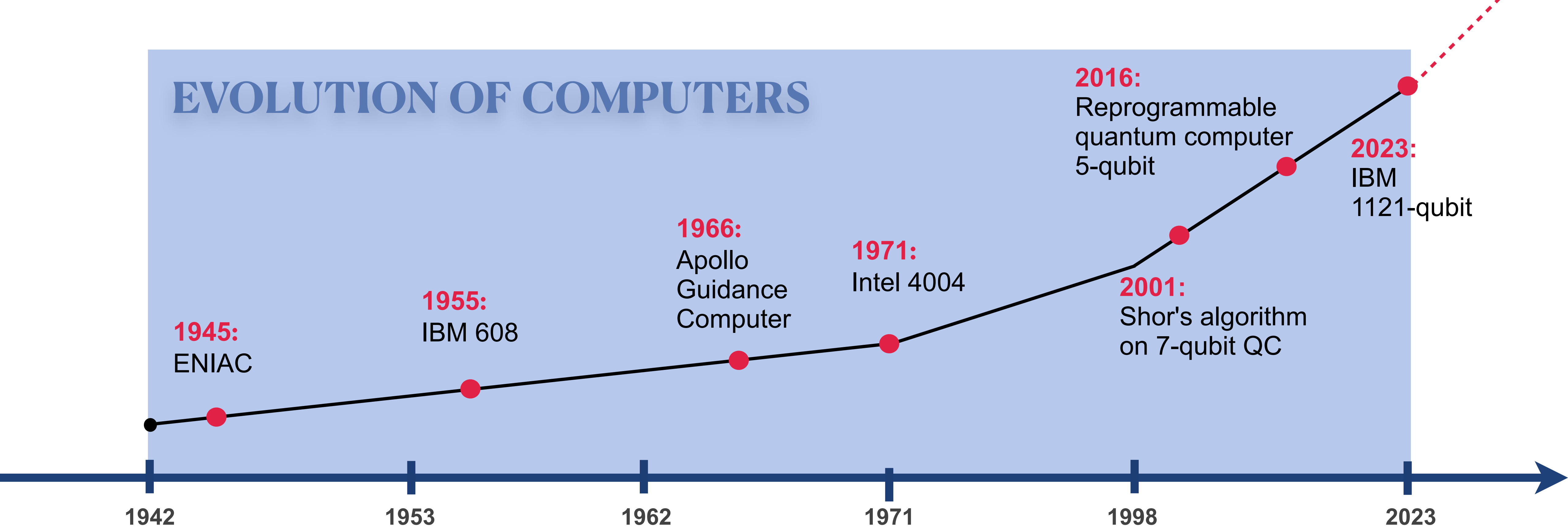
Basics of Quantum Computing

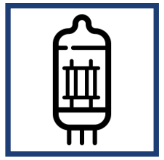
Ema Puljak

CERN

QUANTUM TECHNOLOGY INITIATIVE

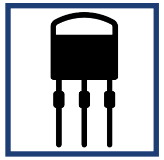
EVOLUTION OF COMPUTERS





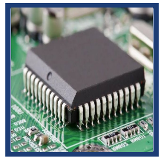
Vacuum tube

1942 - 1950s



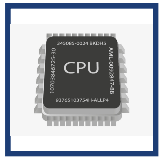
Transistor

1953 - 1960s



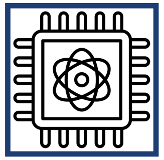
Integrated circuit

1962 - 1969



Microprocessor

1971 - now



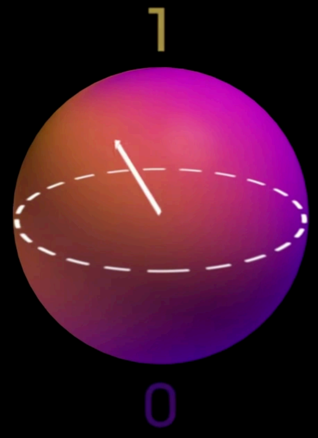
Quantum processor

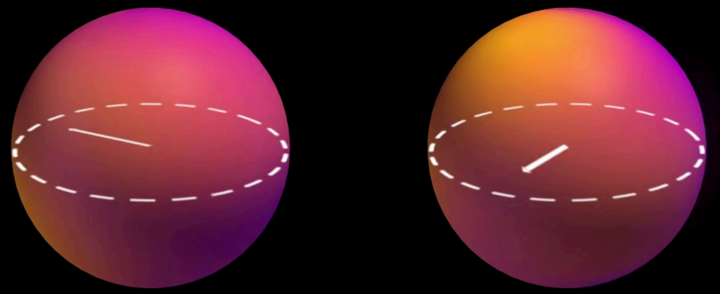
1998 - now

“If you think you understand quantum mechanics, you don’t understand quantum mechanics.”

Richard Feynman

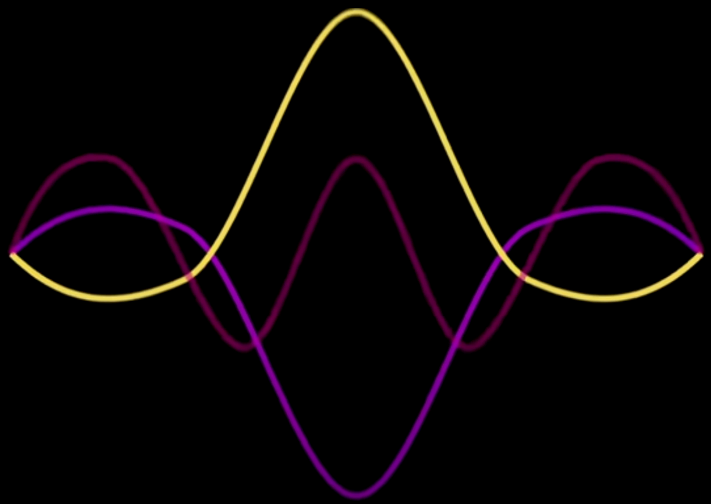
SUPERPOSITION





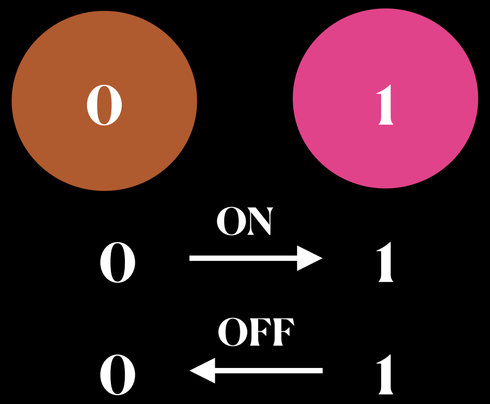
ENTANGLEMENT

INTERFERENCE



SUPERPOSITION

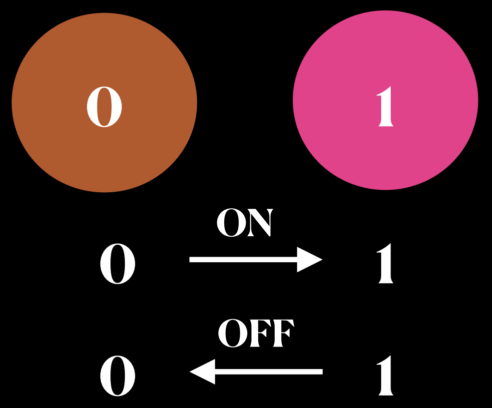
SUPERPOSITION



CLASSIC BIT

SUPERPOSITION

$$|qubit\rangle = C_0|0\rangle + C_1|1\rangle$$



CLASSIC BIT

SUPERPOSITION

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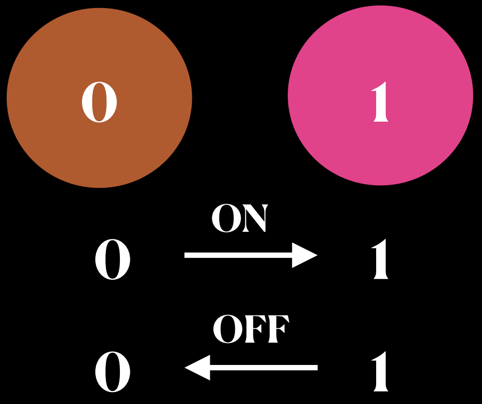
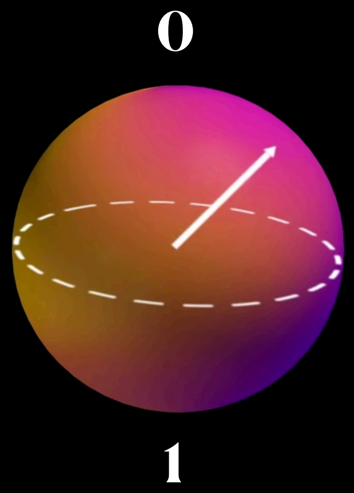


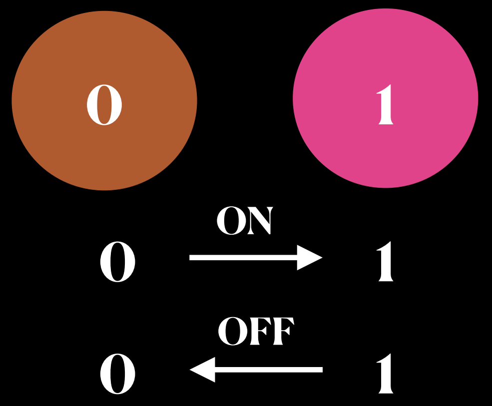
CLASSIC
BIT



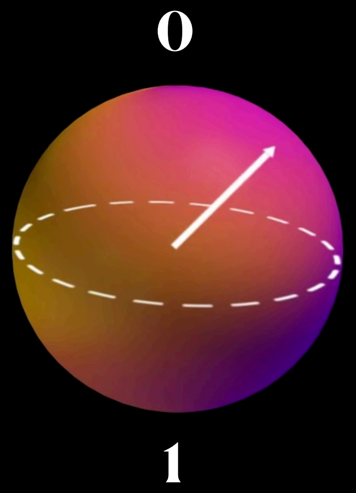
QUANTUM
BIT

SUPERPOSITION

$$|\text{qubit}\rangle = C_0\,|0\rangle + C_1\,|1\rangle$$



Bloch sphere

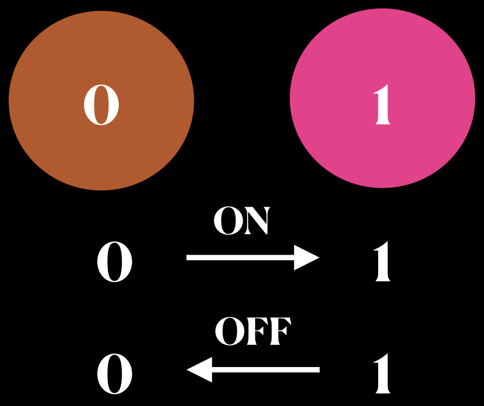


CLASSIC BIT

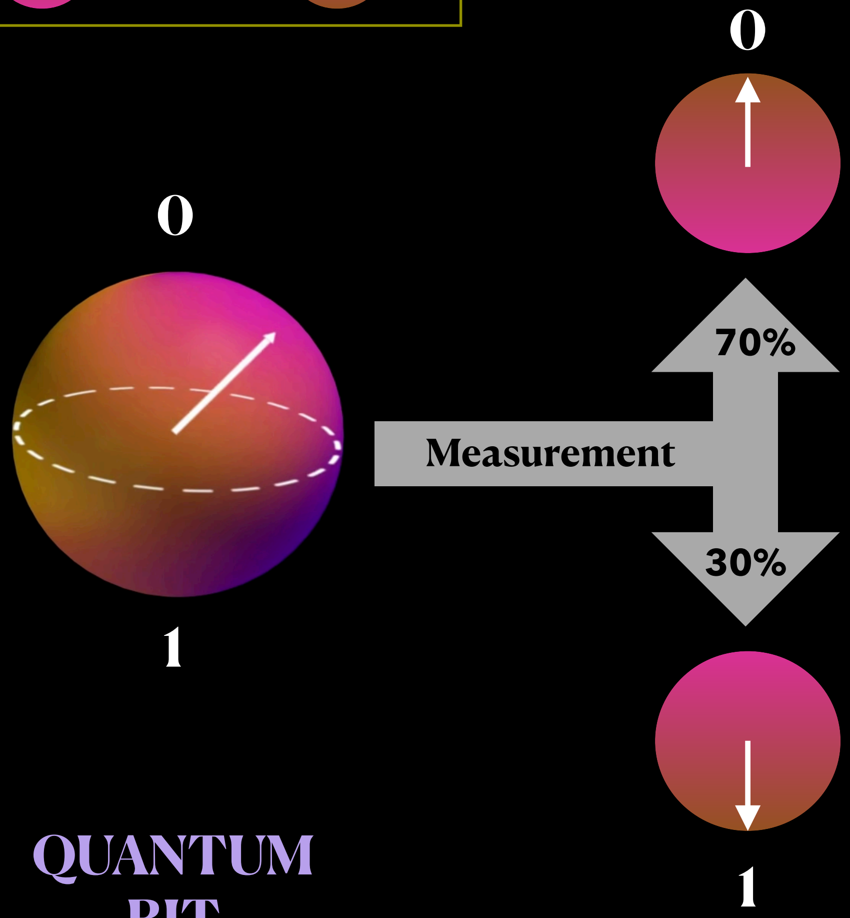
QUANTUM BIT

SUPERPOSITION

$$|\text{qubit}\rangle = C_0|0\rangle + C_1|1\rangle$$



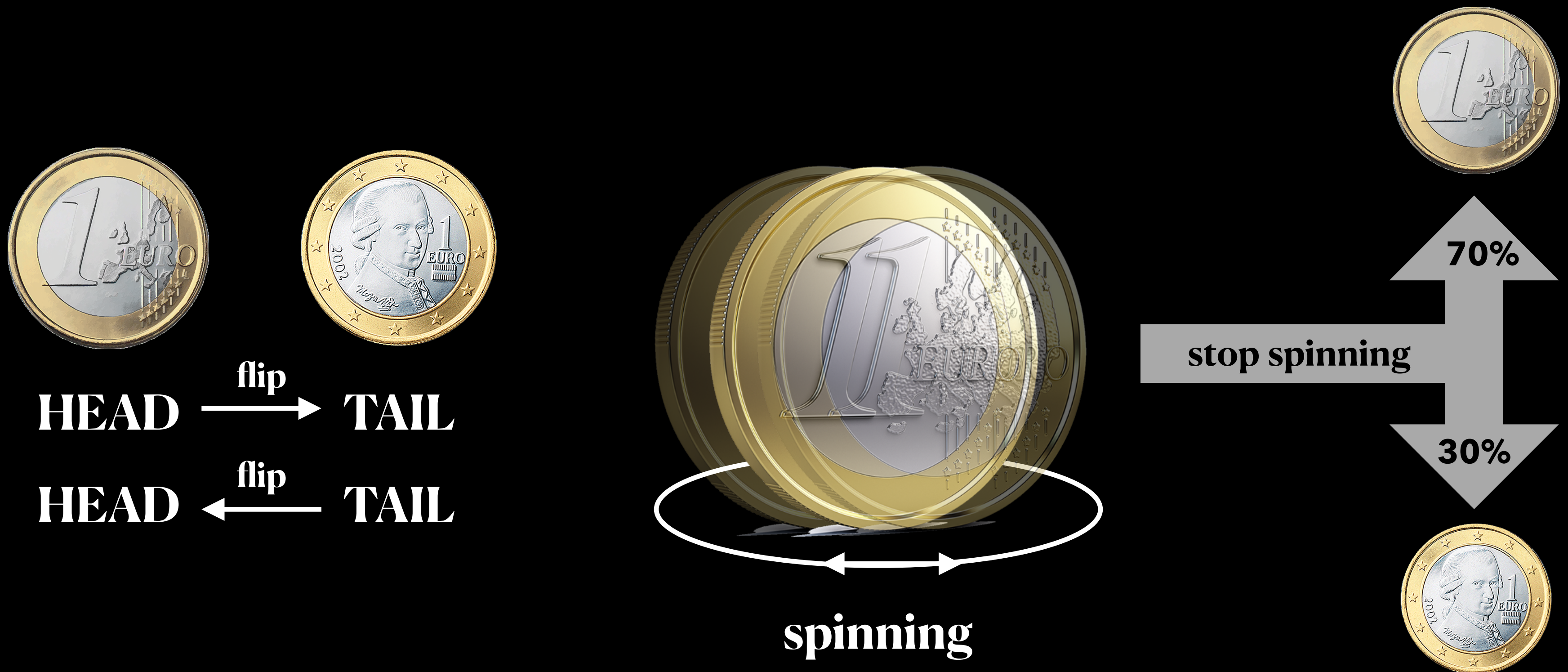
CLASSIC BIT



QUANTUM BIT

SUPERPOSITION

$|qubit\rangle = C_{head}|$  $\rangle + C_{tail}|$  $\rangle$



CLASSIC BIT

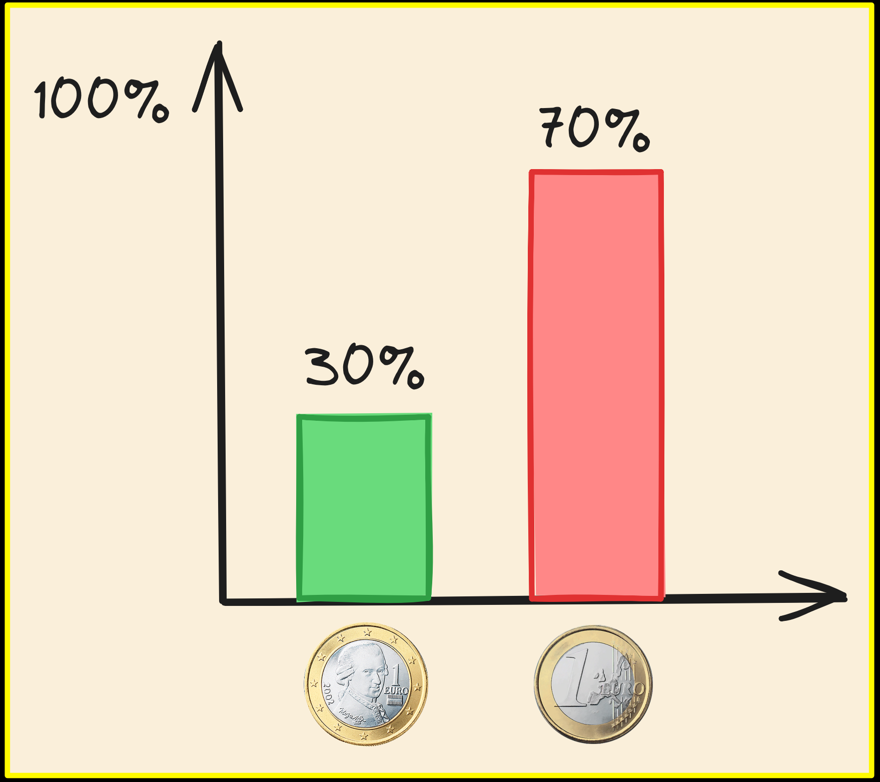
QUANTUM BIT

PROBABILITY DISTRIBUTION

$|\text{qubit}\rangle = C_{head}\,|$  $\rangle + C_{tail}\,|$  $\rangle$

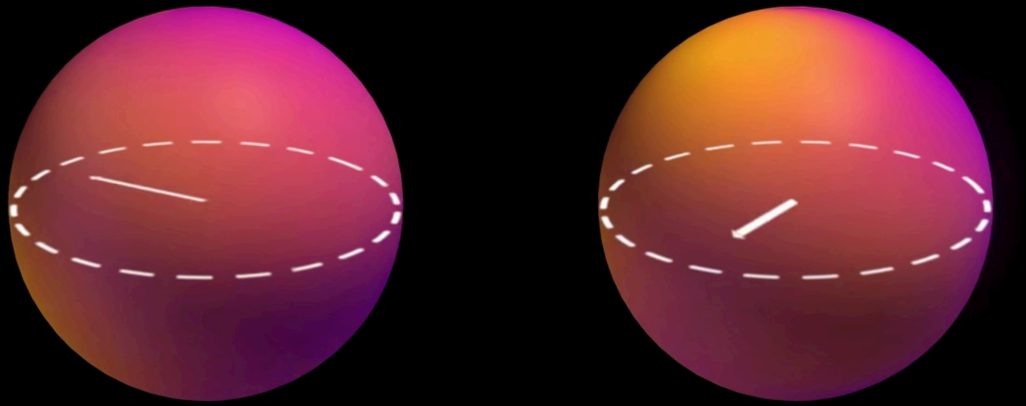
spinning

stop spinning



Probabilistic BIT

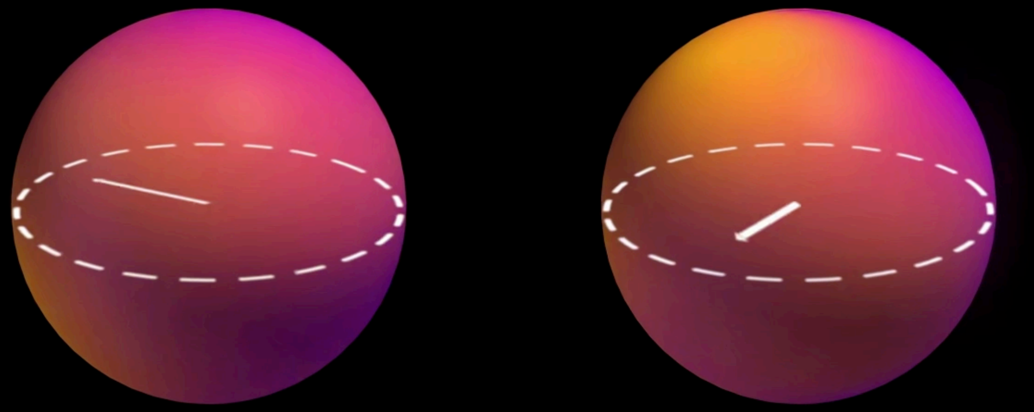
ENTANGLEMENT



2 entangled qubits

Information encoded in joint state

CORRELATION



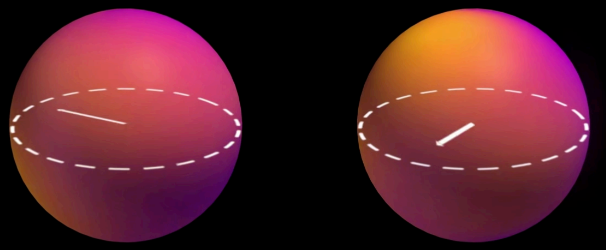
Information encoded in joint state

2 entangled qubits

S

17

ENTANGLEMENT

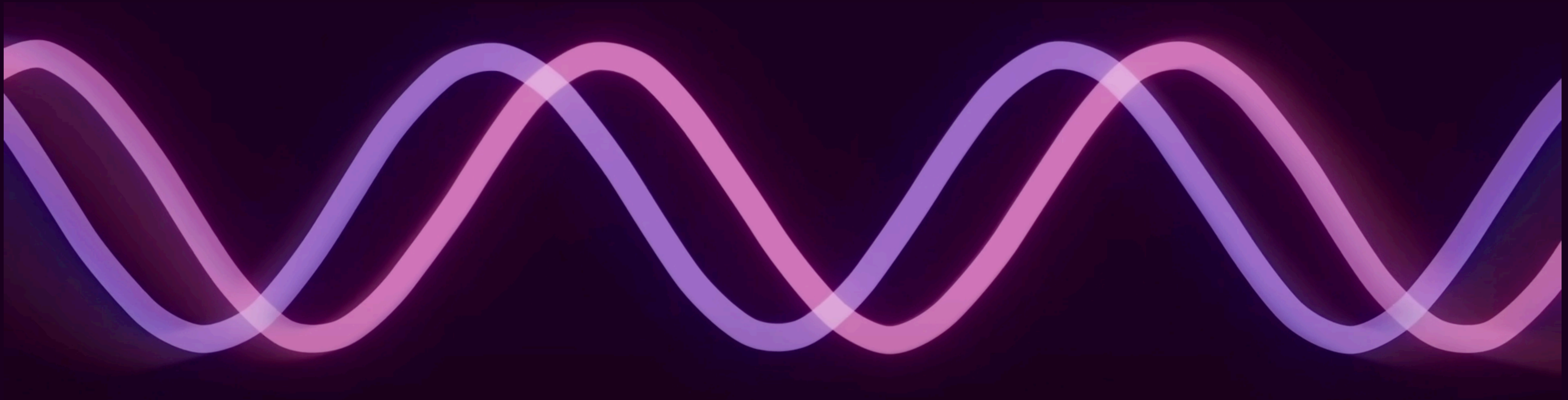


Qubits	2	3	10	16	20	30	35	100	280
Classical bits required to represent an entangled state	512 bits	1,024 bits	16 kilobytes	1 megabyte	17 megabytes	17 gigabytes	550 gigabytes	more than all the atoms on the planet Earth	more than all the atoms in the universe

Exponential power of quantum computers

quantamagazine.org
ibm.com

INTERFERENCE



wave function = ψ

Bra-Ket $|\psi\rangle = C_0|0\rangle + C_1|1\rangle$

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

Complex vector representation

$$C_0 = a + bi \qquad C_1 = c + di \qquad C = \begin{bmatrix} C_0 \\ C_1 \end{bmatrix}$$

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

Complex vector representation

$$C_0 = a + bi \qquad C_1 = c + di \qquad C = \begin{bmatrix} C_0 \\ C_1 \end{bmatrix} \longrightarrow \text{4 parameters}$$

BORN RULE

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

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BORN RULE

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Normalization constraint

$$|C_0|^2 + |C_1|^2 = 1$$

Complex vector representation

$$C_0 = a + bi \qquad C_1 = c + di$$

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$$a^2 + b^2 + c^2 + d^2 = 1$$

BORN RULE

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$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

Normalization constraint $\quad |C_0|^2 + |C_1|^2 = 1$

Complex vector representation

$$C_0 = a + bi \qquad C_1 = c + di \qquad C = \begin{bmatrix} C_0 \\ C_1 \end{bmatrix} \longrightarrow 4\ \text{dof}$$

$$a^2 + b^2 + c^2 + d^2 = 1 \longrightarrow d = \sqrt{1 - a^2 - b^2 - c^2} \longrightarrow 3\ \text{dof}$$

BORN RULE

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

Normalization constraint $|C_0|^2 + |C_1|^2 = 1$

Polar representation of C_i

$$C_0 = |C_0|e^{i\phi_{C_0}} \qquad C_1 = |C_1|e^{i\phi_{C_1}}$$

magnitude

BORN RULE

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

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Polar representation of C_i

$$C_0 = |C_0|e^{i\phi_{C_0}} \qquad C_1 = |C_1|e^{i\phi_{C_1}}$$

magnitude: $|C_0|$

phase: ϕ_{C_0}

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

BORN RULE

$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

Normalization constraint

$$|C_0|^2 + |C_1|^2 = 1$$

Polar representation of C_i

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phase

magnitude

$$|\psi\rangle = |C_0|e^{i\phi_{C_0}}|0\rangle + |C_1|e^{i\phi_{C_1}}|1\rangle$$

BORN RULE

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

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magnitude — phase

$$e^{-i\phi_{C_0}}|\psi\rangle = e^{-i\phi_{C_0}}(|C_0|e^{i\phi_{C_0}}|0\rangle + |C_1|e^{i\phi_{C_1}}|1\rangle)$$

BORN RULE

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

Normalization constraint

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Polar representation of C_i

$$C_0 = |C_0|e^{i\phi_{C_0}} \qquad C_1 = |C_1|e^{i\phi_{C_1}}$$

magnitude

phase

Global phase invariance

$$e^{-i\phi_{C_0}}|\psi\rangle = e^{-i\phi_{C_0}}(|C_0|e^{i\phi_{C_0}}|0\rangle + |C_1|e^{i\phi_{C_1}}|1\rangle)$$

$$= |C_0||0\rangle + |C_1|e^{i(\phi_{C_0} - \phi_{C_1})}|1\rangle$$

BORN RULE

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

$$P_0|0\rangle = |C_0|^2 \qquad P_1|1\rangle = |C_1|^2$$

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magnitude

phase

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phase

Global phase invariance

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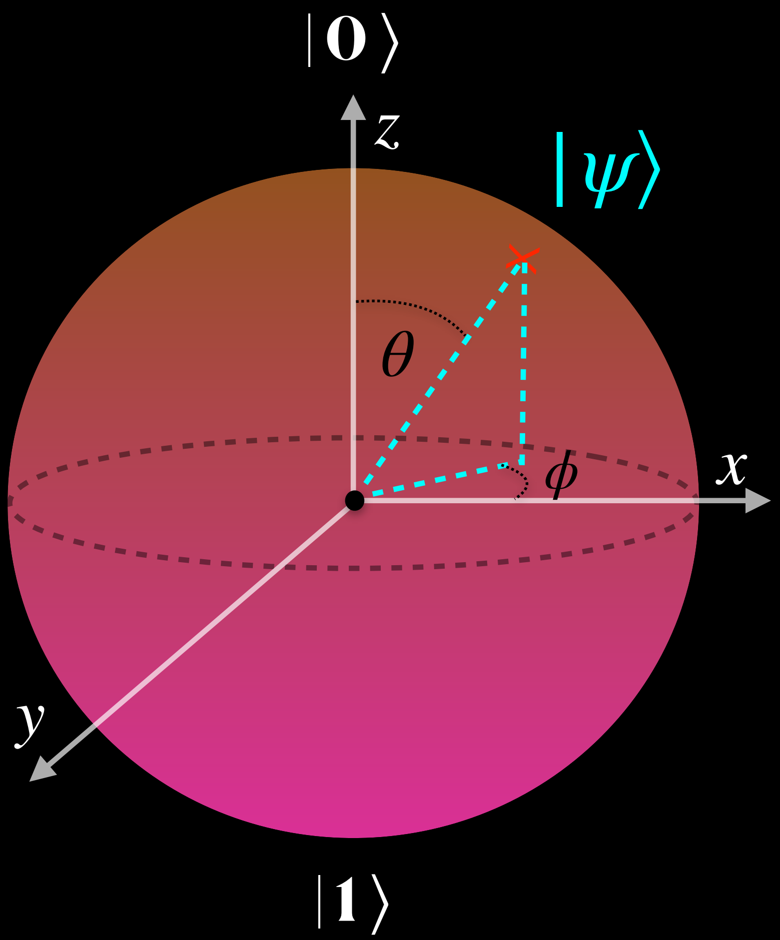
$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$

Bloch sphere

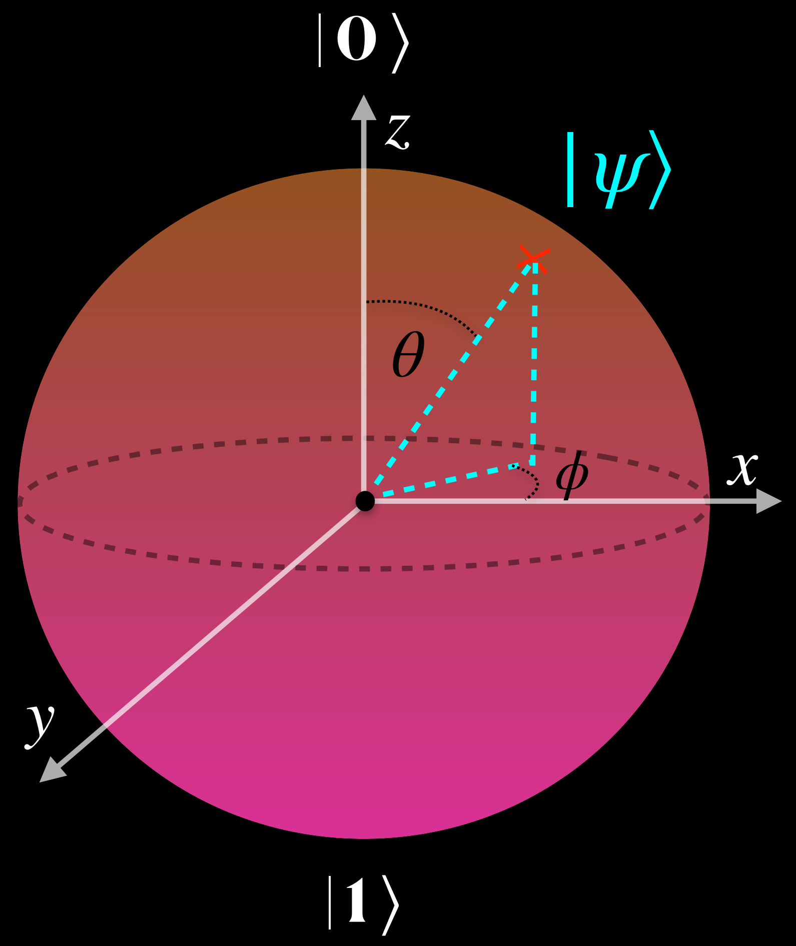


Angle representation

$$C_0 = \cos\left(\frac{\theta}{2}\right) \qquad C_1 = e^{i\phi}\sin\left(\frac{\theta}{2}\right)$$

Bloch sphere

$$|\psi\rangle = C_0|0\rangle + C_1|1\rangle$$



Angle representation

$$C_0 = \cos\left(\frac{\theta}{2}\right) \qquad C_1 = e^{i\phi}\sin\left(\frac{\theta}{2}\right)$$

θ → relative magnitudes

ϕ → relative phase difference

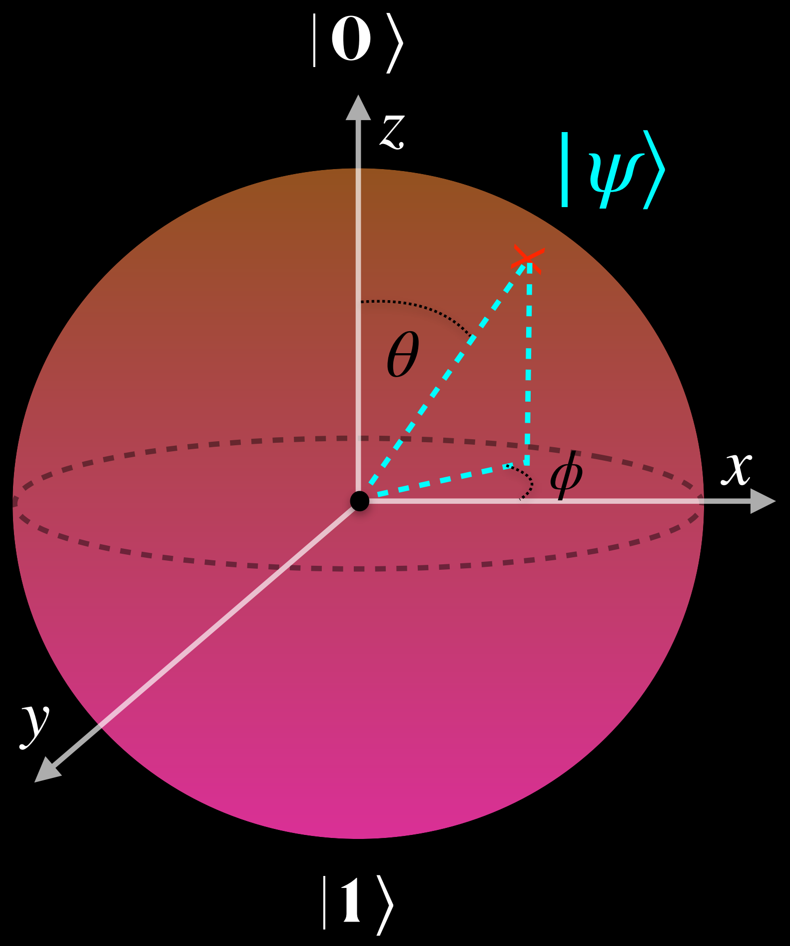
Bloch sphere

$$|\psi\rangle = C_0 |0\rangle + C_1 |1\rangle$$

Angle representation

$$C_0 = \cos\left(\frac{\theta}{2}\right) \qquad C_1 = e^{i\phi} \sin\left(\frac{\theta}{2}\right)$$

θ	$\longrightarrow$ relative magnitudes	$[0 - \pi]$
ϕ	$\longrightarrow$ relative phase difference	$[0 - 2\pi]$



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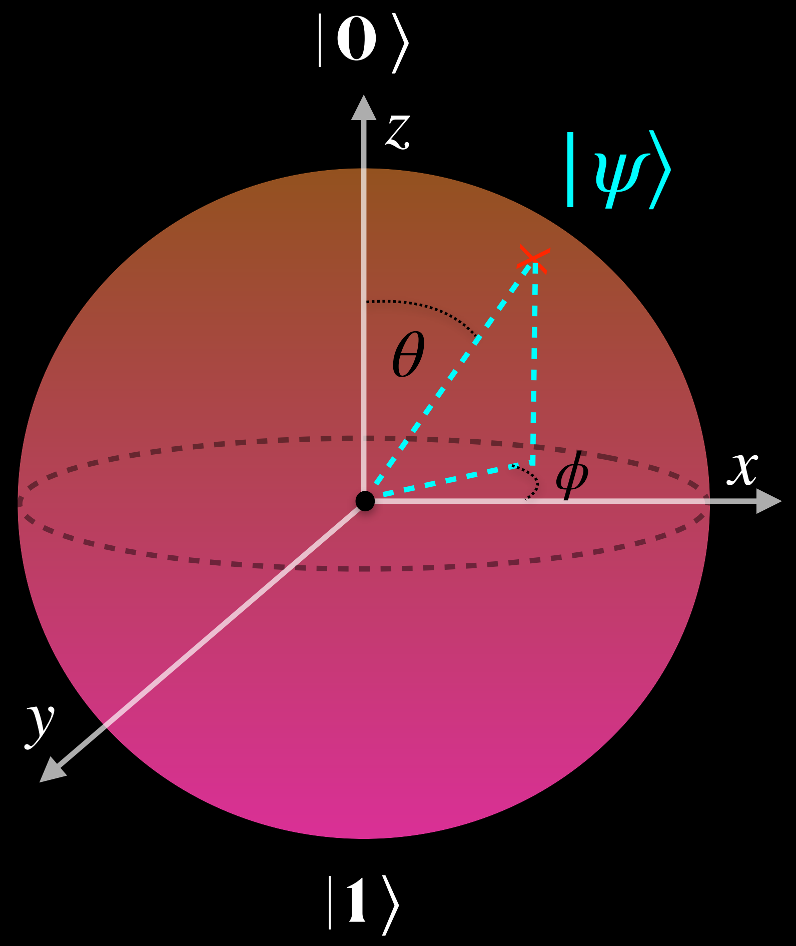


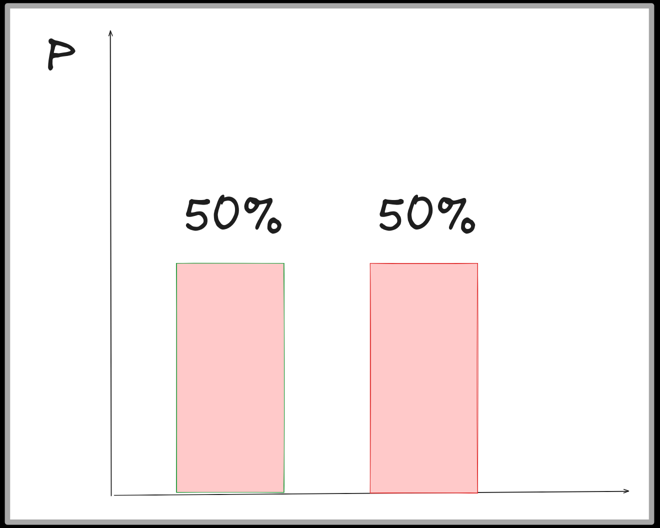
Angle representation

$$C_0 = \cos\left(\frac{\theta}{2}\right) \qquad C_1 = e^{i\phi}\sin\left(\frac{\theta}{2}\right)$$

θ ⟶ latitude

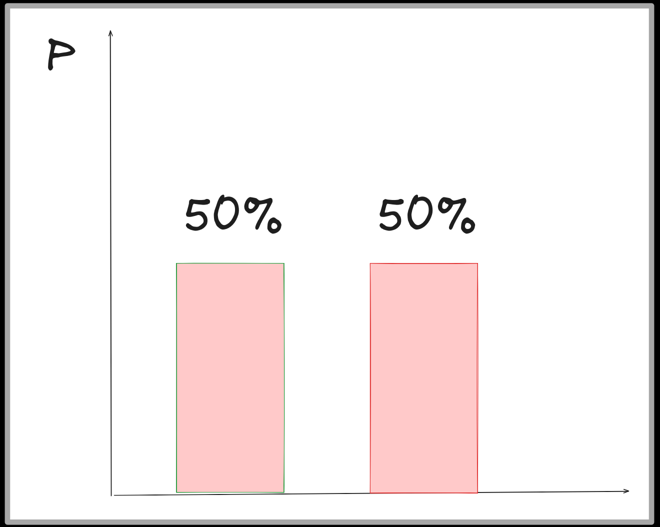
ϕ ⟶ longitude

$P_0|0\rangle = 50\%$ $P_1|1\rangle = 50\%$

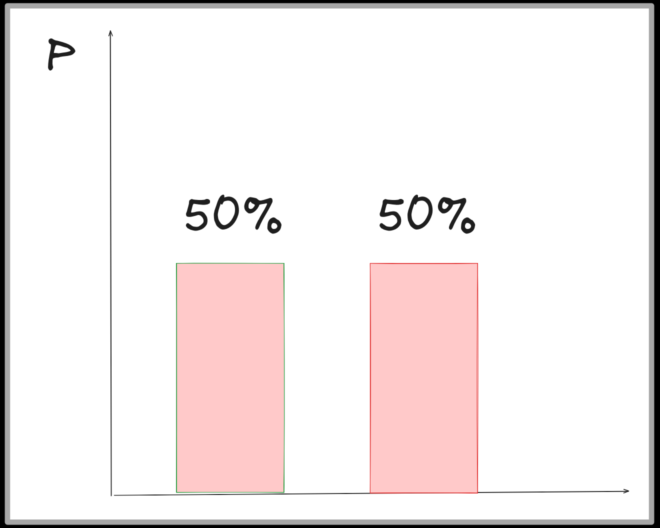


$$P_0|0\rangle = 50\% \qquad P_1|1\rangle = 50\%$$

$$C_0 = \frac{1}{\sqrt{2}} \qquad C_1 = \frac{1}{\sqrt{2}}$$



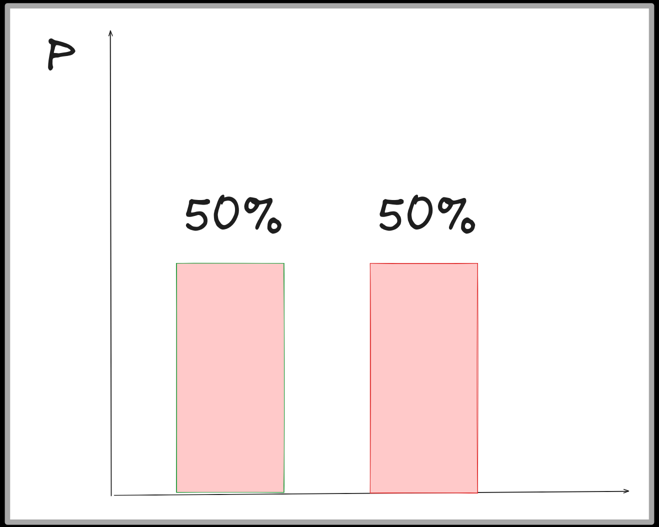
$$P_0 | 0 \rangle = 50\% \qquad P_1 | 1 \rangle = 50\%$$



$$C_0 = \frac{1}{\sqrt{2}} \qquad C_1 = \frac{1}{\sqrt{2}}$$

$$C_0 = cos\left(\frac{\theta}{2}\right) \qquad C_1 = e^{i\phi} sin\left(\frac{\theta}{2}\right) \qquad \rightarrow \theta = \frac{\pi}{2}, \phi = 0$$

$$P_0 |0\rangle = 50\% \qquad P_1 |1\rangle = 50\%$$



$$C_0 = \frac{1}{\sqrt{2}} \qquad C_1 = \frac{1}{\sqrt{2}}$$

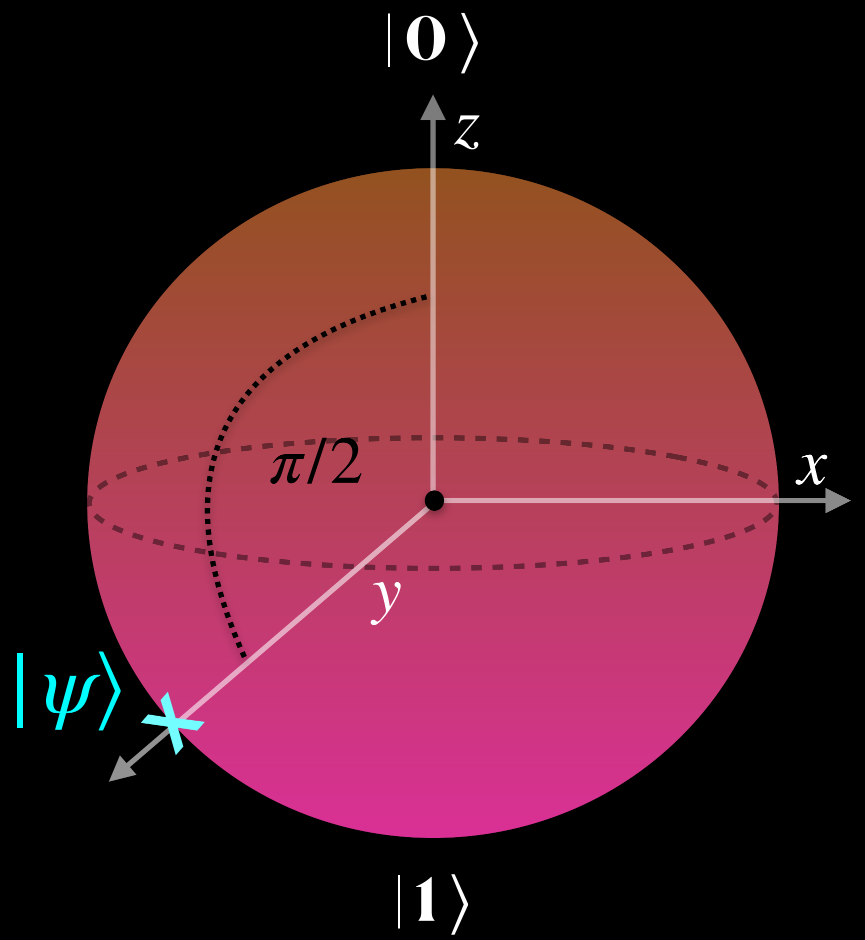
$$C_0 = cos\left(\frac{\pi}{4}\right) \qquad C_1 = e^{i \cdot 0} sin\left(\frac{\pi}{4}\right)$$

$$P_0 |0\rangle = 50\% \qquad P_1 |1\rangle = 50\%$$

$$C_0 = \frac{1}{\sqrt{2}} \qquad C_1 = \frac{1}{\sqrt{2}}$$

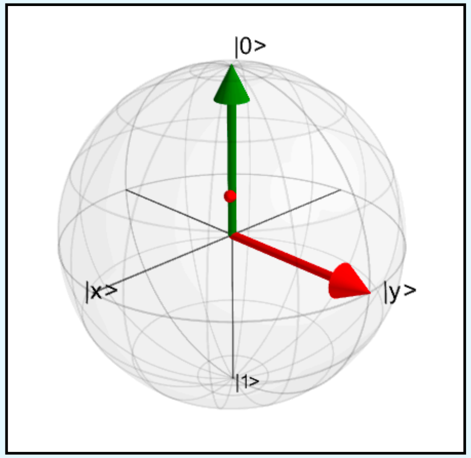
$$C_0 = cos\left(\frac{\pi}{4}\right) \qquad C_1 = e^{i \cdot 0} sin\left(\frac{\pi}{4}\right)$$

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



Building blocks of quantum computer

Quantum bits (QUBITS)



Building blocks of quantum computer

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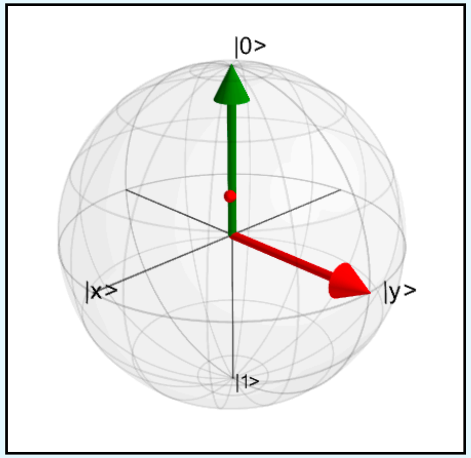
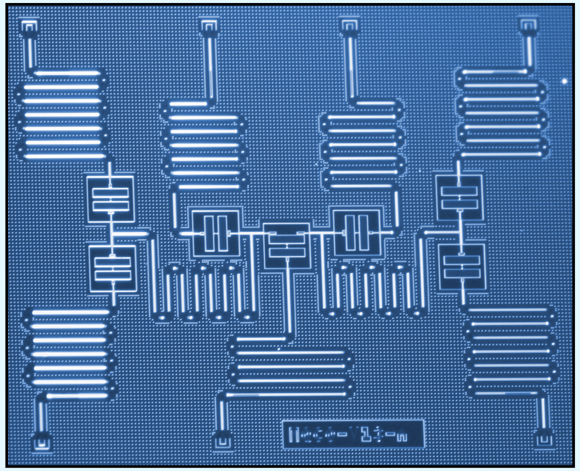


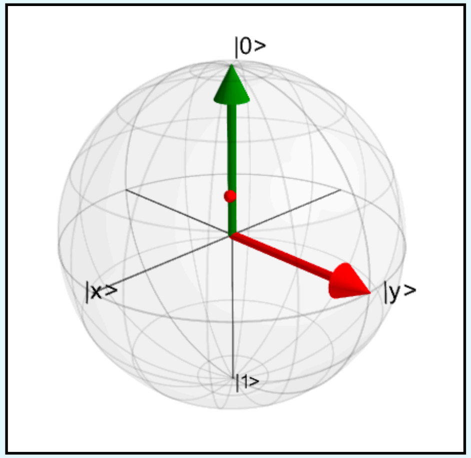
Superconducting qubits Built on a chip



IBM 7-qubit QPU

Building blocks of quantum computer

Quantum bits (QUBITS)



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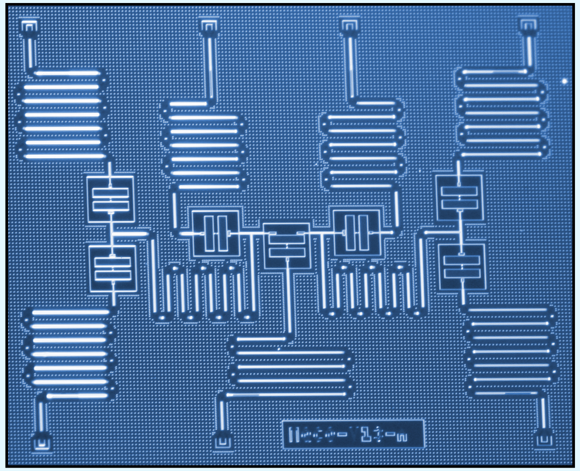

IBM 7-qubit QPU

Quantum Computer

The Qubit Game

Build a quantum computer, one qubit at a time.

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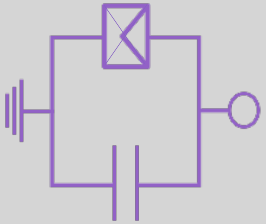
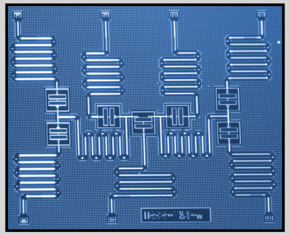
Qubit technology

Superconducting qubits



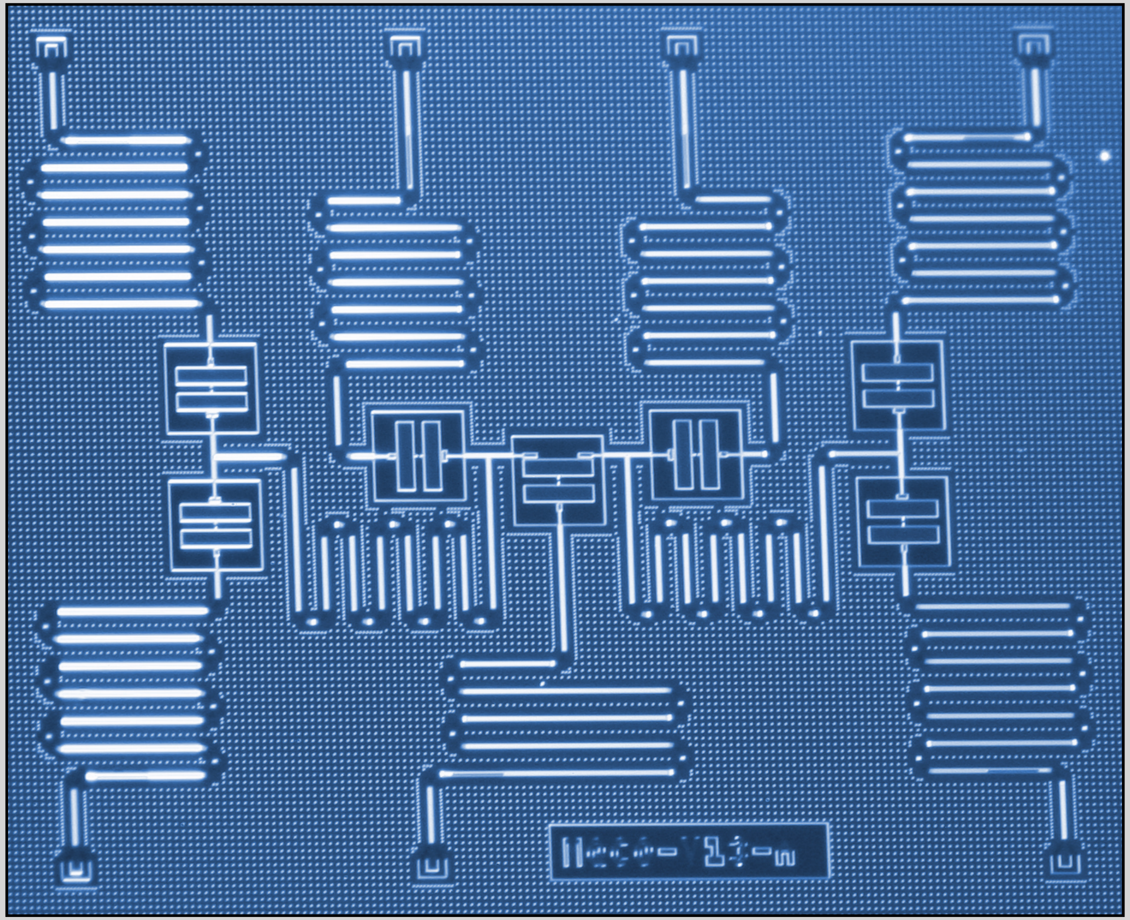
	$\lvert 0\rangle$	$\lvert 1\rangle$
Charge	+	-
or **Energy**	E_0	E_1

~ 0 K temperature



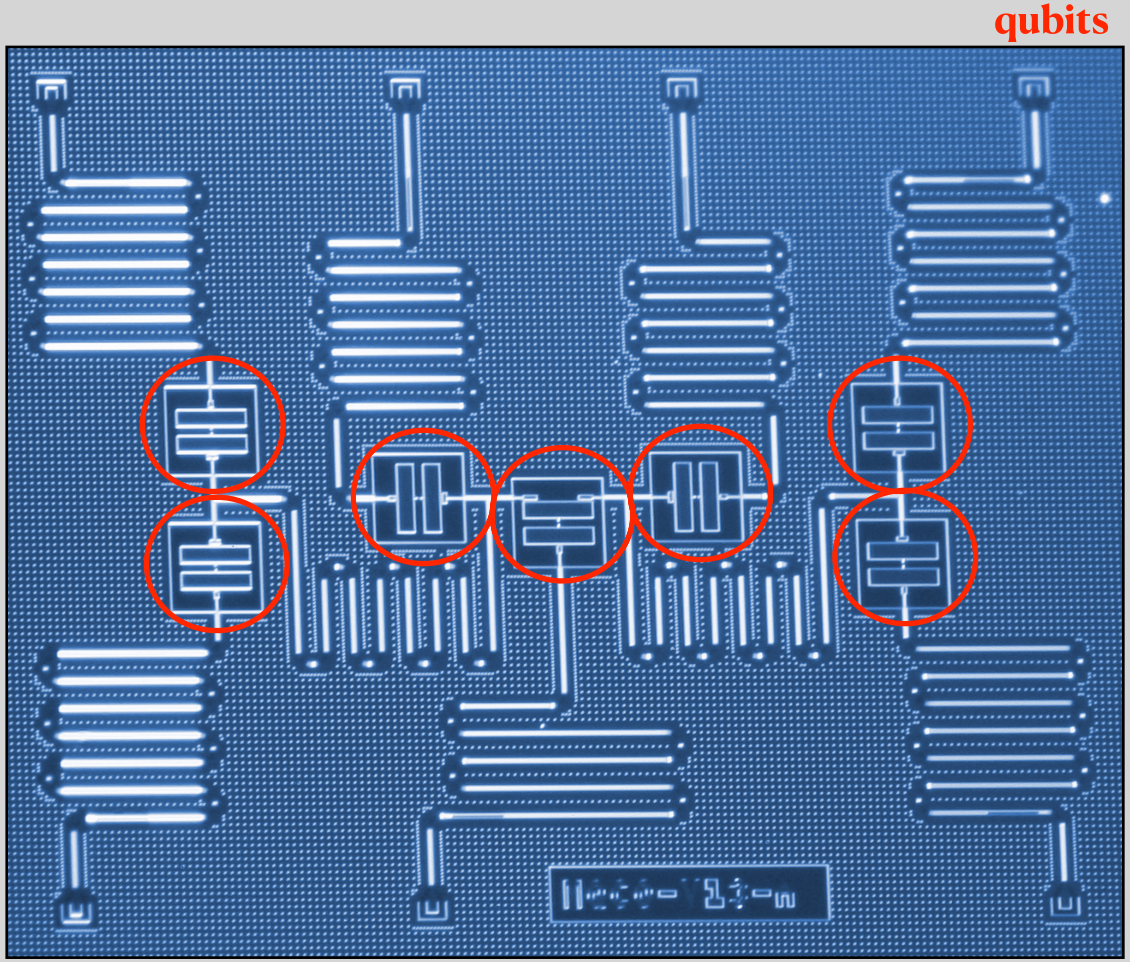
IBM 7-qubit chip

Qubit technology



IBM 7-qubit QPU

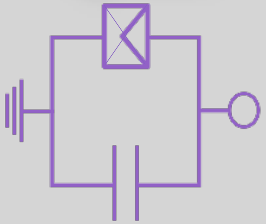
Qubit technology



IBM 7-qubit QPU

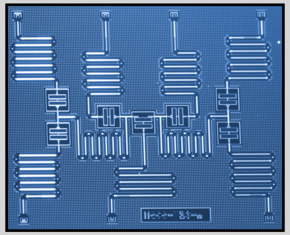
Qubit technology

Superconducting qubits



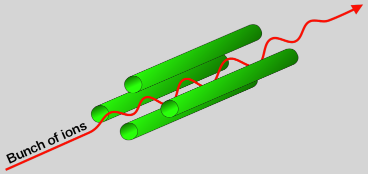
	$|0\rangle$	$|1\rangle$
Charge	+	-
or		
Energy	E_0	E_1

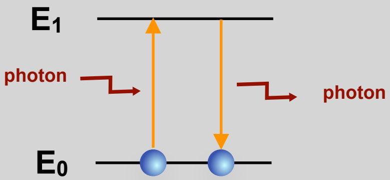
~ 0 K temperature

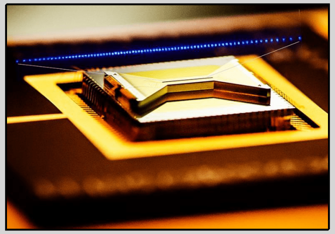


IBM 7-qubit chip

Trapped ions



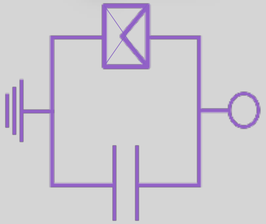




IonQ's trapped ions chip

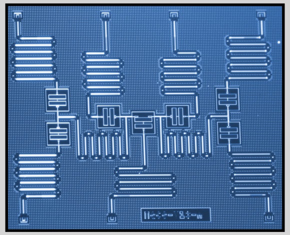
Qubit technology

Superconducting qubits



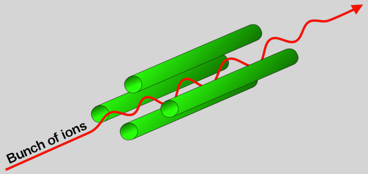
	$\|0\rangle$	$\|1\rangle$
Charge	+	-
or **Energy**	E_0	E_1

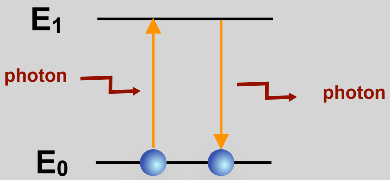
~ 0 K temperature

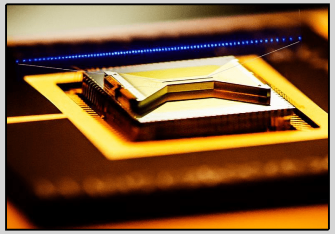


IBM 7-qubit chip

Trapped ions

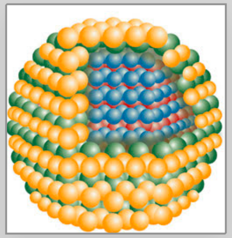


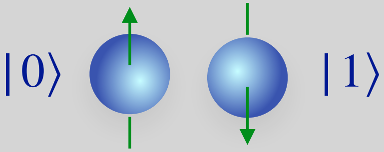




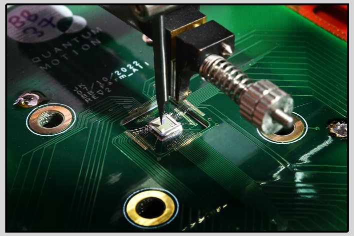
IonQ's trapped ions chip

Silicon quantum dots





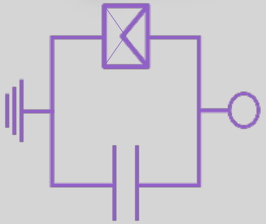
Spin



Quantum Motion's silicon chip

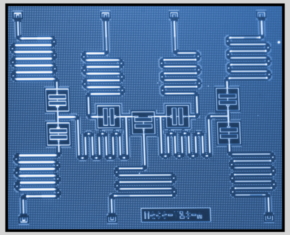
Qubit technology

Superconducting qubits



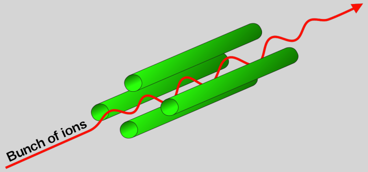
	$\vert 0\rangle$	$\vert 1\rangle$
Charge	+	-
or **Energy**	E_0	E_1

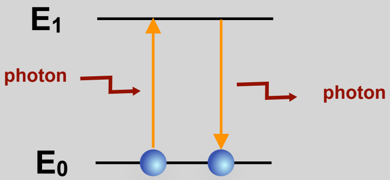
~ 0 K temperature

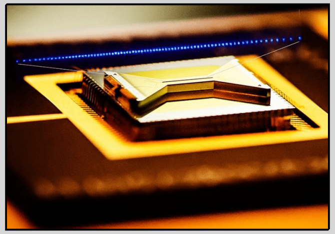


IBM 7-qubit chip

Trapped ions

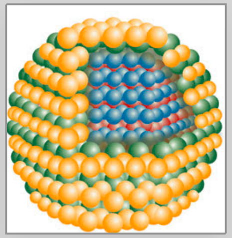


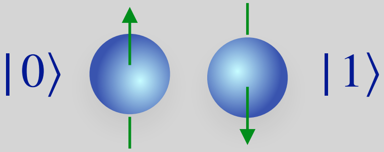




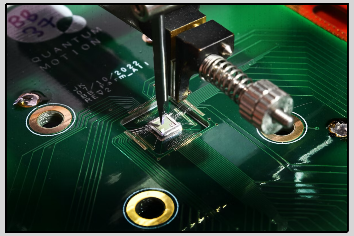
IonQ's trapped ions chip

Silicon quantum dots



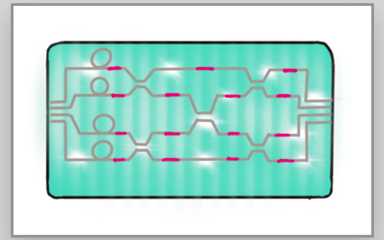


Spin

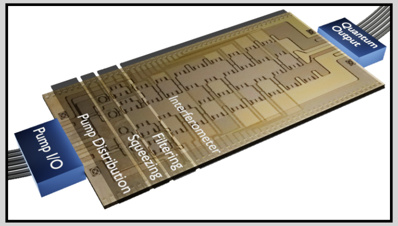


Quantum Motion's silicon chip

Photonic

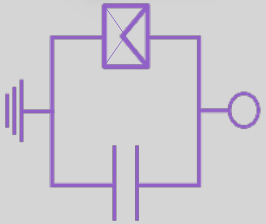


	$\vert 0\rangle$	$\vert 1\rangle$
Path	←	→
or **Polarization**	↑	↓



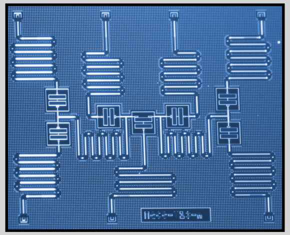
Qubit technology

Superconducting qubits



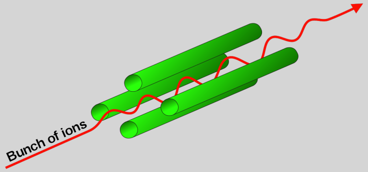
	$\vert 0\rangle$	$\vert 1\rangle$
Charge *or*	+	-
Energy	E_0	E_1

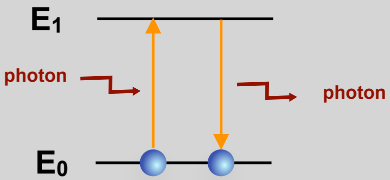
~ 0 K temperature

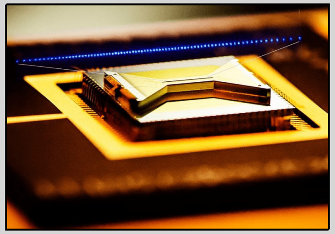


IBM 7-qubit chip

Trapped ions

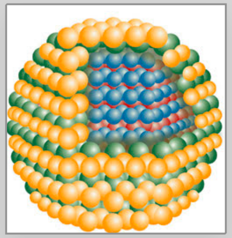


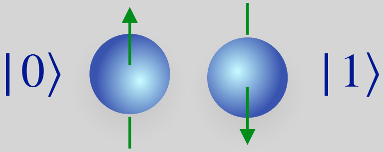




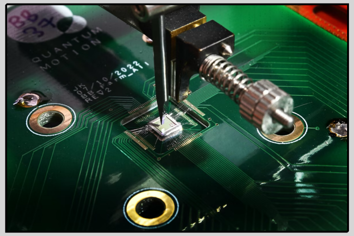
IonQ's trapped ions chip

Silicon quantum dots



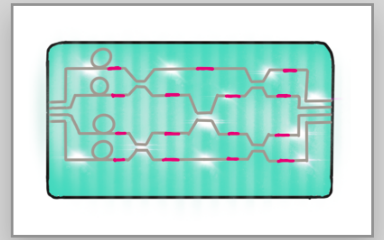


Spin

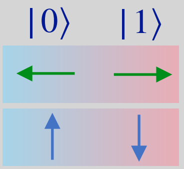


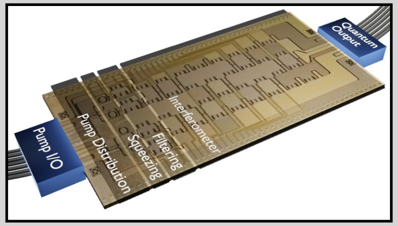
Quantum Motion's silicon chip

Photonic

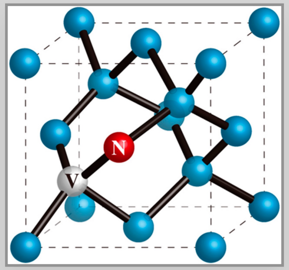


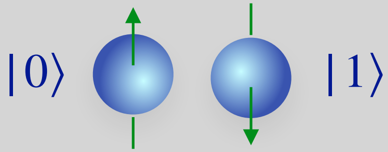
Path *or* **Polarization**





Diamond defect

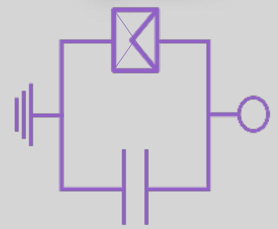




Spin

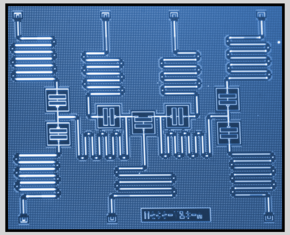
Qubit technology

Superconducting qubits



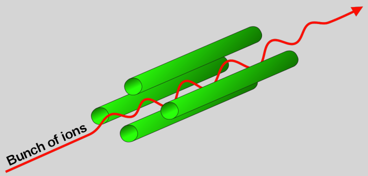
	$\lvert 0 \rangle$	$\lvert 1 \rangle$
Charge *or*	+	-
Energy	E_0	E_1

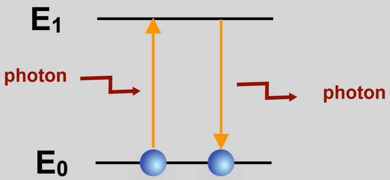
~ 0 K temperature

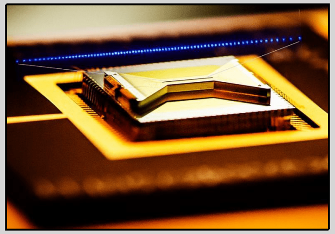


IBM 7-qubit chip

Trapped ions

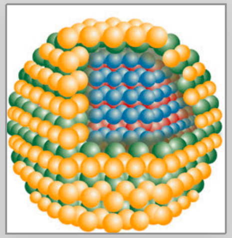


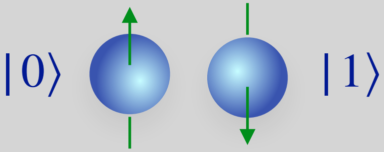




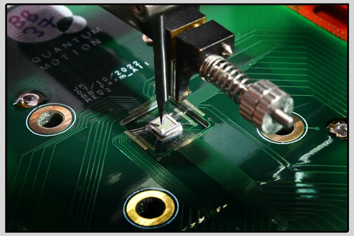
IonQ's trapped ions chip

Silicon quantum dots



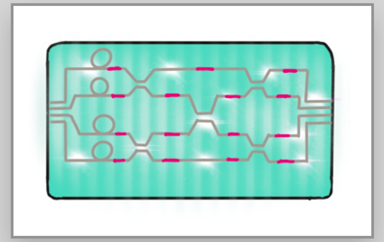


Spin

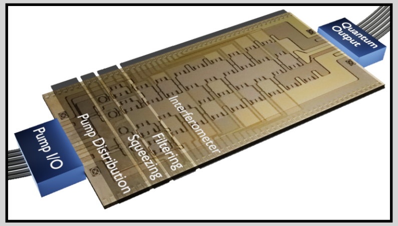


Quantum Motion's silicon chip

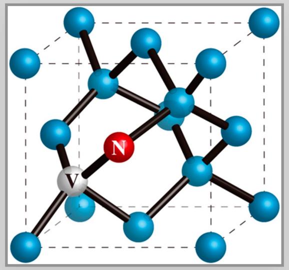
Photonic

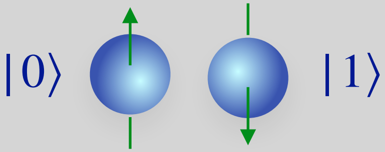


	$\lvert 0 \rangle$	$\lvert 1 \rangle$
Path *or*	←	→
Polarization	↑	↓



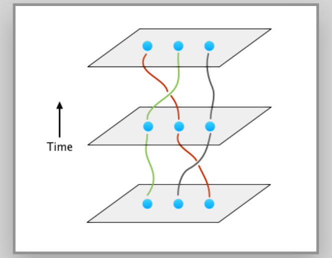
Diamond defect





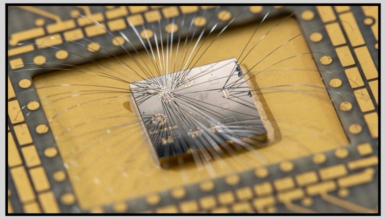
Spin

Majorana topological



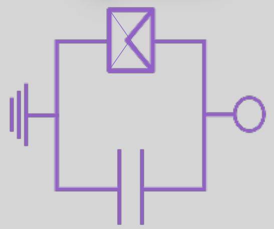
Quasiparticles

Qubit: path of particle



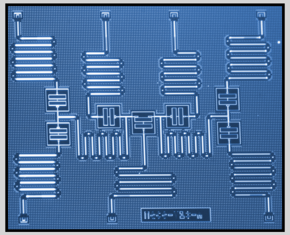
Qubit technology

Superconducting qubits



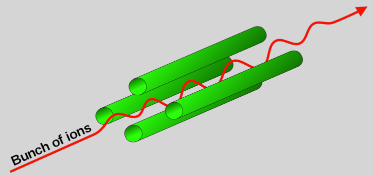
	$\vert 0\rangle$	$\vert 1\rangle$
Charge *or* **Energy**	+	-
	E_0	E_1

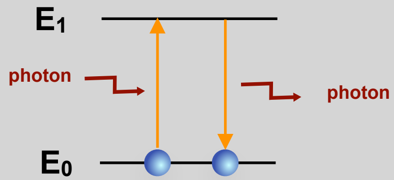
~ 0 K temperature

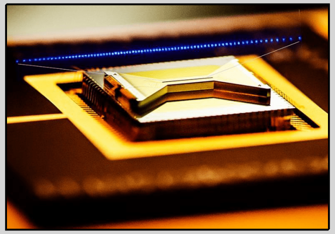


IBM 7-qubit chip

Trapped ions

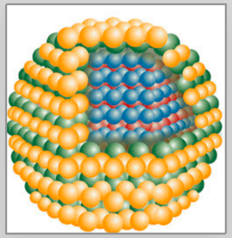


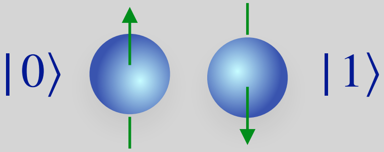




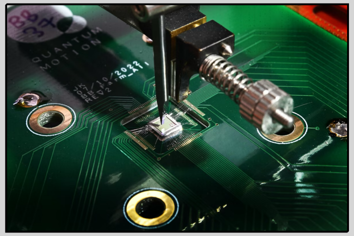
IonQ's trapped ions chip

Silicon quantum dots



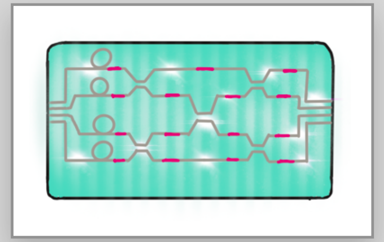


Spin

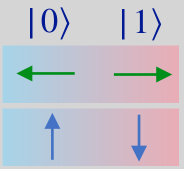


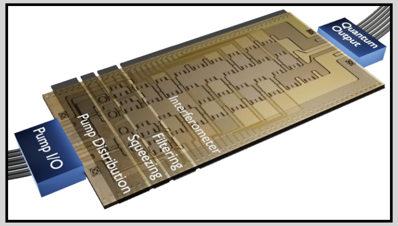
Quantum Motion's silicon chip

Photonic

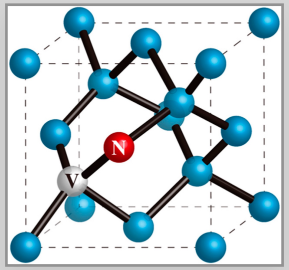


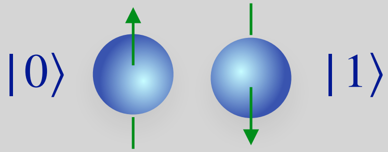
Path *or* **Polarization**





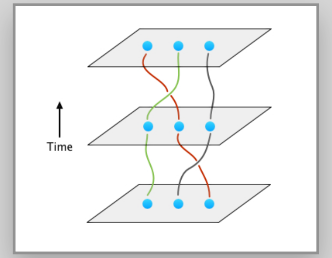
Diamond defect





Spin

Majorana topological



Quasiparticles

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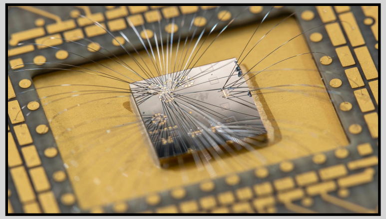
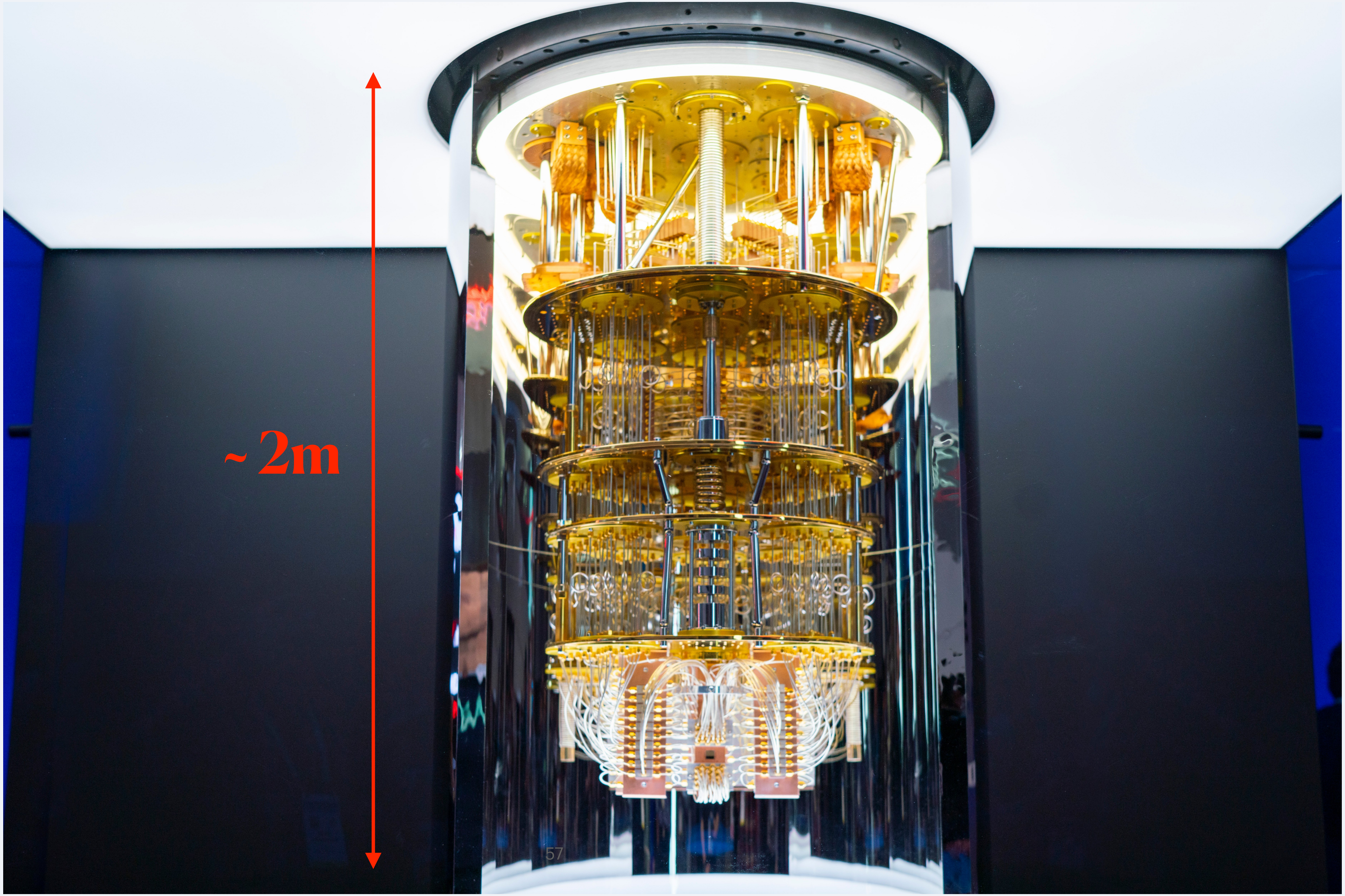


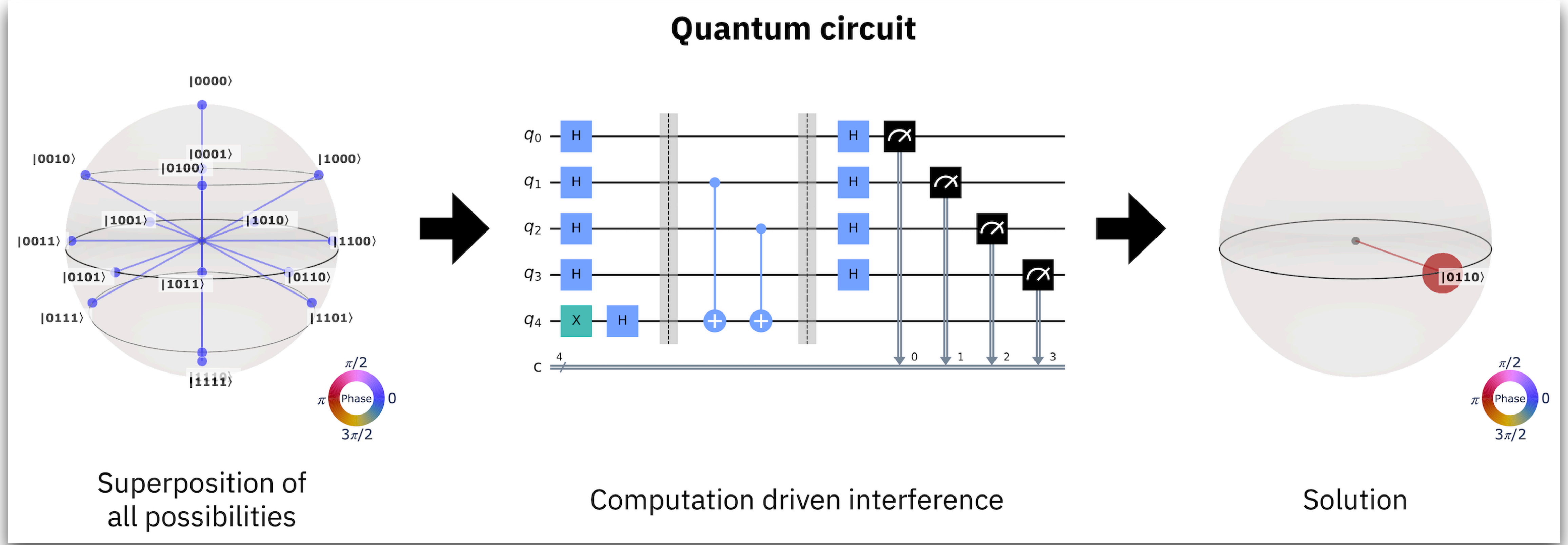
55

IBM system one

IBM system one



space size = 2^N



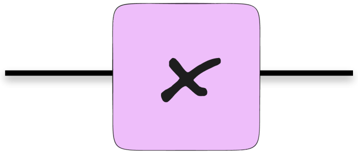
[IBM]

Gate-based model

Universal gate quantum computing

Quantum Gates

Pauli-X



NOT gate

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

$|0\rangle \rightarrow |1\rangle$

$|1\rangle \rightarrow |0\rangle$

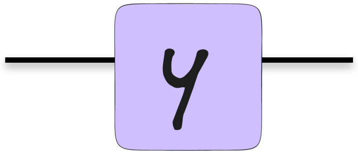
Quantum Gates

Pauli-X

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

$|0\rangle \rightarrow |1\rangle$ $\quad$ $|1\rangle \rightarrow |0\rangle$

Pauli-Y



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

$|0\rangle \rightarrow i|1\rangle$ $\quad$ $|1\rangle \rightarrow -i|0\rangle$

Quantum Gates

Pauli-X

X

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

$|0\rangle \rightarrow |1\rangle$ $|1\rangle \rightarrow |0\rangle$

Pauli-Y

Y

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

$|0\rangle \rightarrow i|1\rangle$ $|1\rangle \rightarrow -i|0\rangle$

Pauli-Z

Z

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

$|0\rangle \rightarrow |0\rangle$ $|1\rangle \rightarrow -|1\rangle$

Quantum Gates

Pauli-X

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

$|0\rangle \rightarrow |1\rangle$ $\quad$ $|1\rangle \rightarrow |0\rangle$

Pauli-Y

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

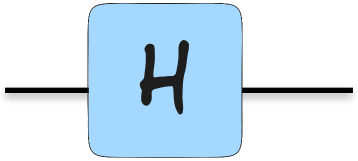
$|0\rangle \rightarrow i|1\rangle$ $\quad$ $|1\rangle \rightarrow -i|0\rangle$

Pauli-Z

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

$|0\rangle \rightarrow |0\rangle$ $\quad$ $|1\rangle \rightarrow -|1\rangle$

Hadamard



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

$|0\rangle \rightarrow |+\rangle$ $\quad$ $|1\rangle \rightarrow |-\rangle$

Quantum Gates

Pauli-X

X

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad |0\rangle \rightarrow |1\rangle \qquad |1\rangle \rightarrow |0\rangle$$

Pauli-Y

Y

$$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad |0\rangle \rightarrow i|1\rangle \qquad |1\rangle \rightarrow -i|0\rangle$$

Pauli-Z

Z

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad |0\rangle \rightarrow |0\rangle \qquad |1\rangle \rightarrow -|1\rangle$$

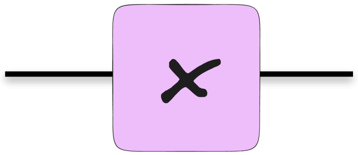
Hadamard

H

$$\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \qquad |0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right) \qquad |1\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle - |1\rangle\right)$$

Single-Qubit Gates

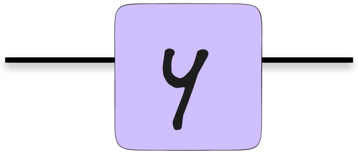
Pauli-X



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

$|0\rangle \rightarrow |1\rangle$ $\quad$ $|1\rangle \rightarrow |0\rangle$

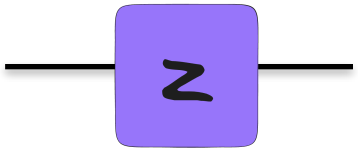
Pauli-Y



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

$|0\rangle \rightarrow i|1\rangle$ $\quad$ $|1\rangle \rightarrow -i|0\rangle$

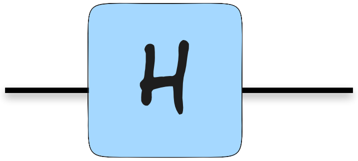
Pauli-Z



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

$|0\rangle \rightarrow |0\rangle$ $\quad$ $|1\rangle \rightarrow -|1\rangle$

Hadamard

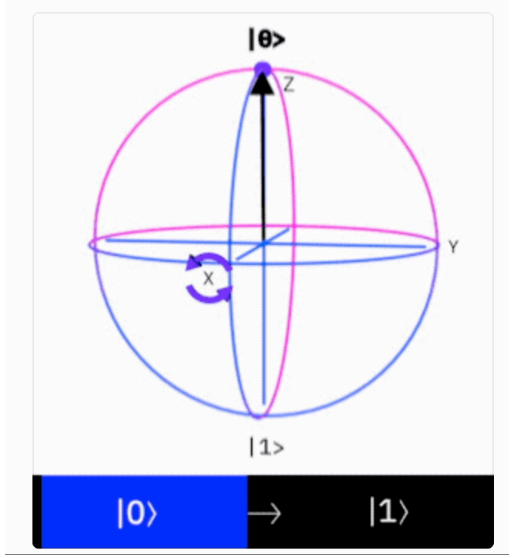


$$\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

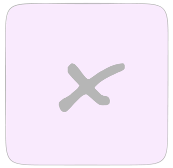
$|0\rangle \rightarrow |+\rangle$ $\quad$ $|1\rangle \rightarrow |-\rangle$

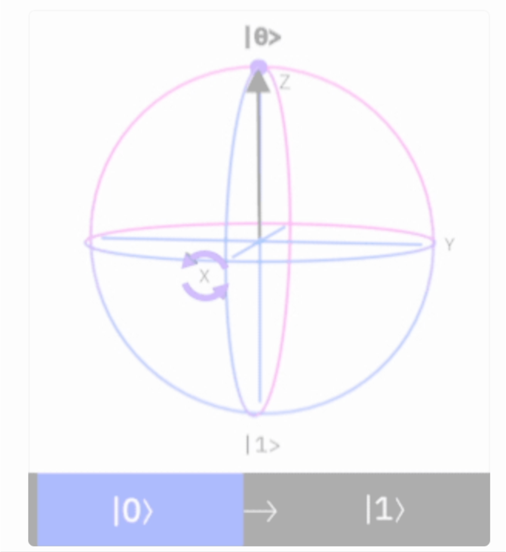
Quantum Gates as rotations

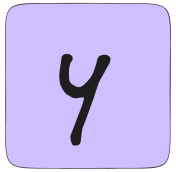
X

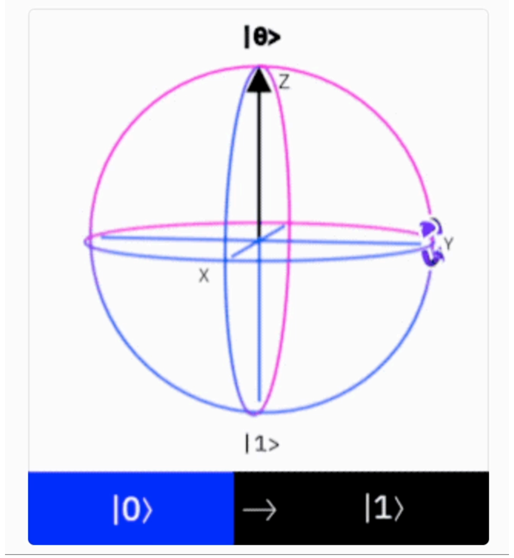


Quantum Gates as rotations



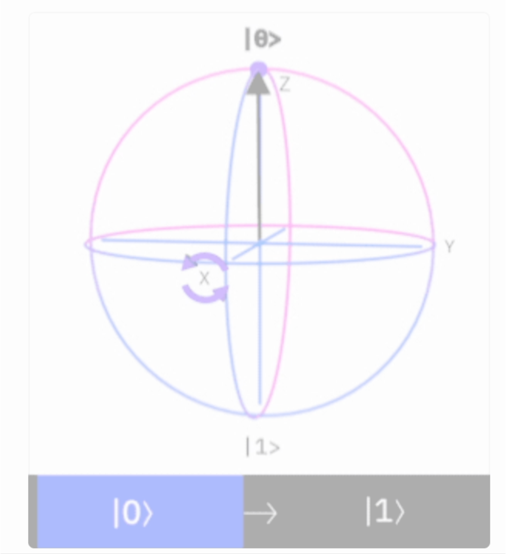




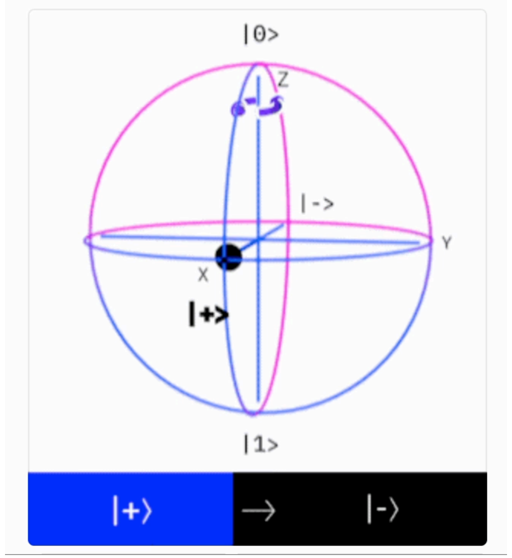


Quantum Gates as rotations

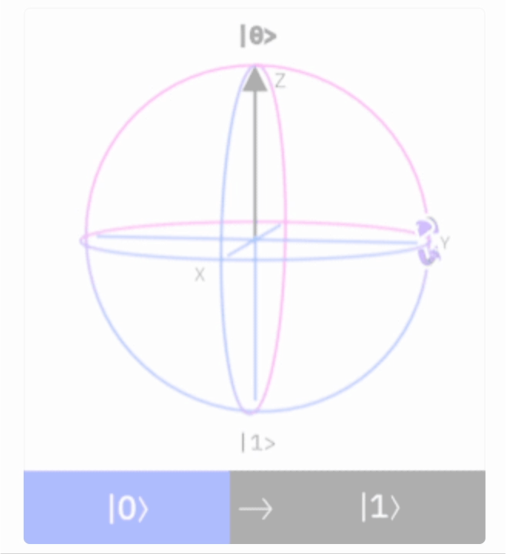
X



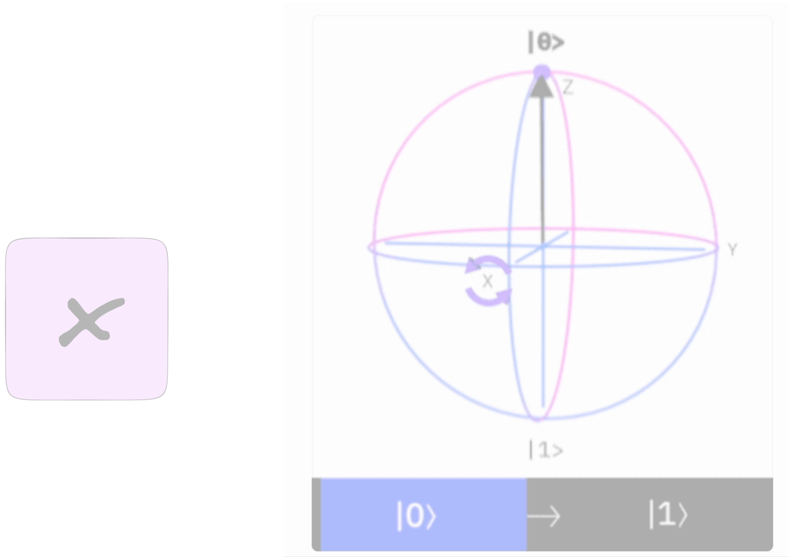
Z

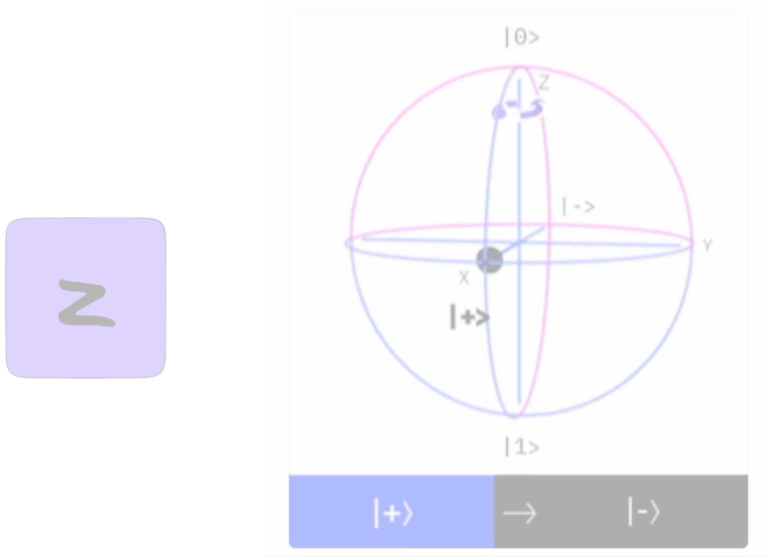


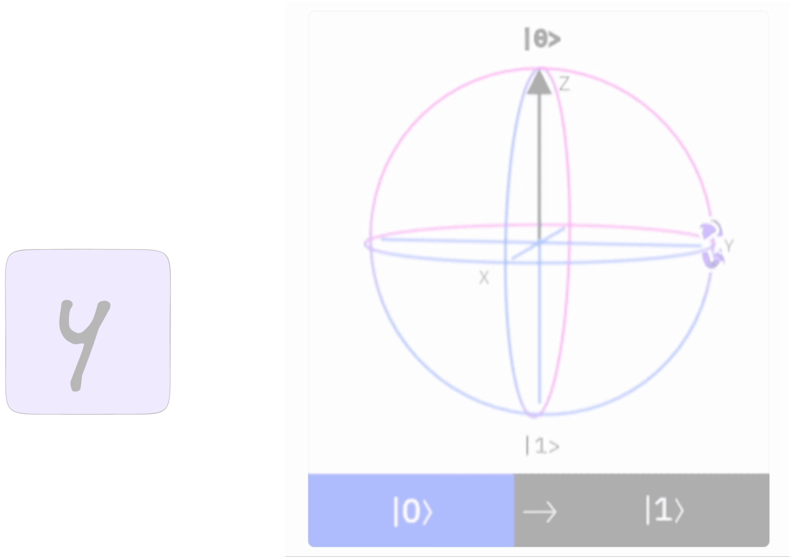
Y

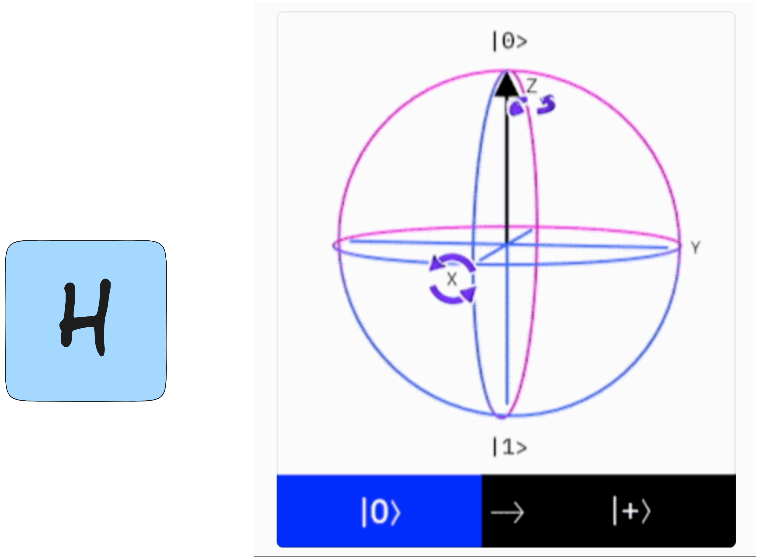


Quantum Gates as rotations







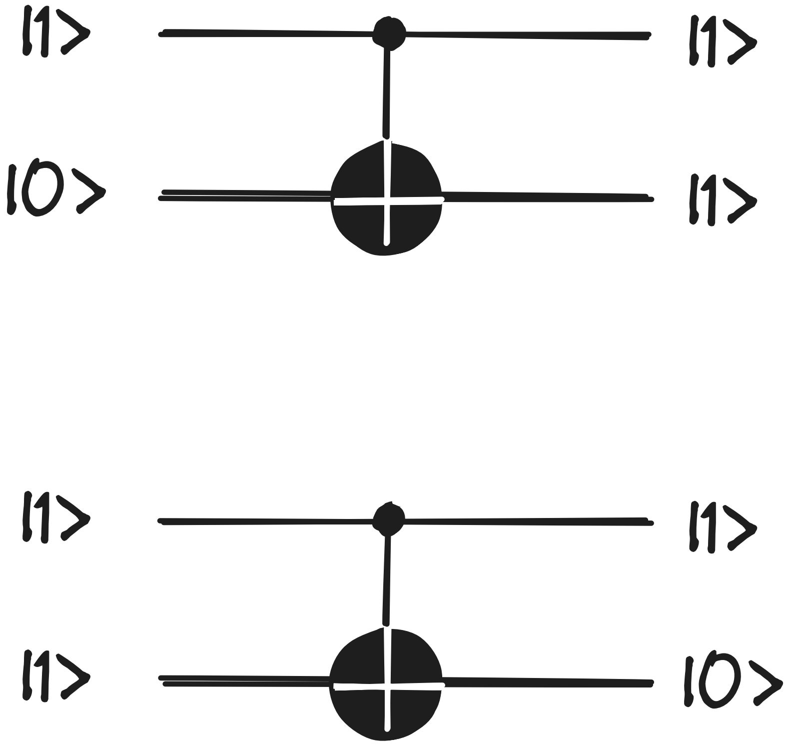


Unitary conditon

$$U \cdot U^{\dagger} = I$$

$$\dagger = (*)^T$$

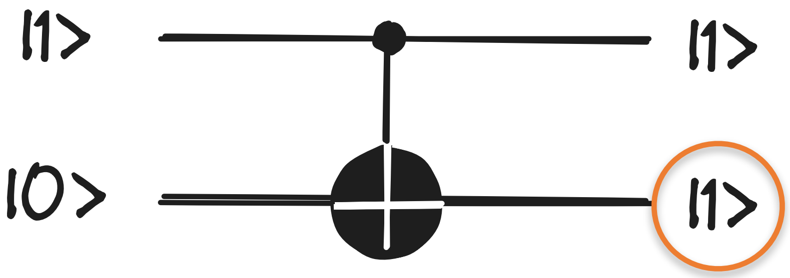
Two-Qubit Gate

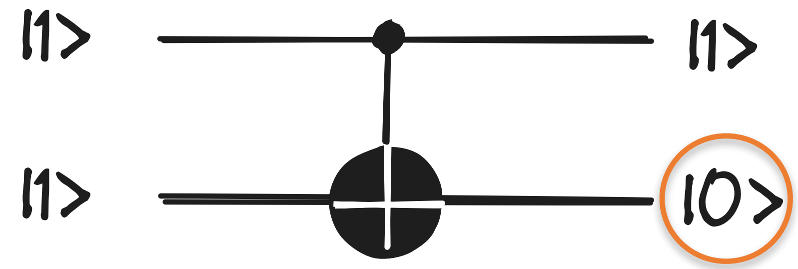


Controlled - NOT

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

Two-Qubit Gate

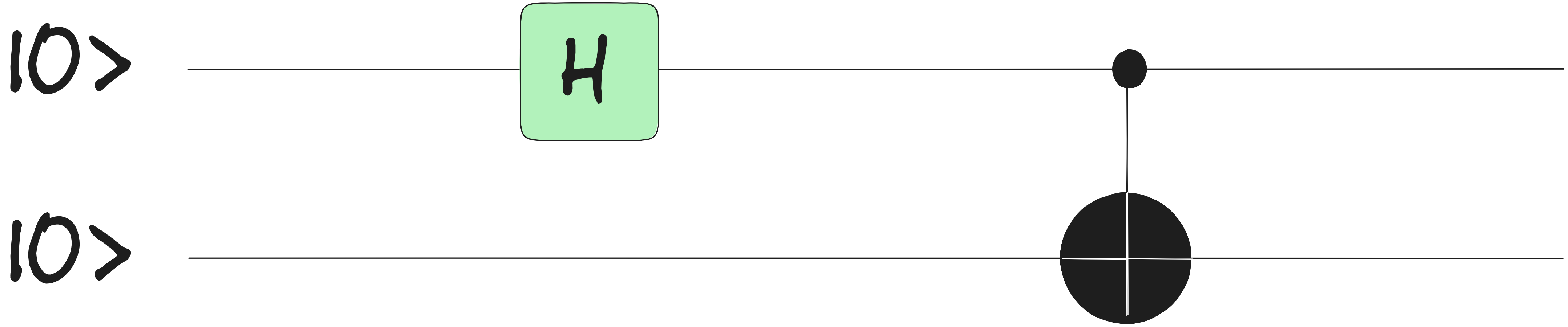




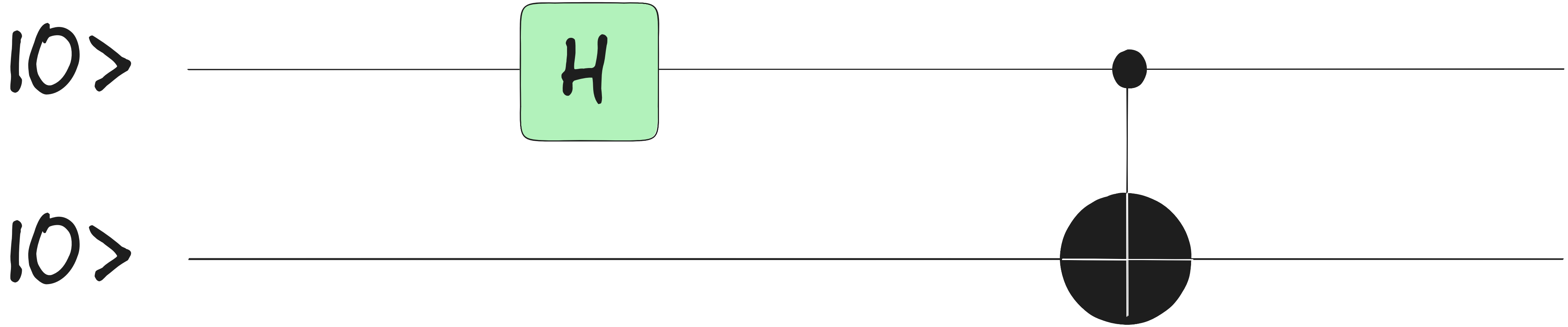
Controlled - NOT

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

Quantum Circuit



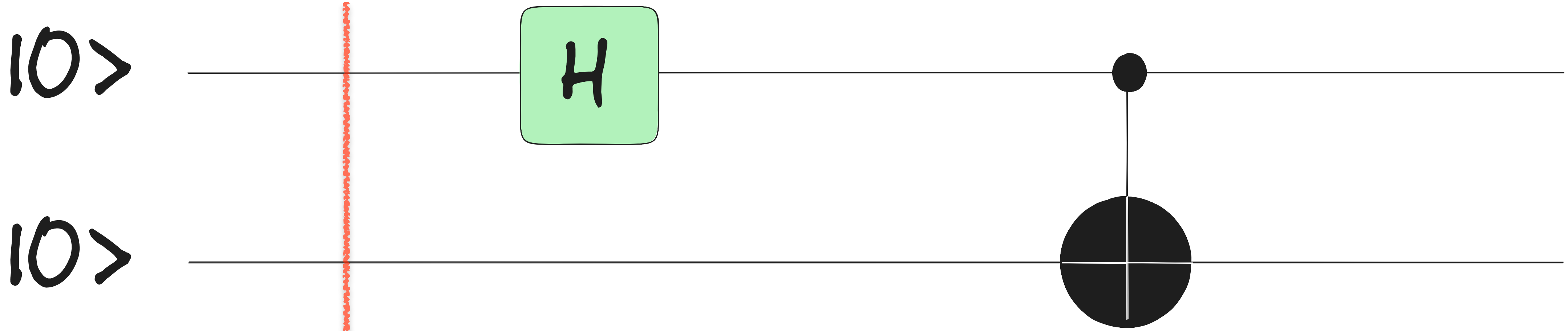
Quantum Circuit



$$|0\rangle \otimes |0\rangle$$

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

Quantum Circuit



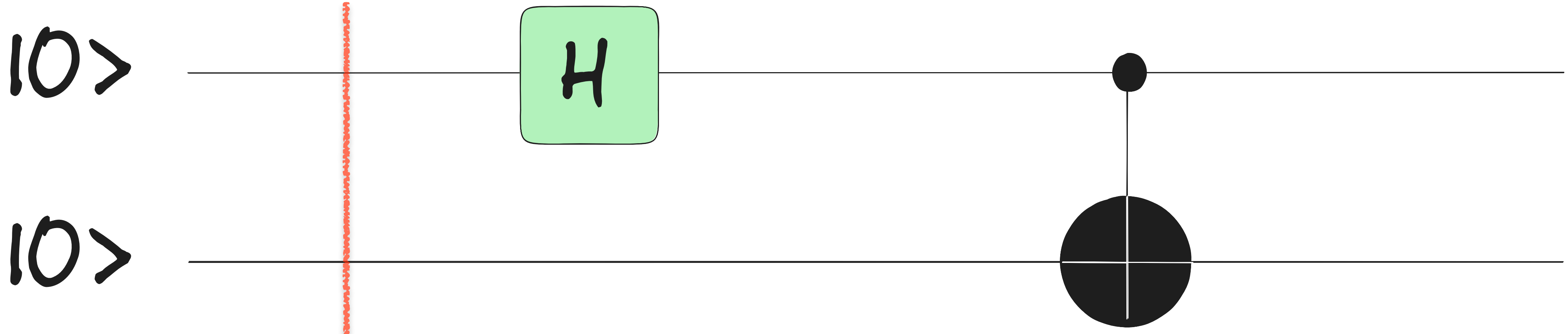
$$|0\rangle \otimes |0\rangle$$

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

$$|+\rangle \otimes |0\rangle$$

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

Quantum Circuit

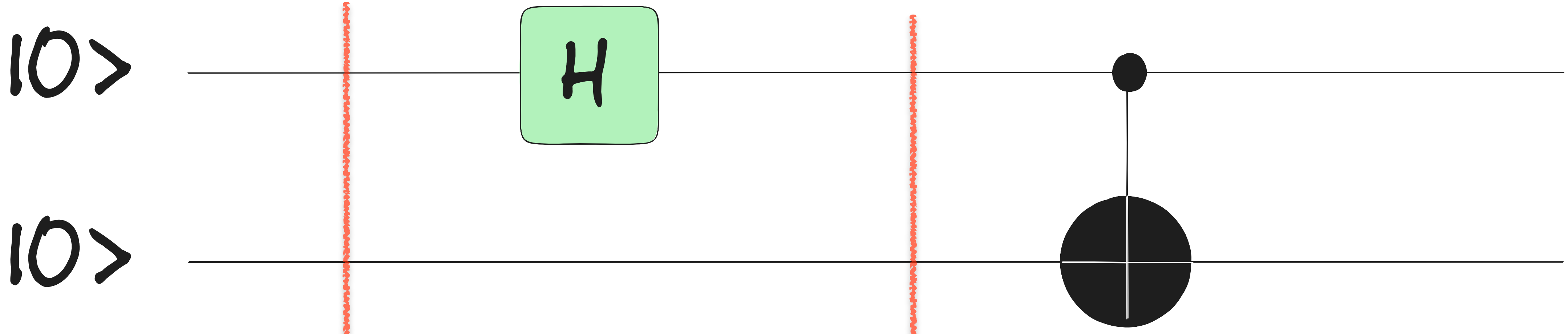


$$|0\rangle \otimes |0\rangle \qquad \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$|+\rangle \otimes |0\rangle \qquad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

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

Quantum Circuit



$|0\rangle \otimes |0\rangle$

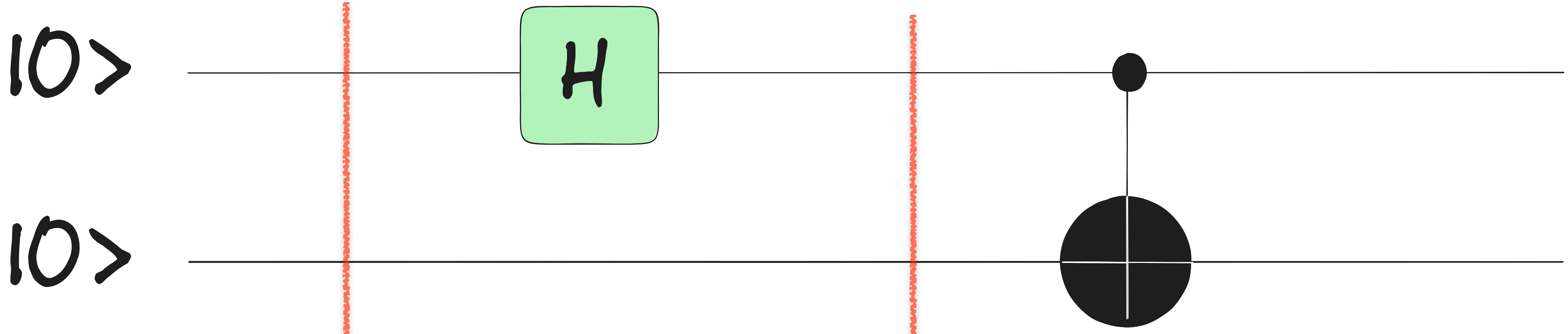
$$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$|+\rangle \otimes |0\rangle$

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

$$\frac{|00\rangle + |11\rangle}{\sqrt{2}} \qquad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Bell State

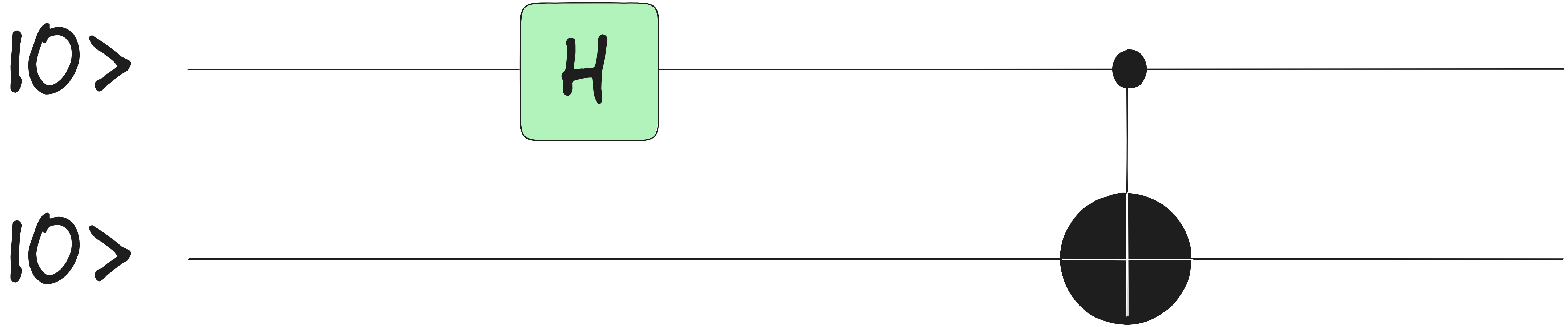


$$|0\rangle \otimes |0\rangle \qquad \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$|+\rangle \otimes |0\rangle \qquad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

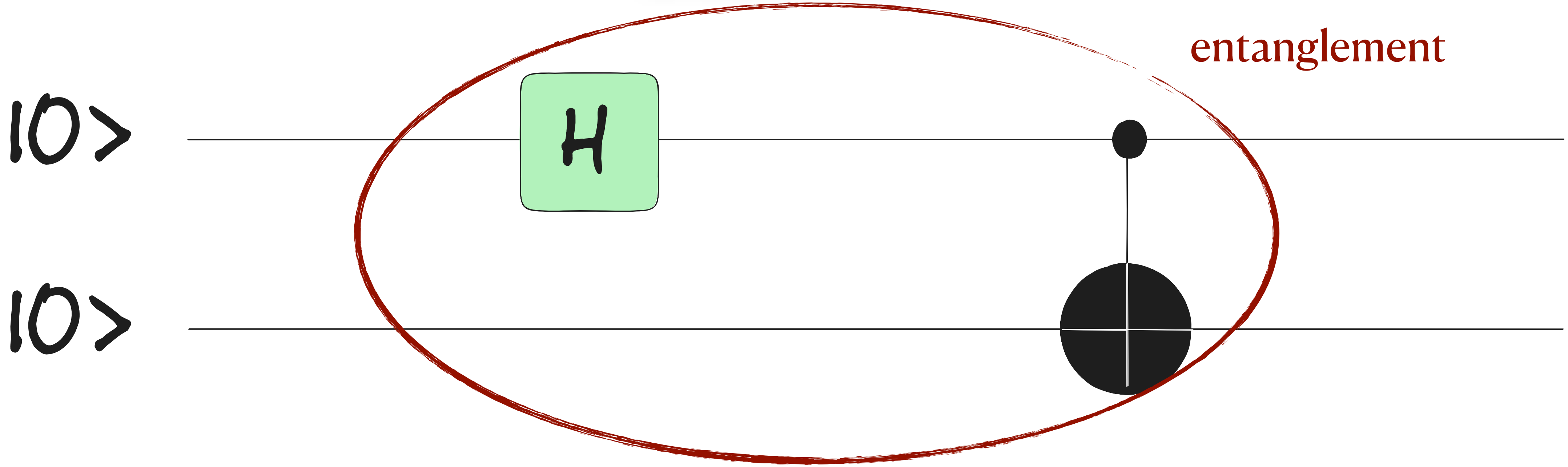
$$\frac{|00\rangle + |11\rangle}{\sqrt{2}} \qquad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Bell State



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

Bell State

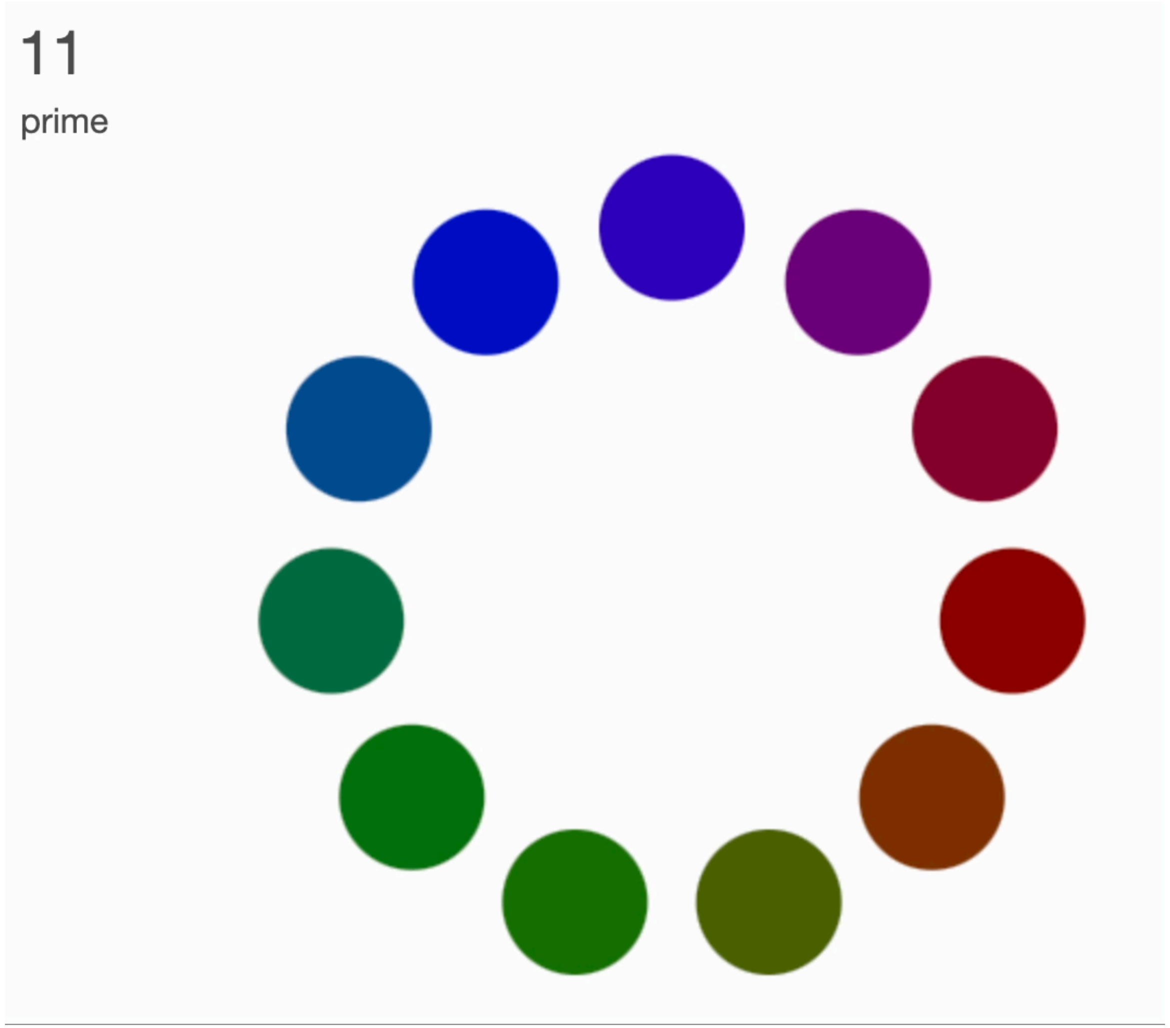


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

Shor's algorithm

integer factorization

$$\mathcal{O}(log(N)^3) \ll \mathcal{O}(exp(N))$$



Animated diagram [link]

Grover's algorithm

unstructured seach problem

$$\mathcal{O}(\sqrt{N}) < \mathcal{O}(N)$$

UNORDERED LIST

A searchers nightmare

042	134	423	623	031	084	902	017	184	391	284	783
320	234	032	602	884	125	672	273	567	865	356	582
022	199	057	903	479	543	456	394	342	091	962	774
753	016	653	168	357	348	185	802	593	347	123	631
072	193	321	039	963	180	089	992	795	730	245	583
534	780	465	162	742	045	278	943	094	302	449	683

Grover is better than Google at search [link]

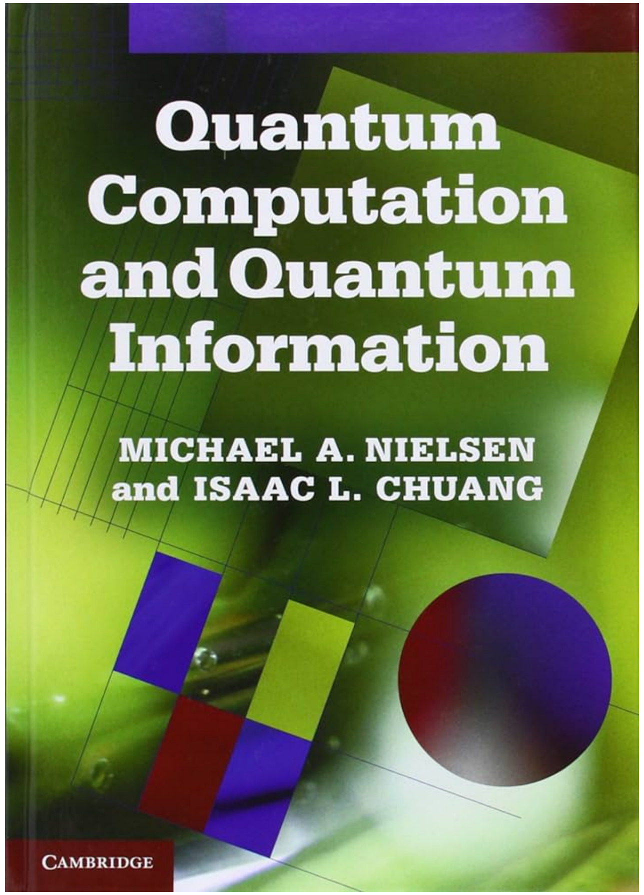
PENNYLANE

Qiskit

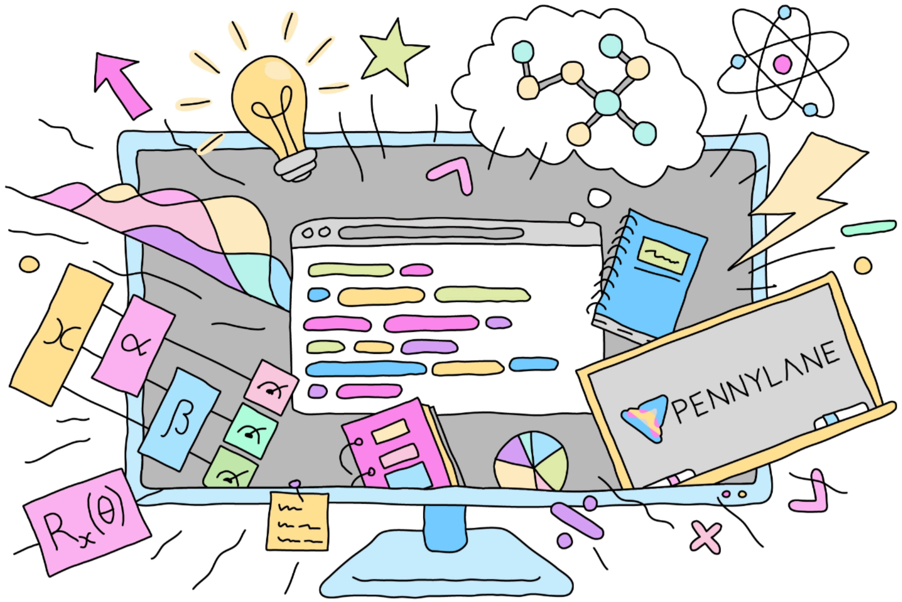
Cirq

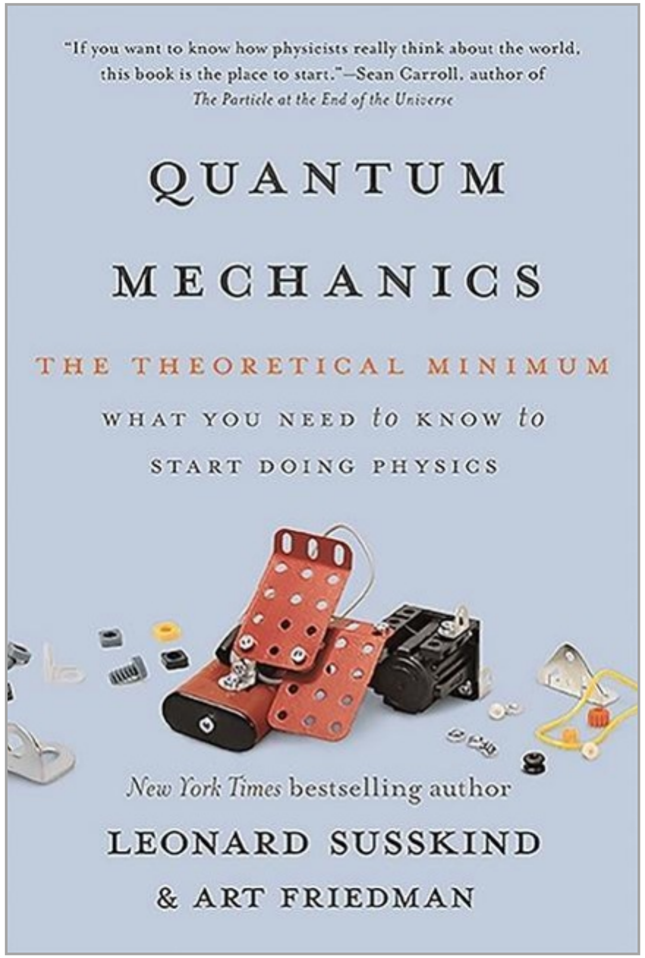
Yao.jl

Learning material



IBM Quantum Learning





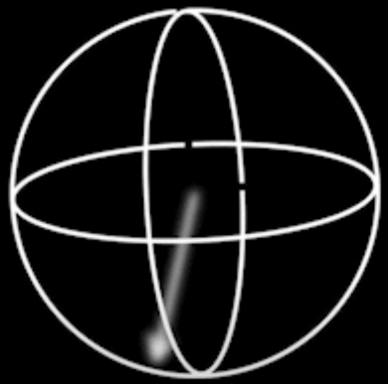
QUESTIONS?

ema.puljak@cern.ch

Interacting with environment makes qubits prone to

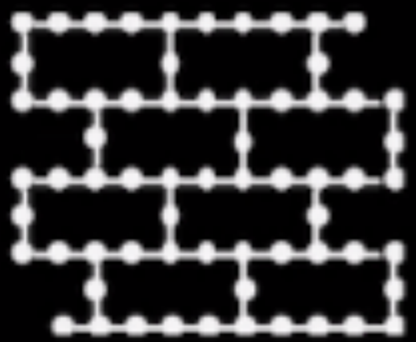
Quantum errors

HEAT, COSMIC RAYS, SYSTEM ERRORS



vs

vs



Linear

Square

Heavy-hex