

QUANTUM, QUANTUM, QUANTUM

SEPTEMBER 19 @NATIONAL TAIWAN UNIVERSITY

YUN-CHIH LIAO IBM QUANTUM COMPUTER HUB AT NTU



Fri, 9/18



Moon

妙天要來請教量子，我拒絕了，你們誰有人要去？

19:08



Acorn

大家陪您去，看看妙天有什麼神通廣大

19:09

OUTLINE

History: From Classical to Quantum

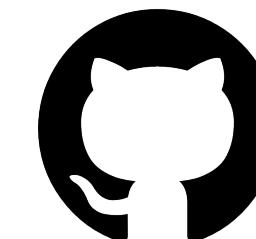
Warm Up: Tools

Quantum Language

Quantum Computers

Your First Quantum Circuit

Advanced: Superconducting Qubits



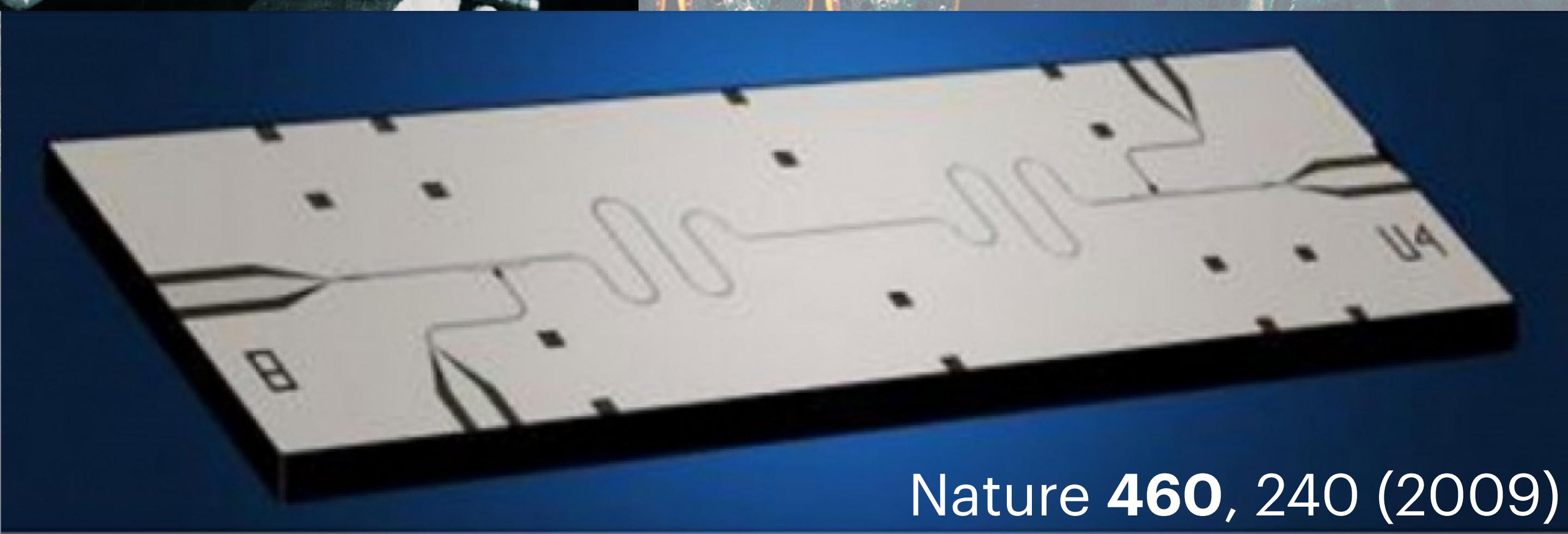
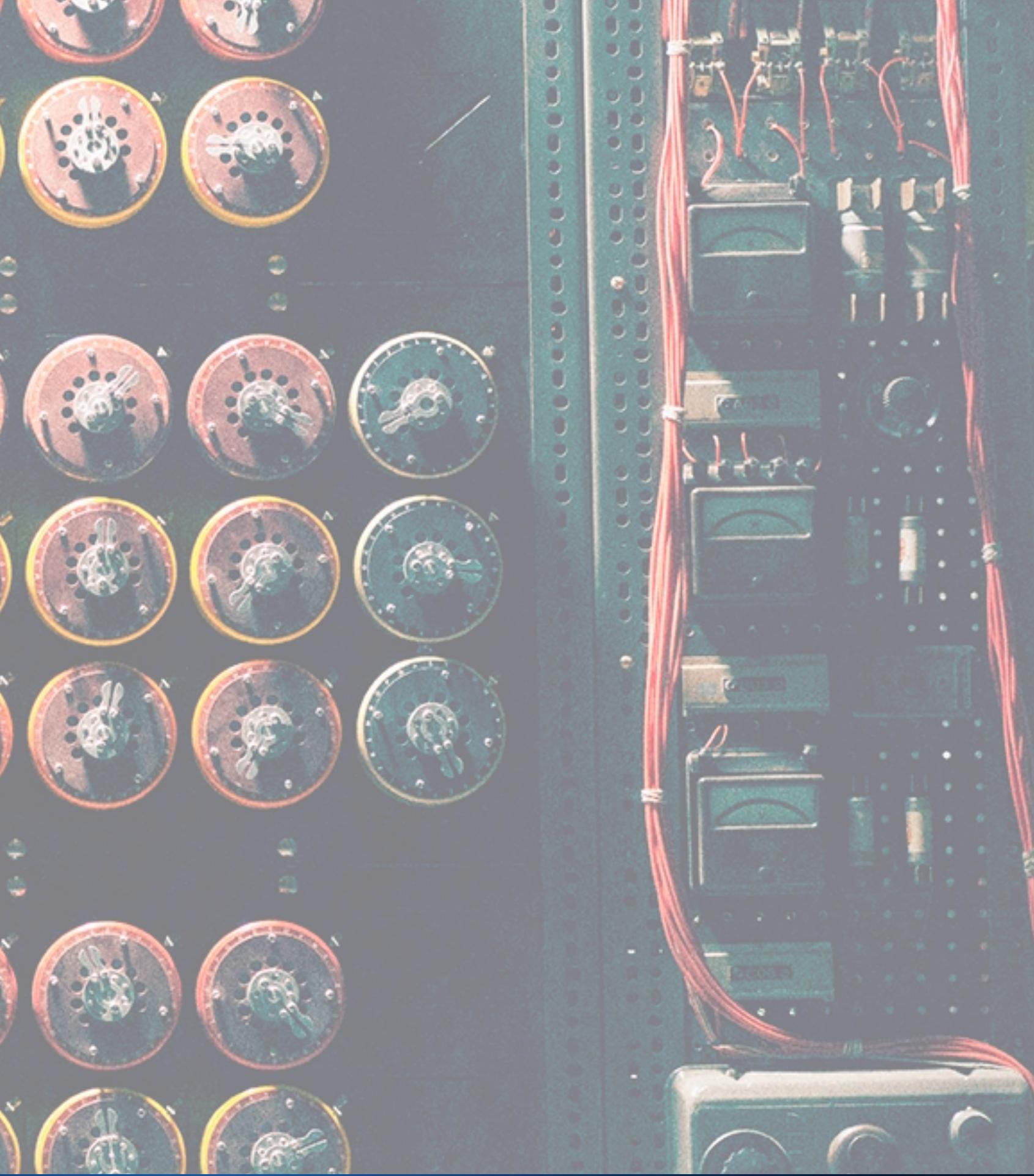
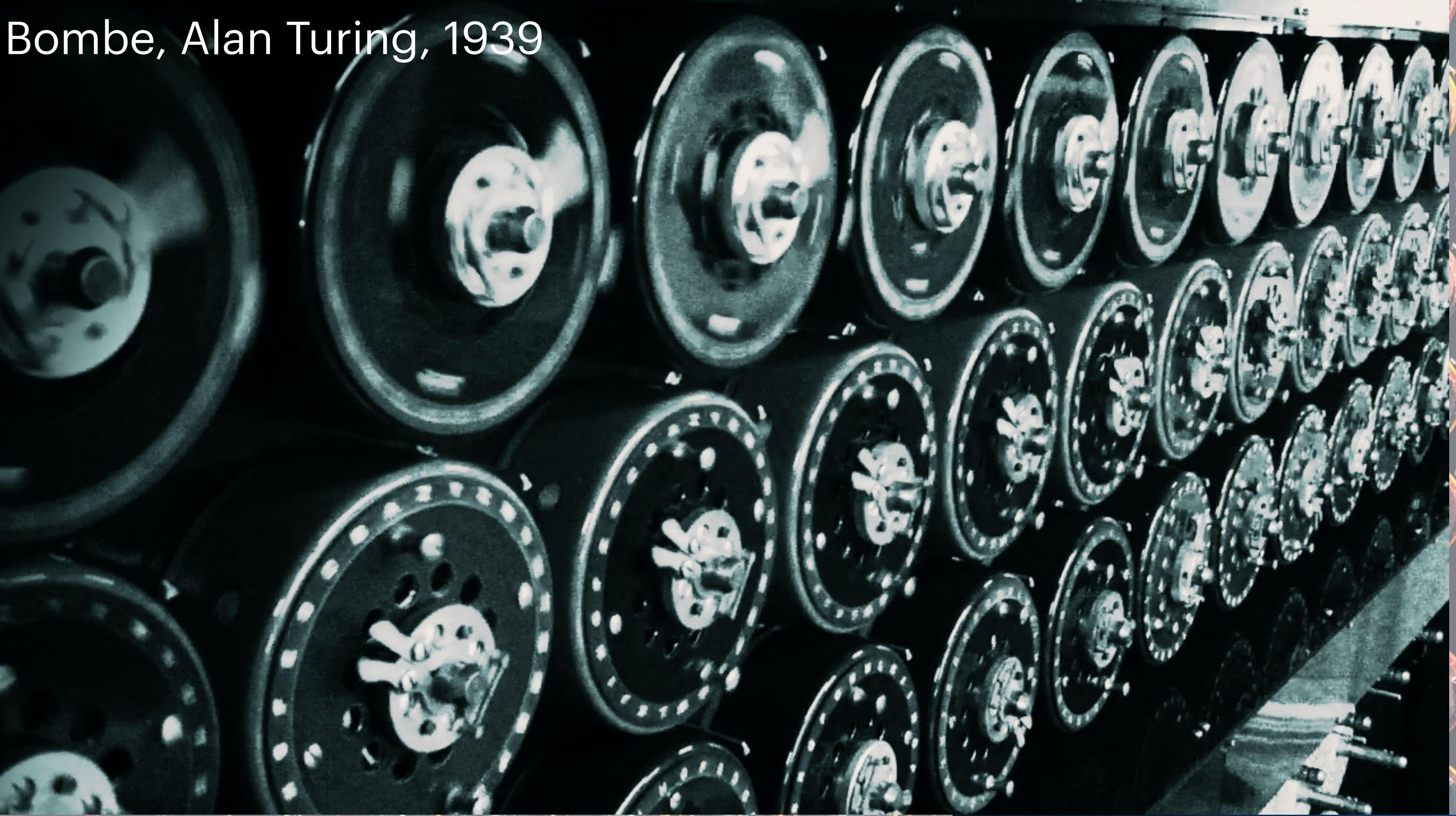
https://github.com/yldingo/QuantumComputer_tw

https://github.com/yldingo/QuantumComputing_2020Summer

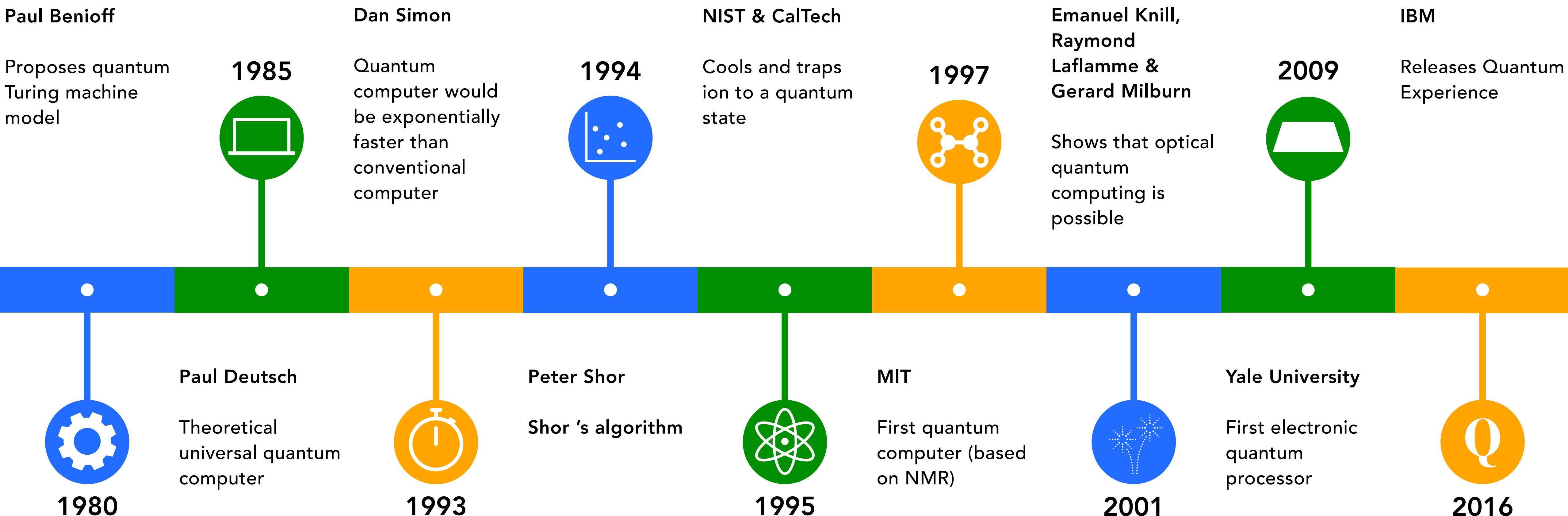
A man in a dark suit stands from behind, facing a wall covered in a grid of circular quantum computing modules. Each module is a complex assembly of red and yellow components, likely lasers or optical lenses, mounted on a dark substrate. The wall is filled with these modules, creating a dense, patterned background. To the left and right of the man, there are vertical panels with various electronic components, wires, and connectors, suggesting a high-tech laboratory or industrial setting.

FROM CLASSICAL TO QUANTUM

Bombe, Alan Turing, 1939

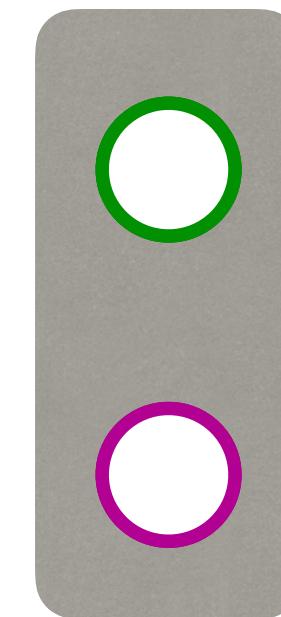


HISTORY

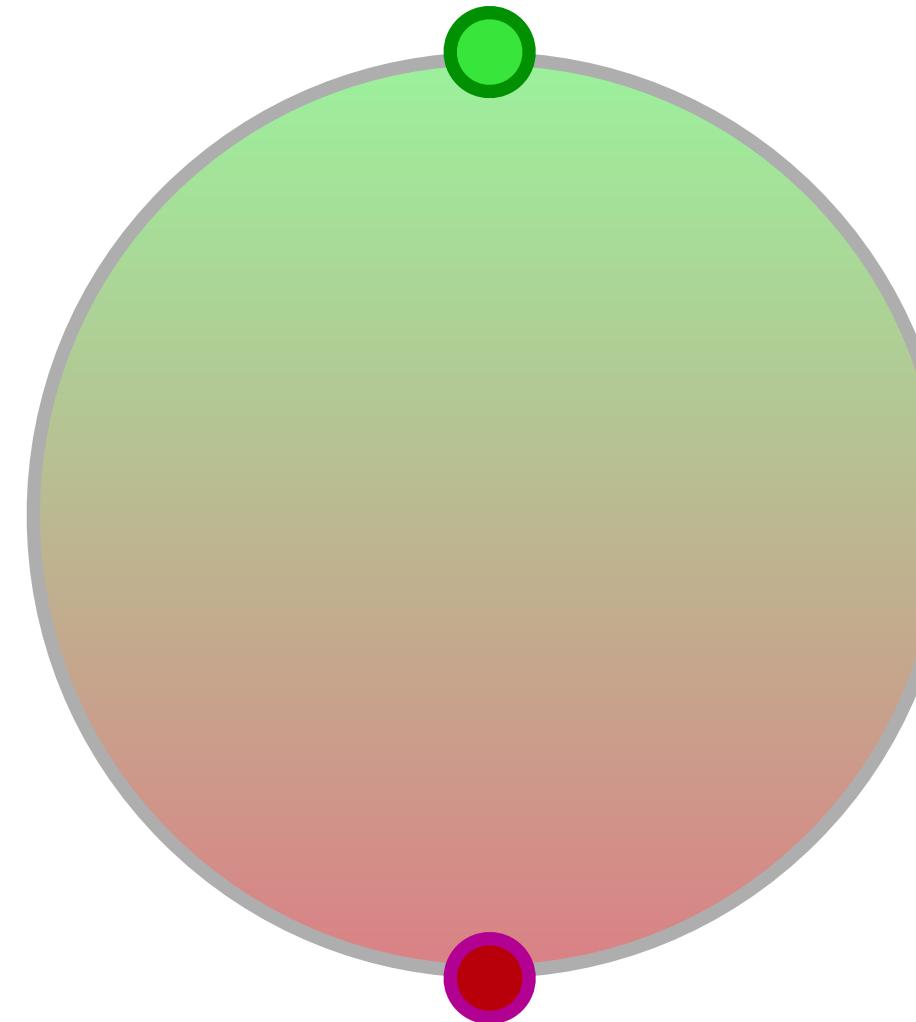


CLASSICAL V.S. QUANTUM

Bit

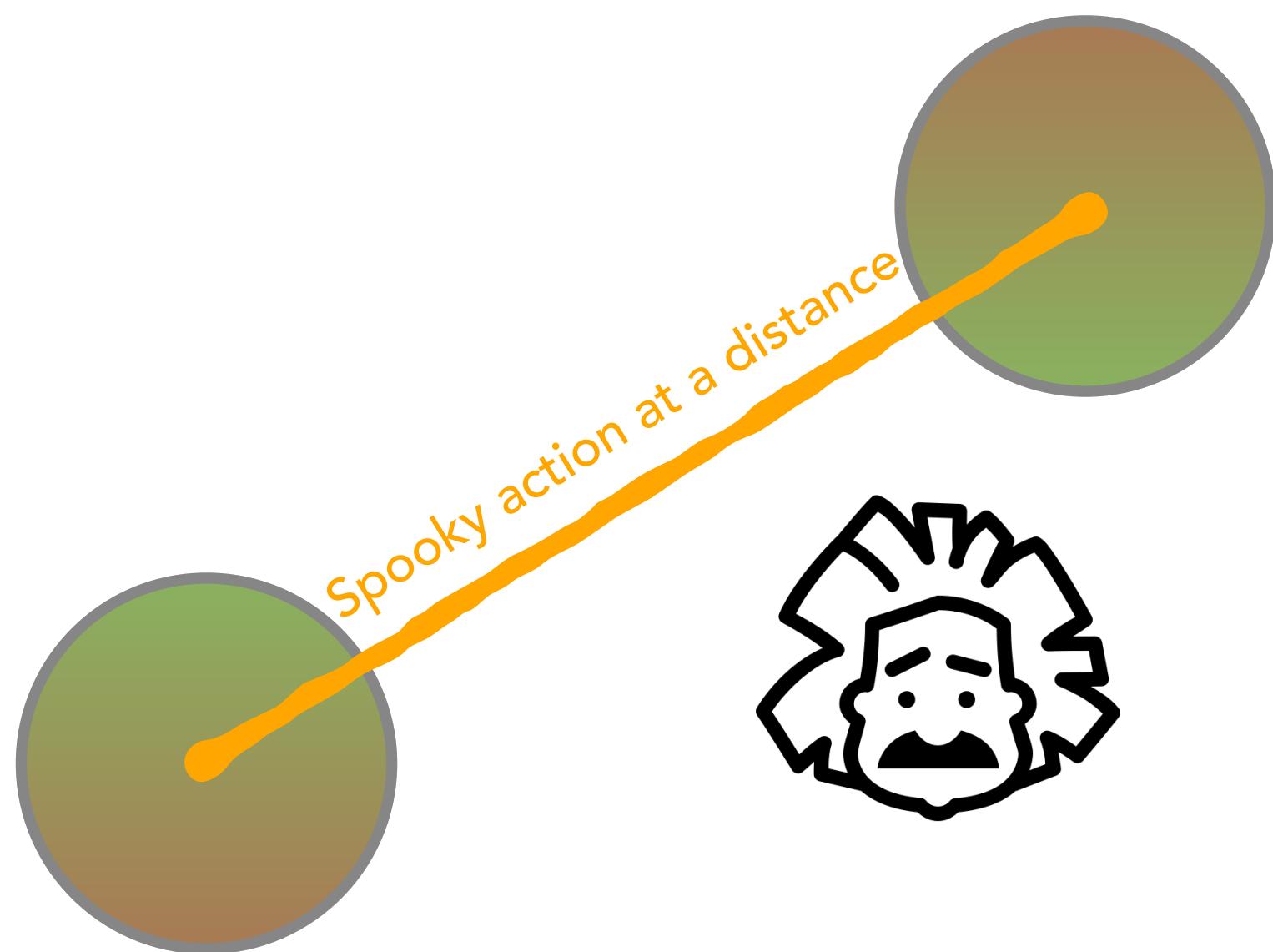


Qubit

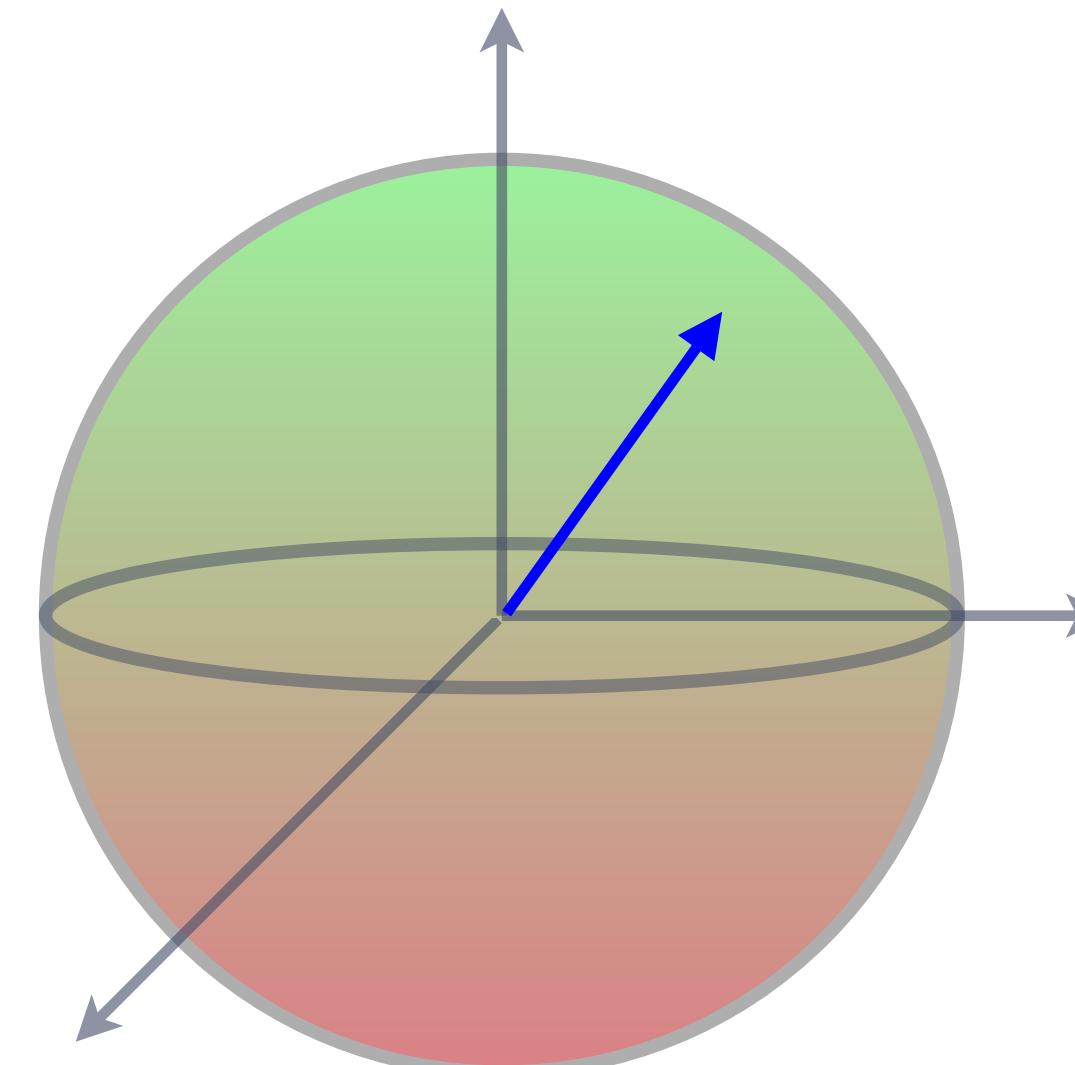


WHY SO POWERFUL ?

Entanglement

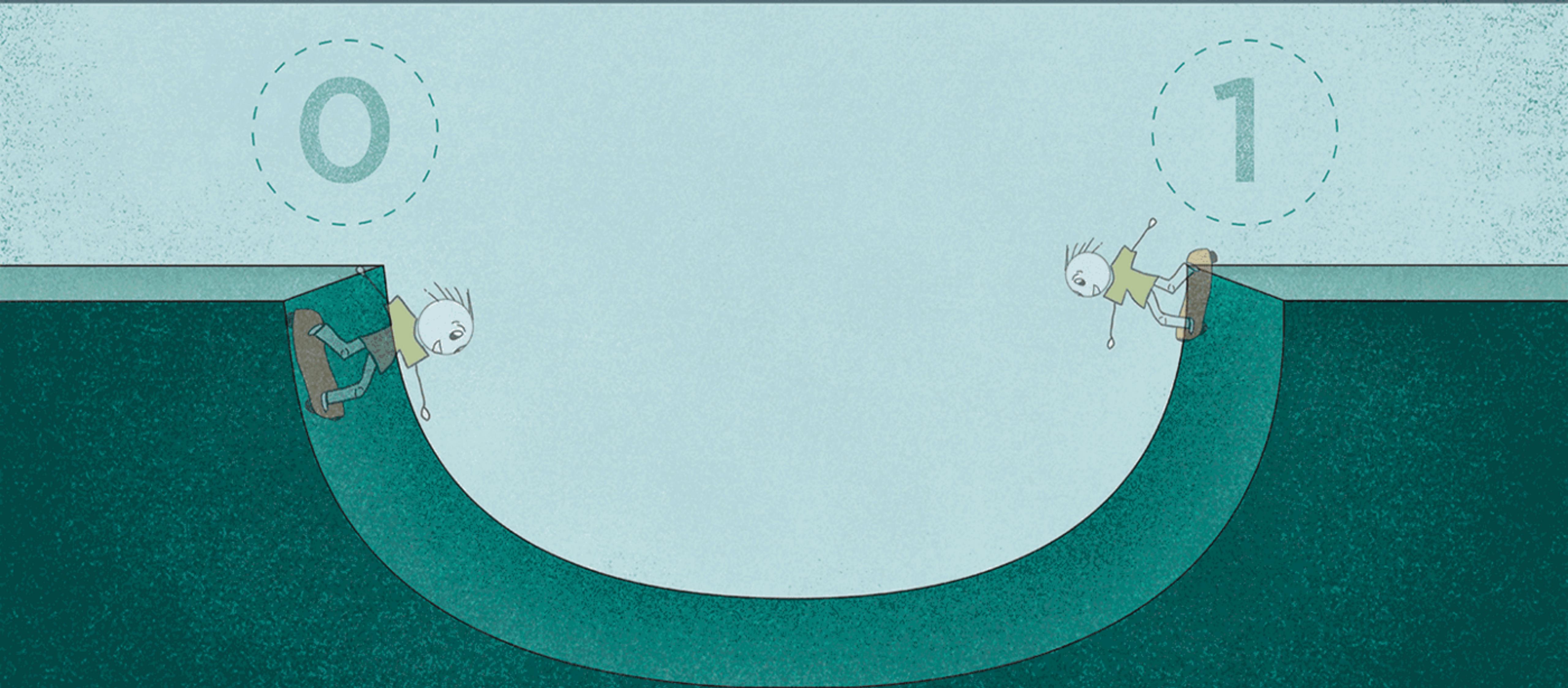


Superposition



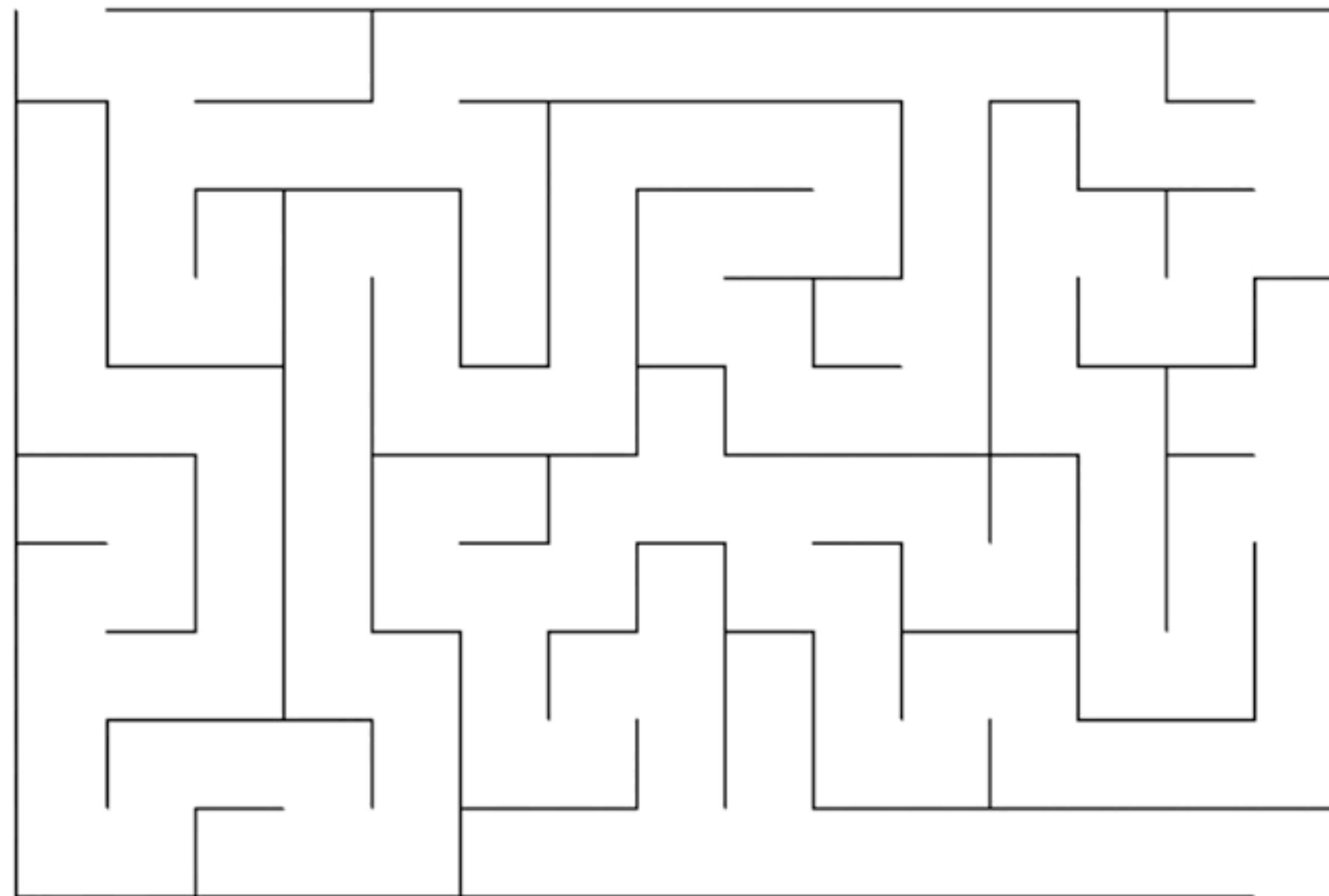
$$\alpha |0\rangle + \beta |1\rangle$$

SUPERPOSITION

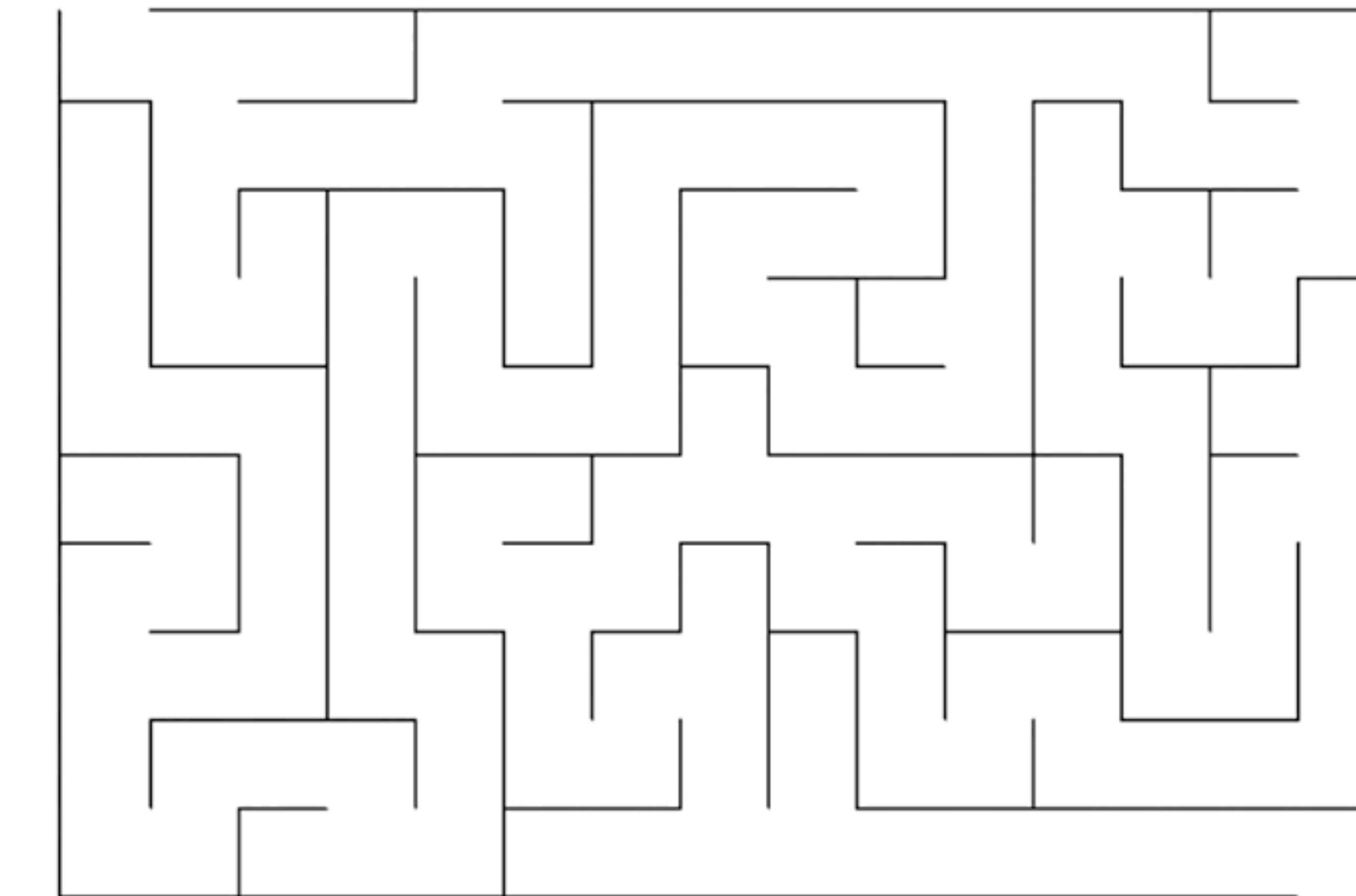


FIND A WAY OUT

Conventional



Quantum



QUANTUM LANGUAGE

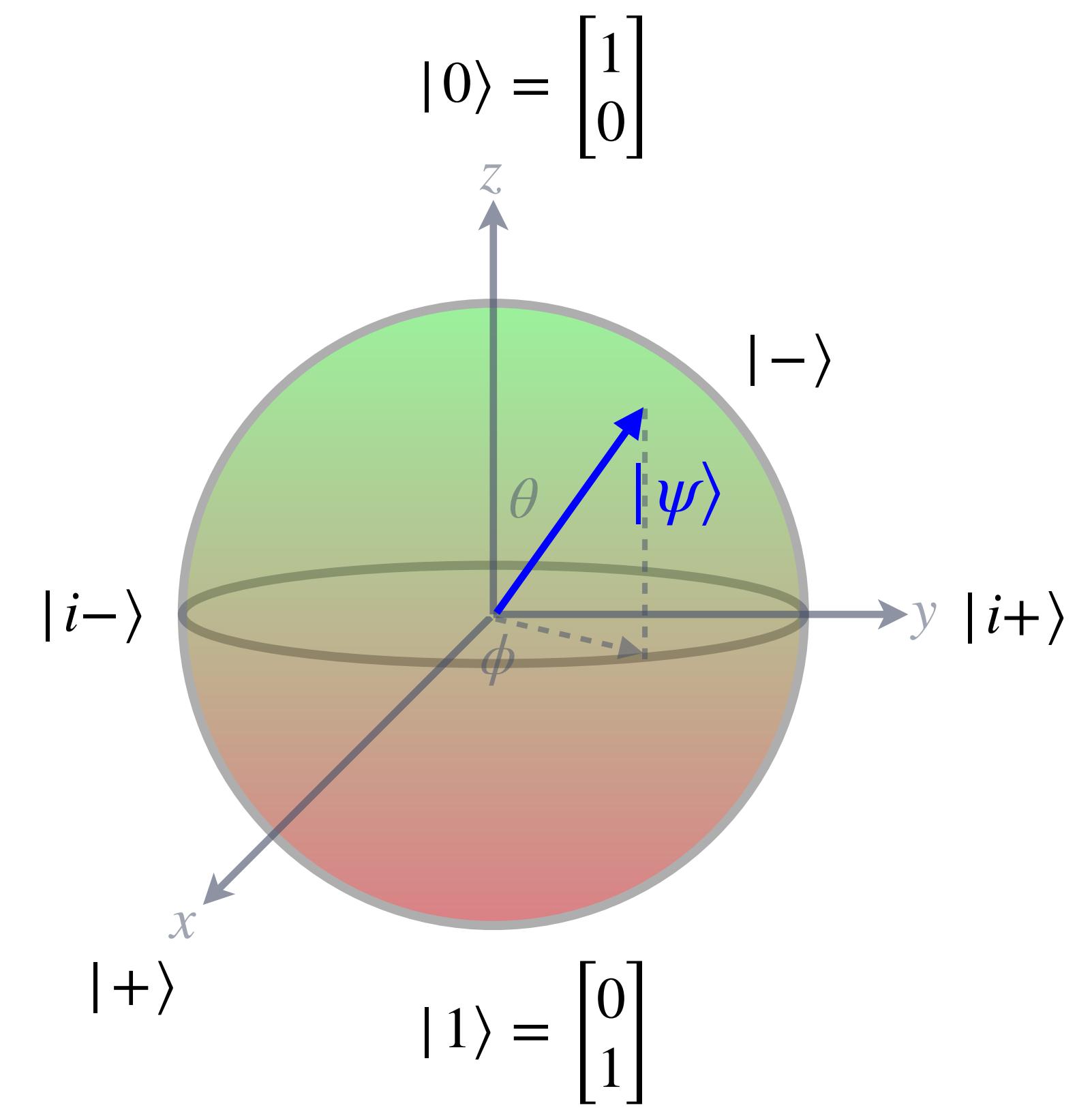
STATES

BLOCH SPHERE

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

$$= \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

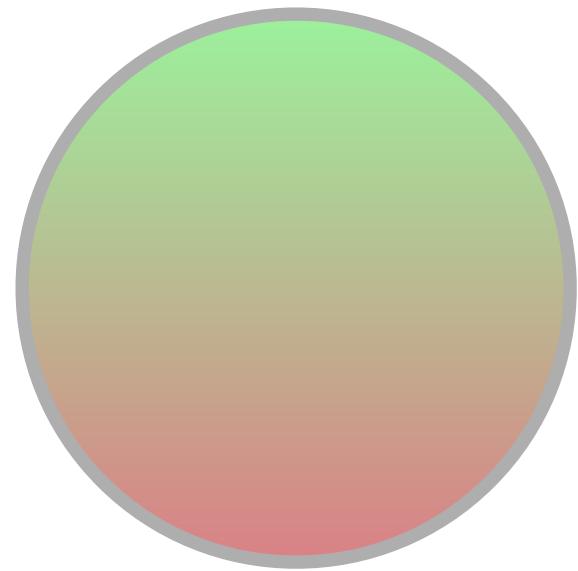
Basis: $\{|0\rangle, |1\rangle\}$



DIRAC NOTATION

Single qubit state

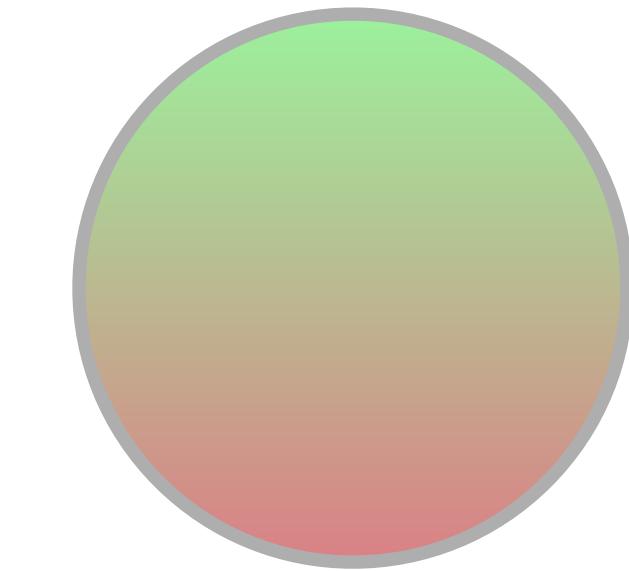
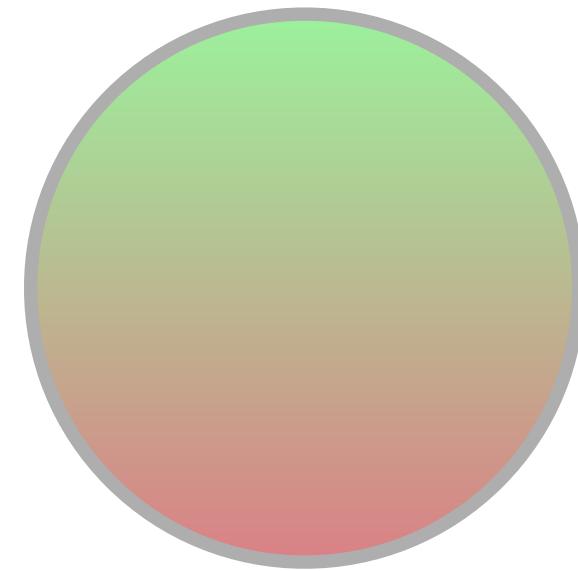
Basis: $\{|0\rangle, |1\rangle\}$



$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Bipartite quantum state

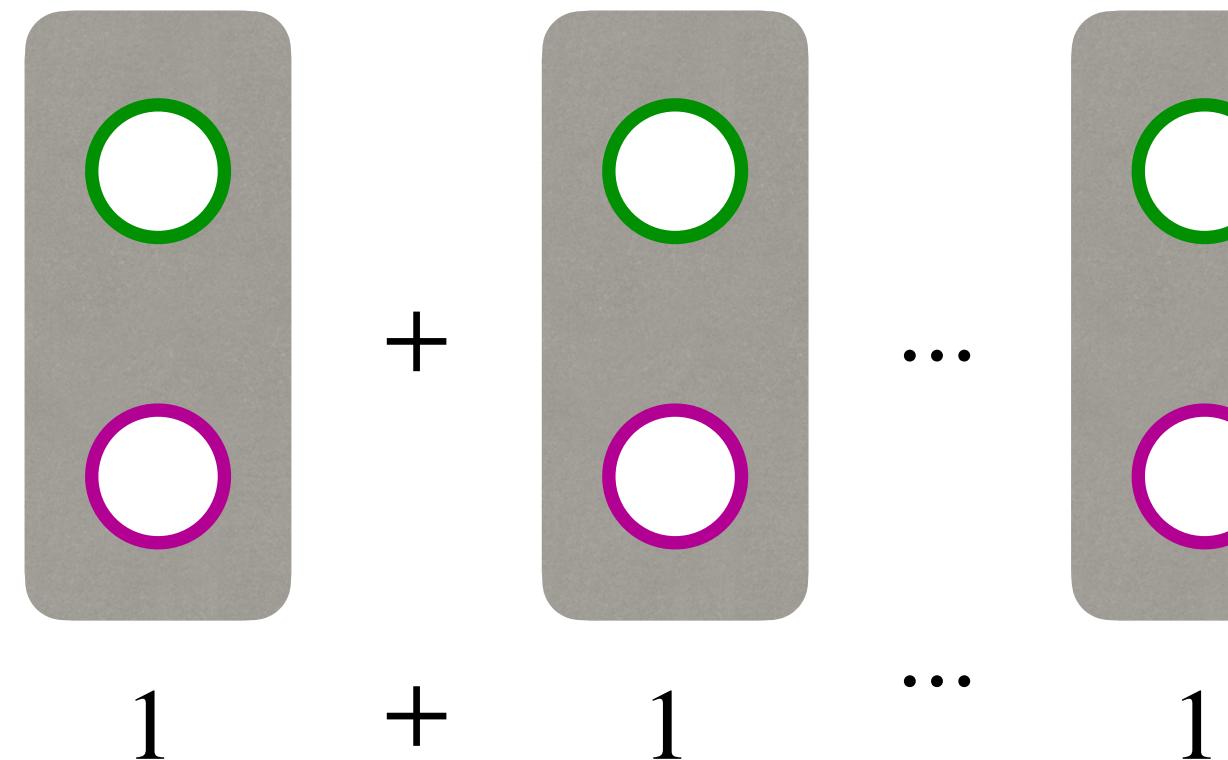
Basis: $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$



$$|\psi_1\rangle \otimes |\psi_2\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \otimes \begin{bmatrix} \gamma \\ \delta \end{bmatrix} = \begin{pmatrix} \alpha\gamma \\ \alpha\delta \\ \beta\gamma \\ \beta\delta \end{pmatrix} = |\psi_1\psi_2\rangle$$

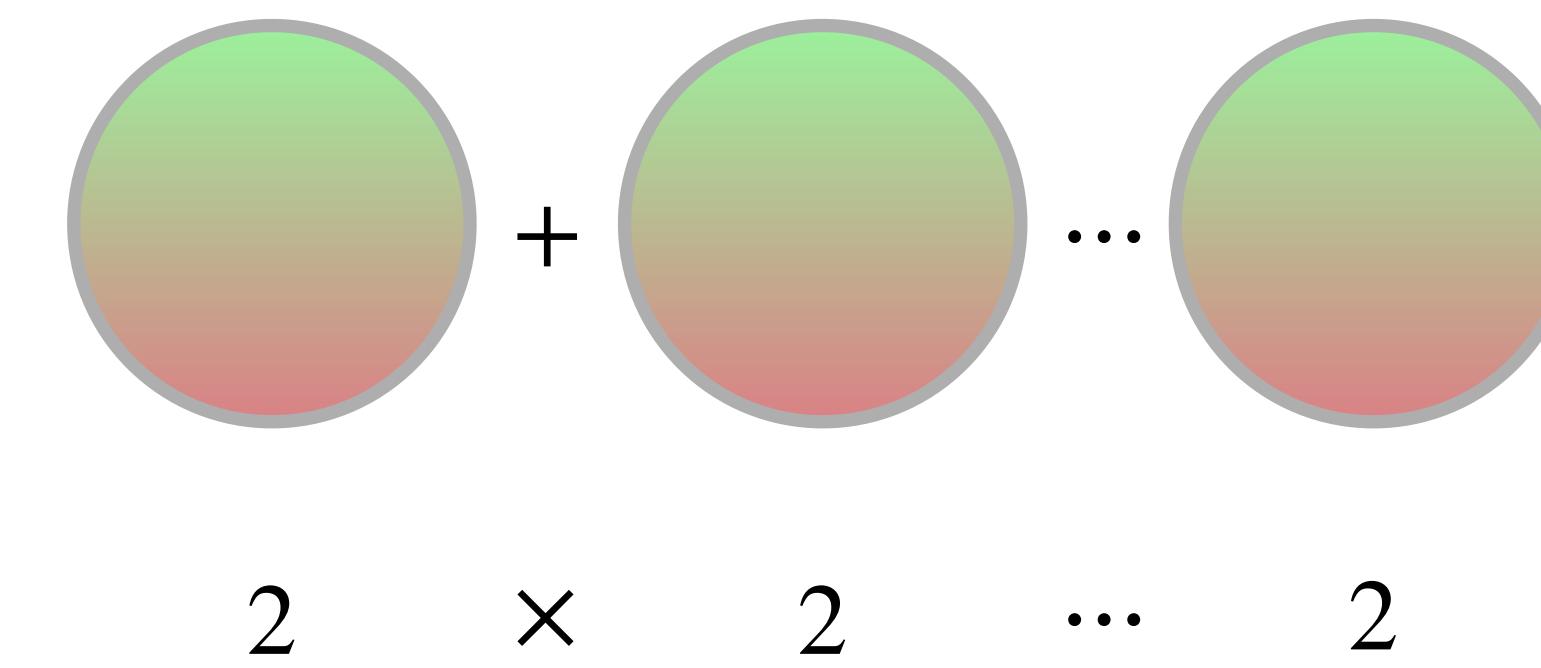
STATES FOR MORE THAN ONE ?

Classical



N

Quantum



2^N

Exponentially speedup!



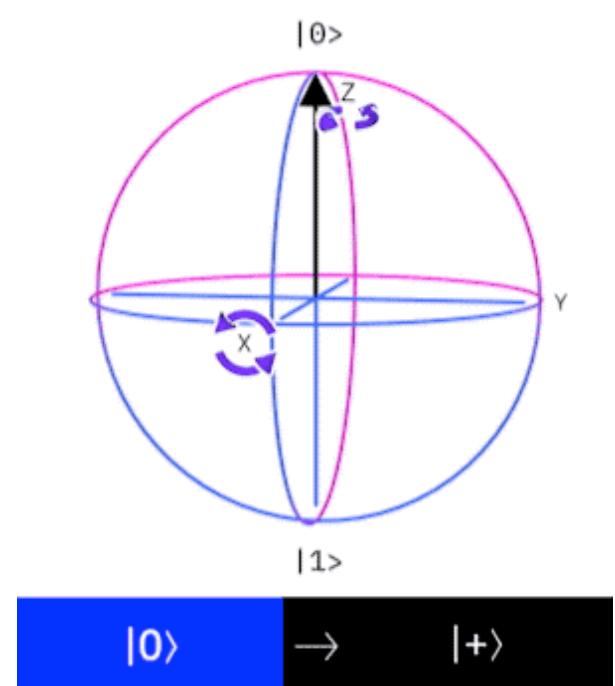
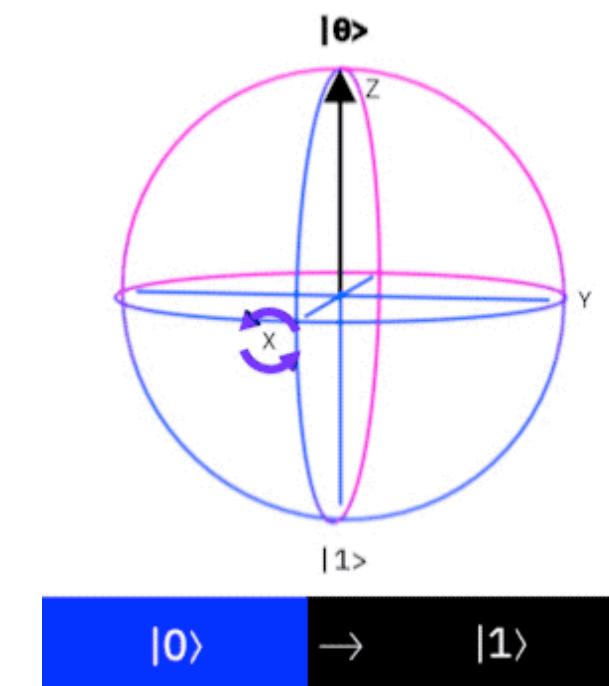
OPERATIONS - QUANTUM GATES

REVERSIBLE!

Single-qubit gates

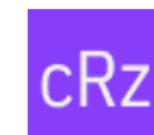
1. Hadamard 

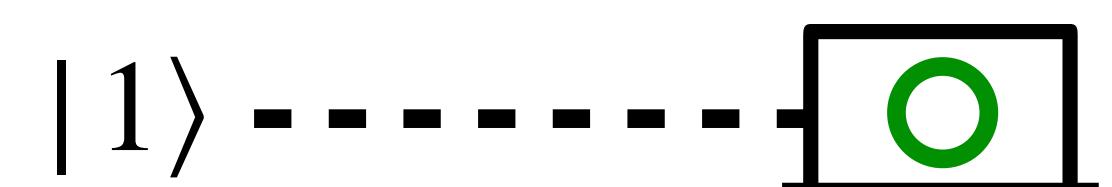
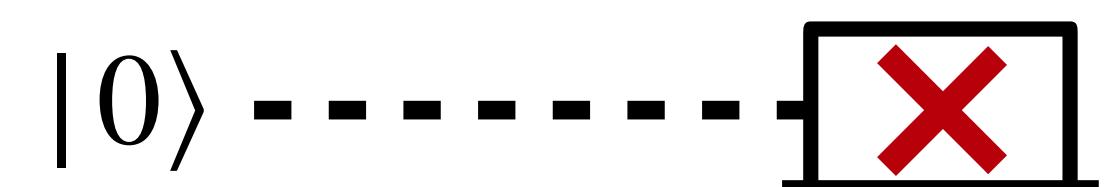
2. Rotation      



Two-qubit gates

1. CNOT 

2. Controlled-rotation   



QUANTUM COMPUTERS

IMPLEMENTANTS

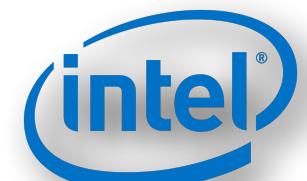
MONEY, MONEY, AND MONEY

Photons, electrons, nucleus



NMR

Quantum dots



Nature atoms



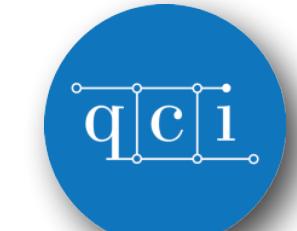
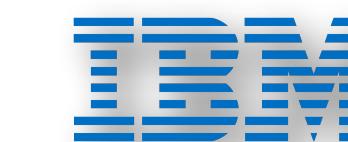
Diamonds



Semiconductors

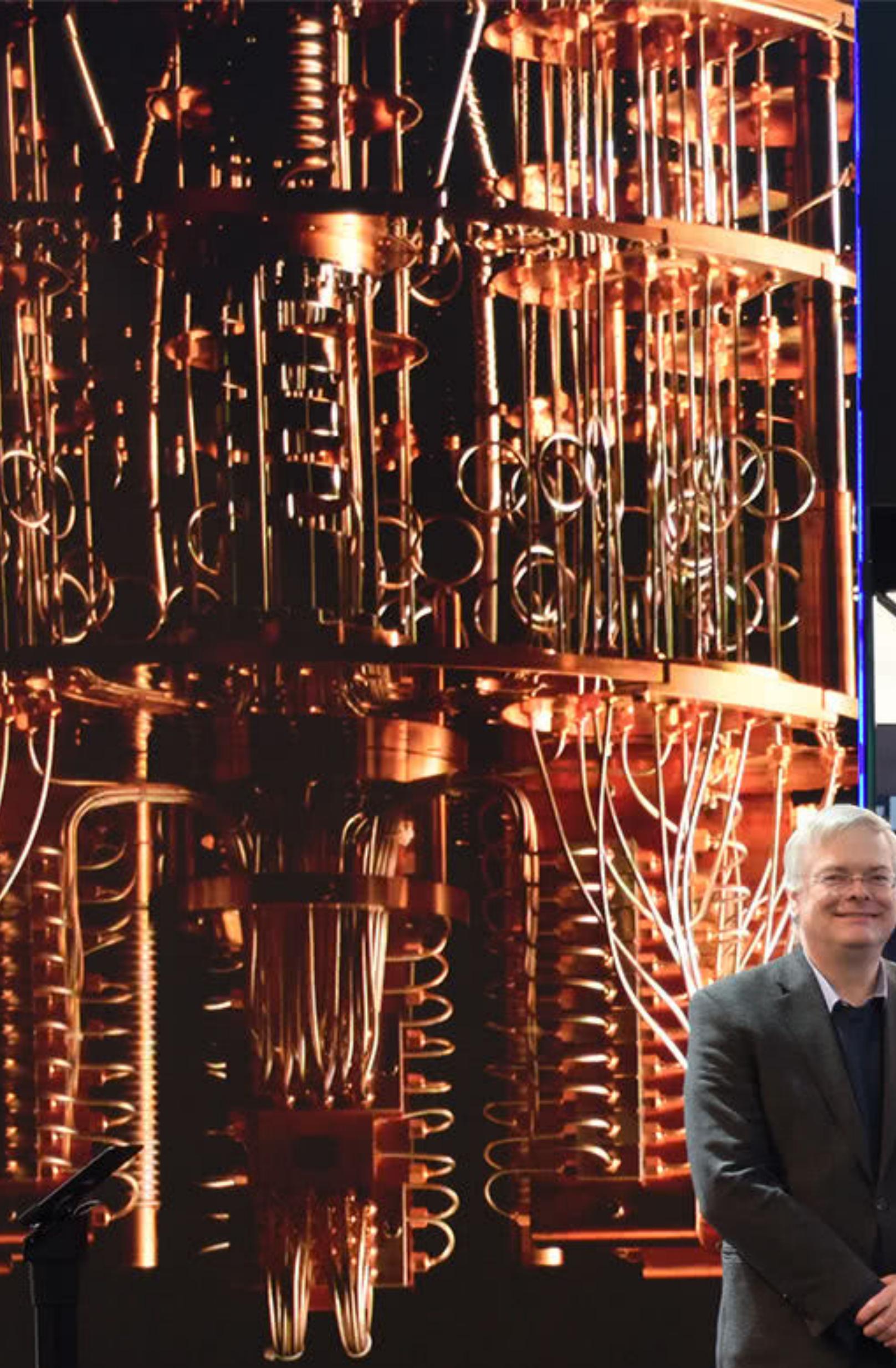


Superconductors

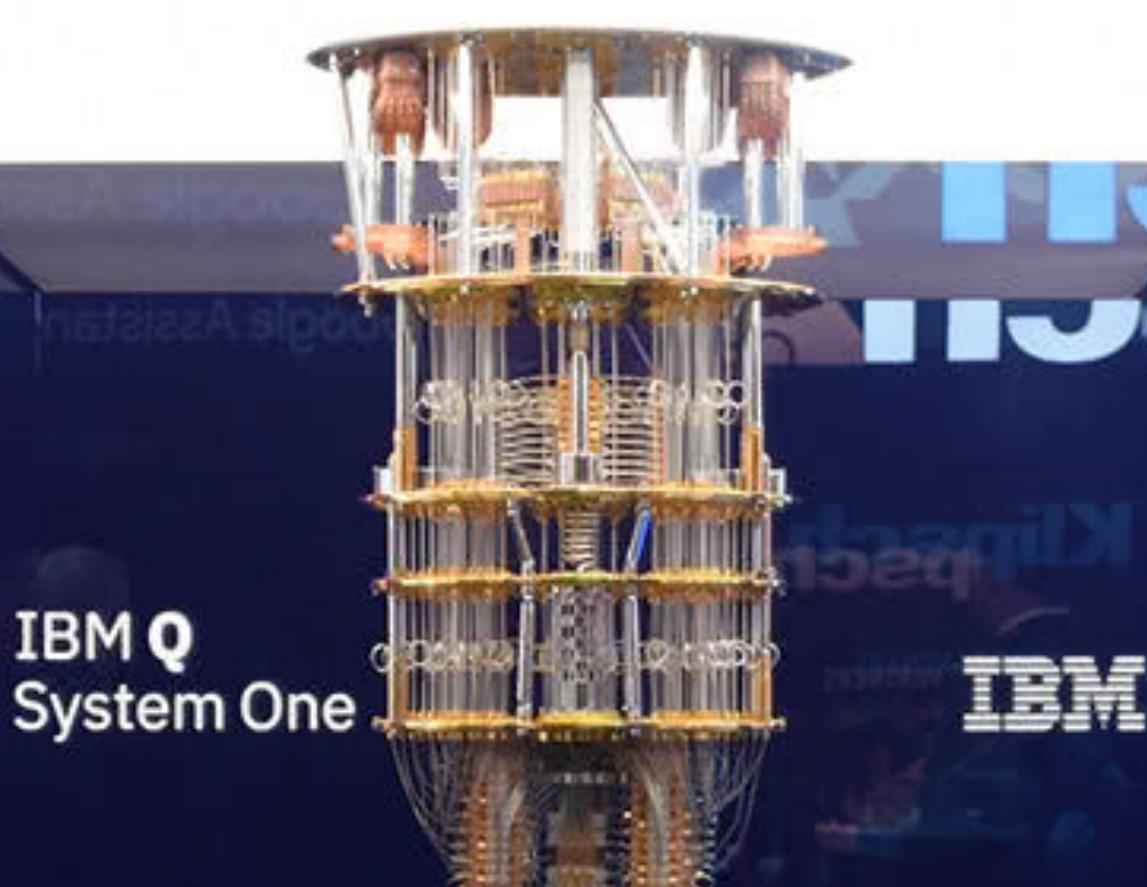


and so on.....



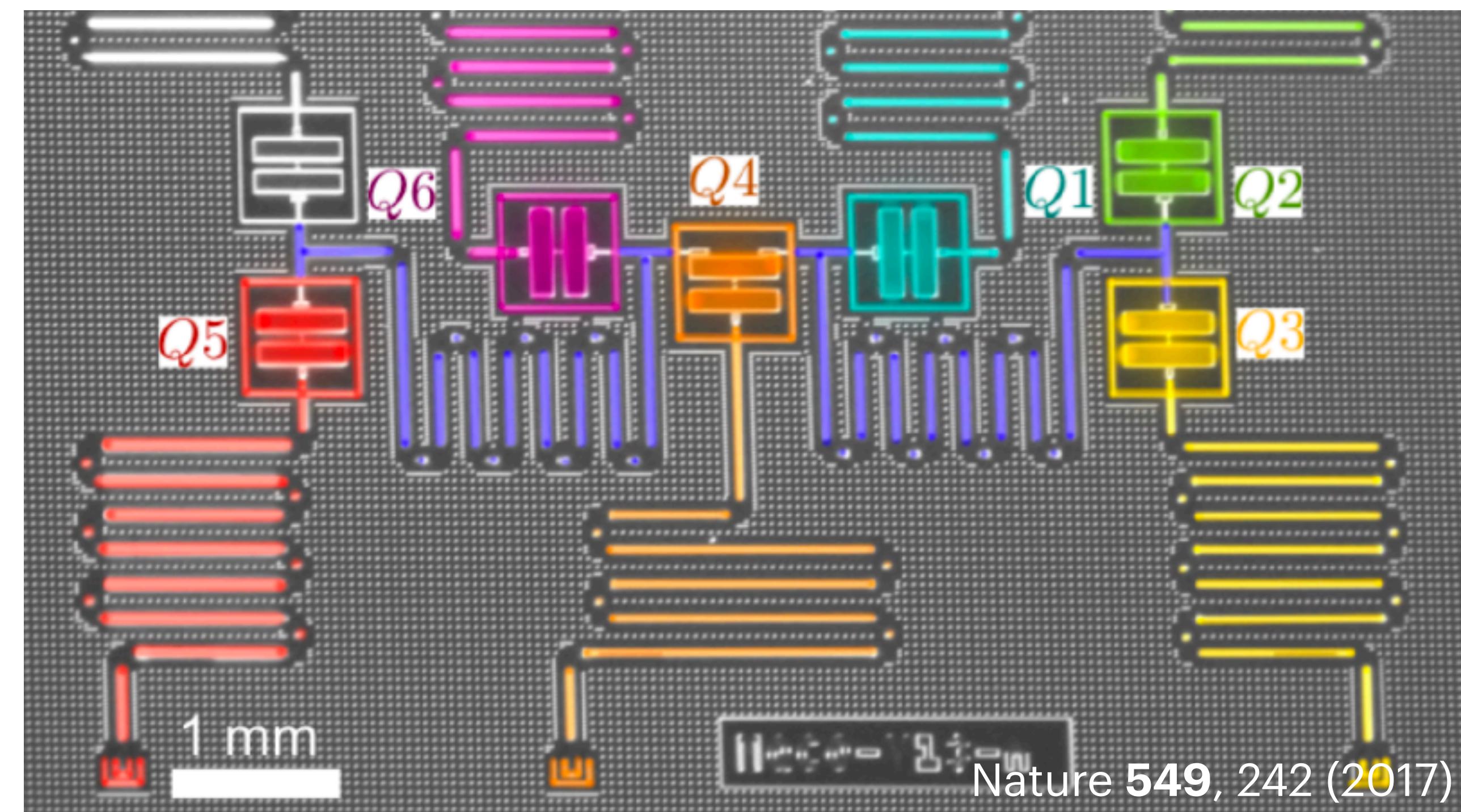
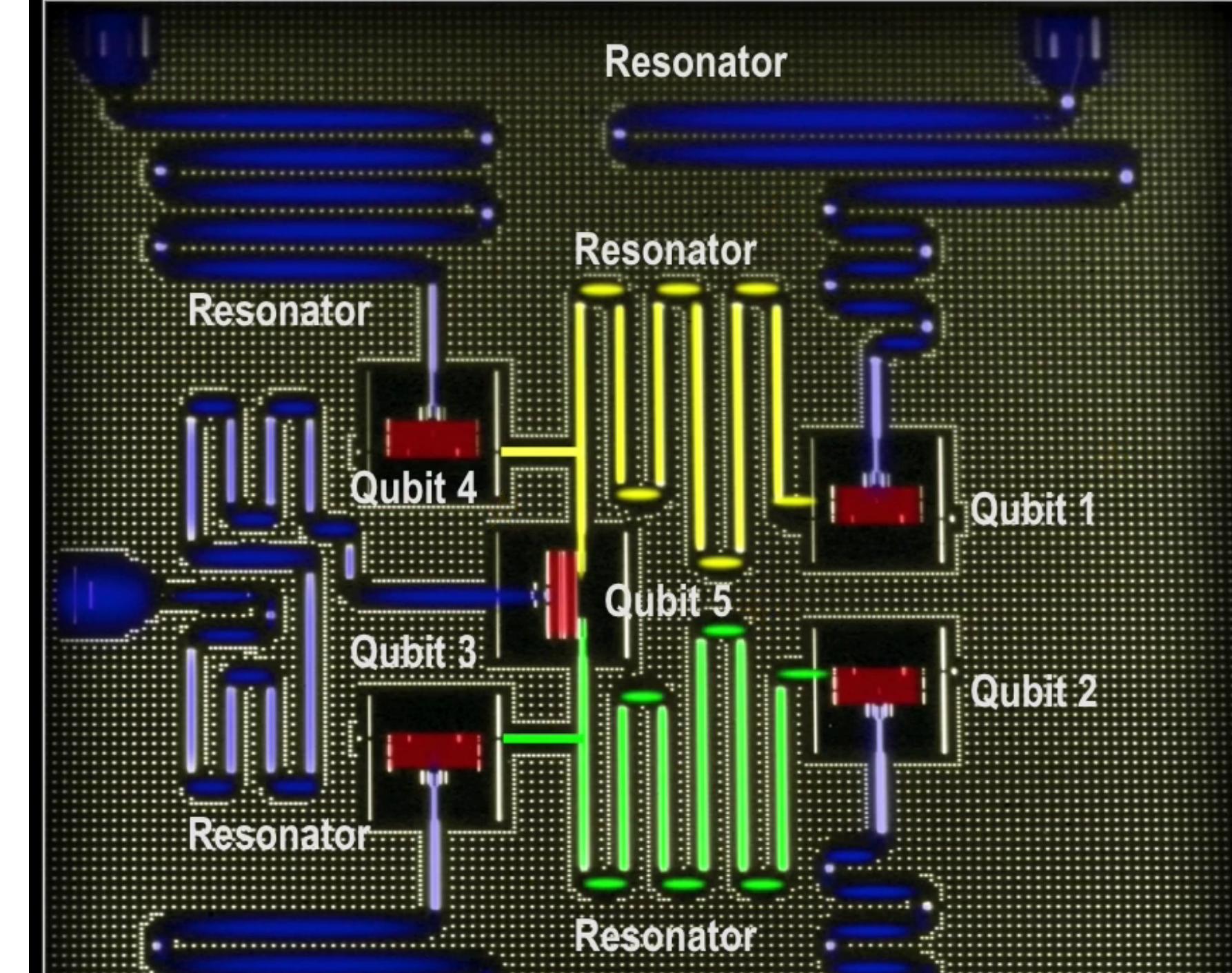
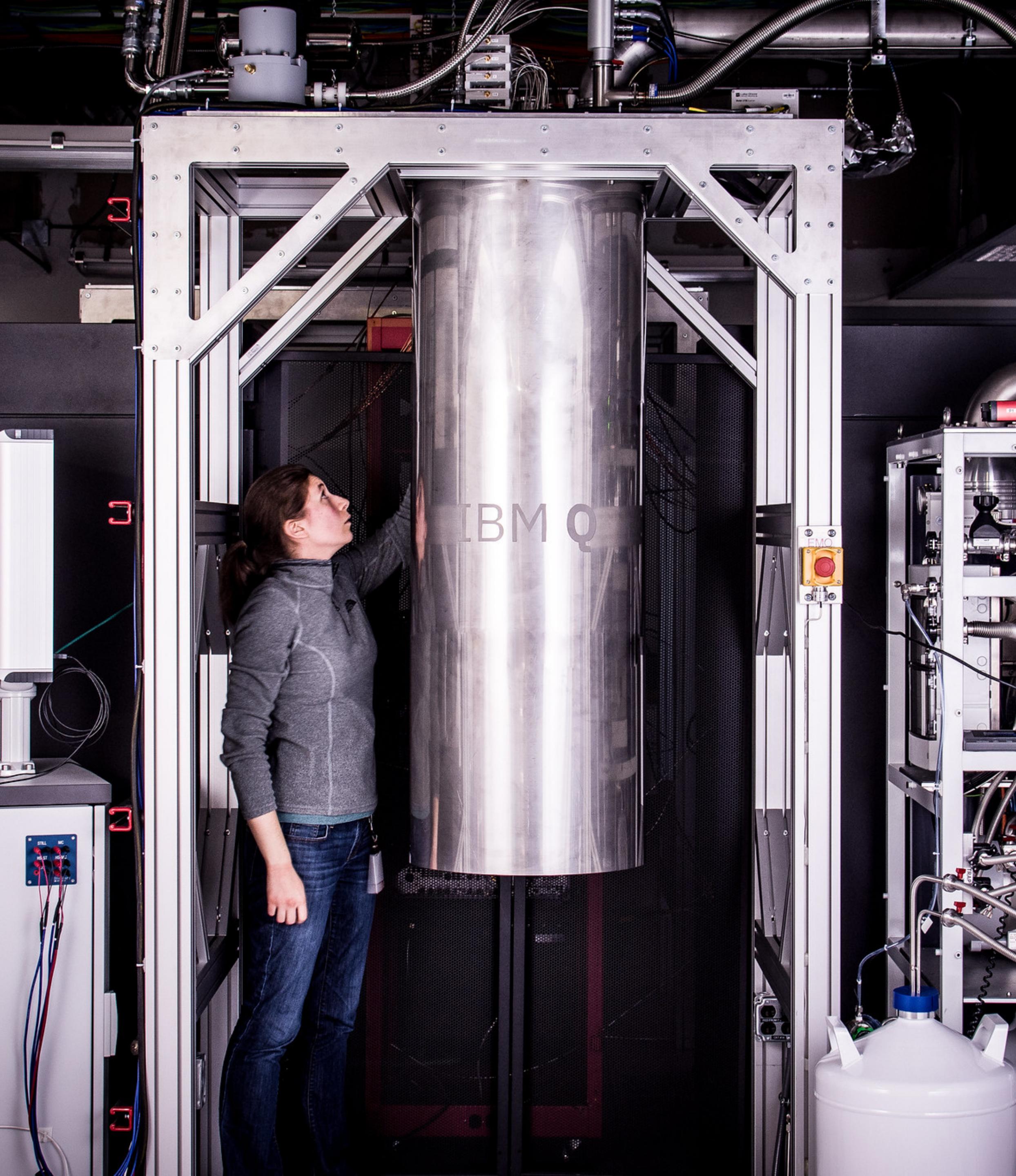


Quantum Computing
—
Intersecting science,
systems and design.



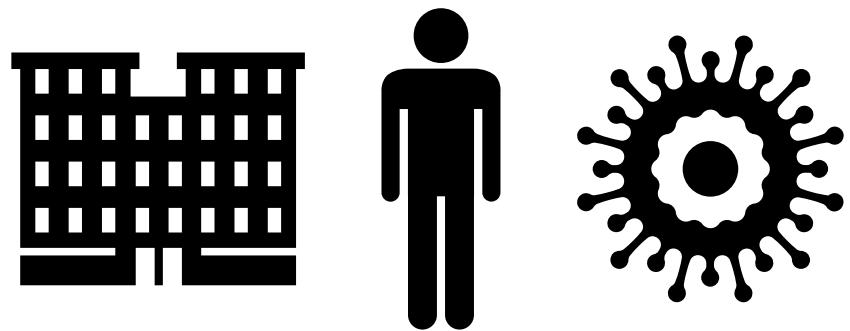
IBM Q
System One



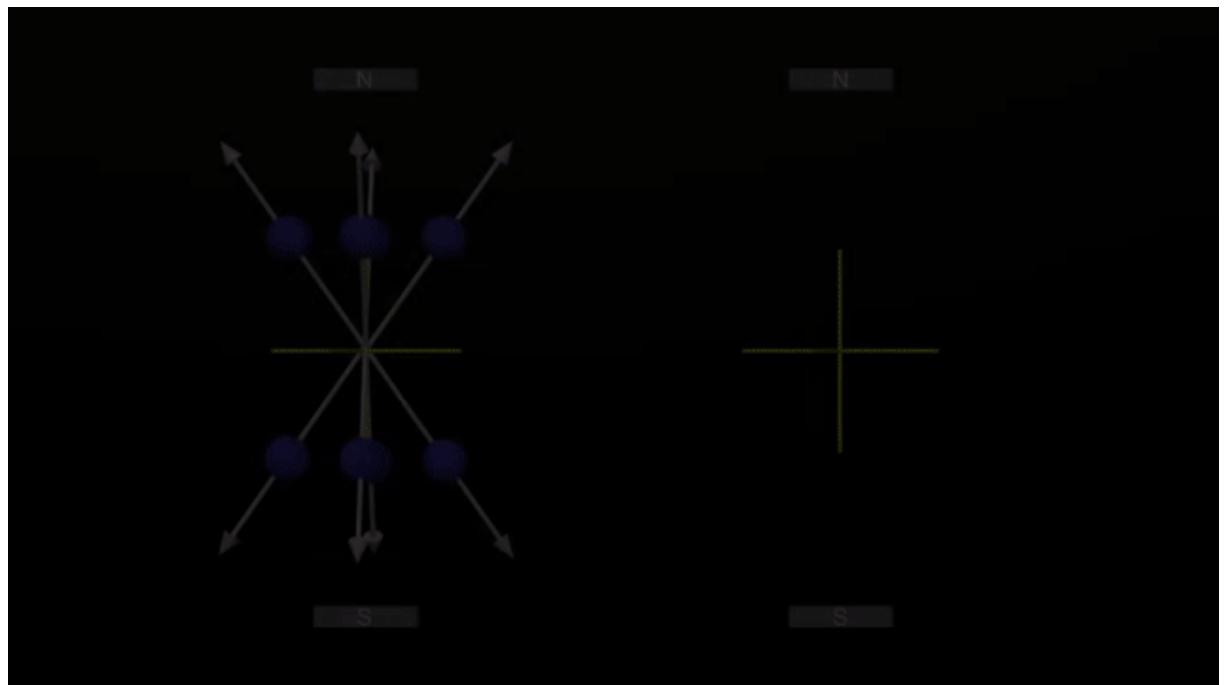
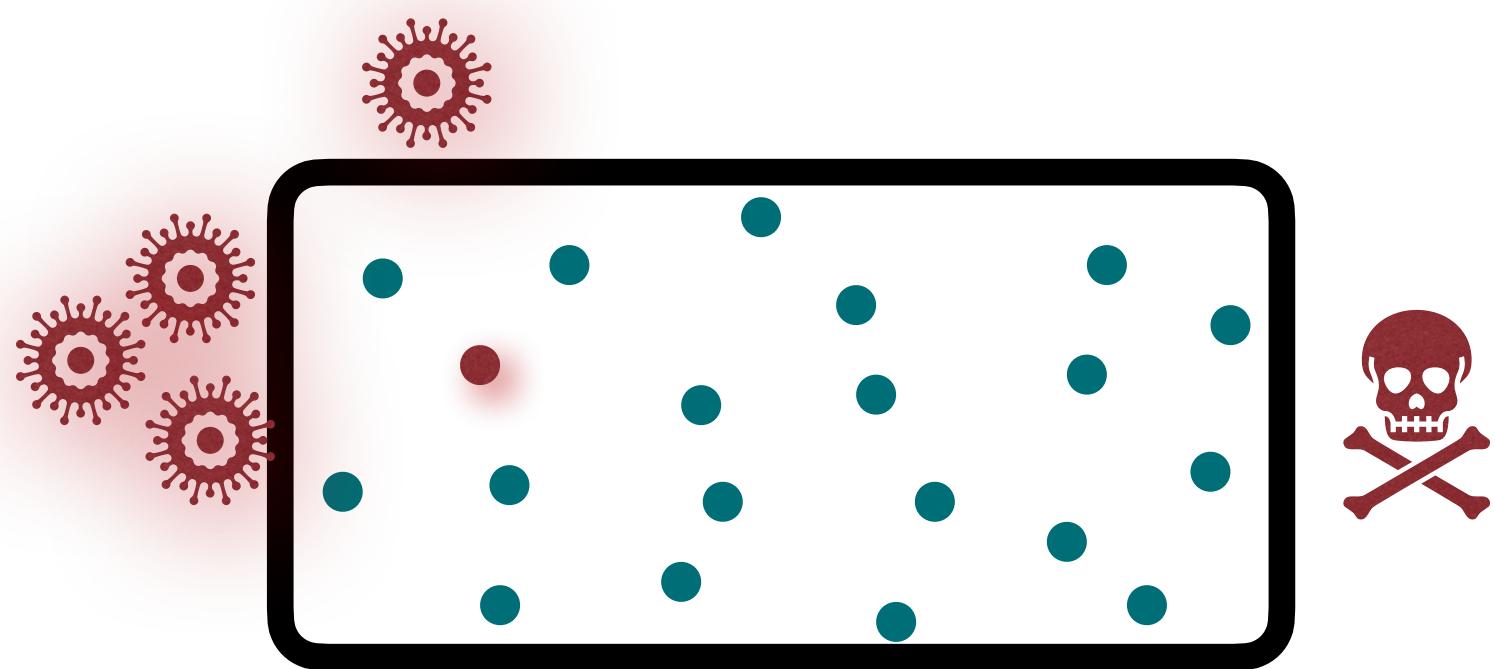


RELAXATION

COVID-19 MODEL

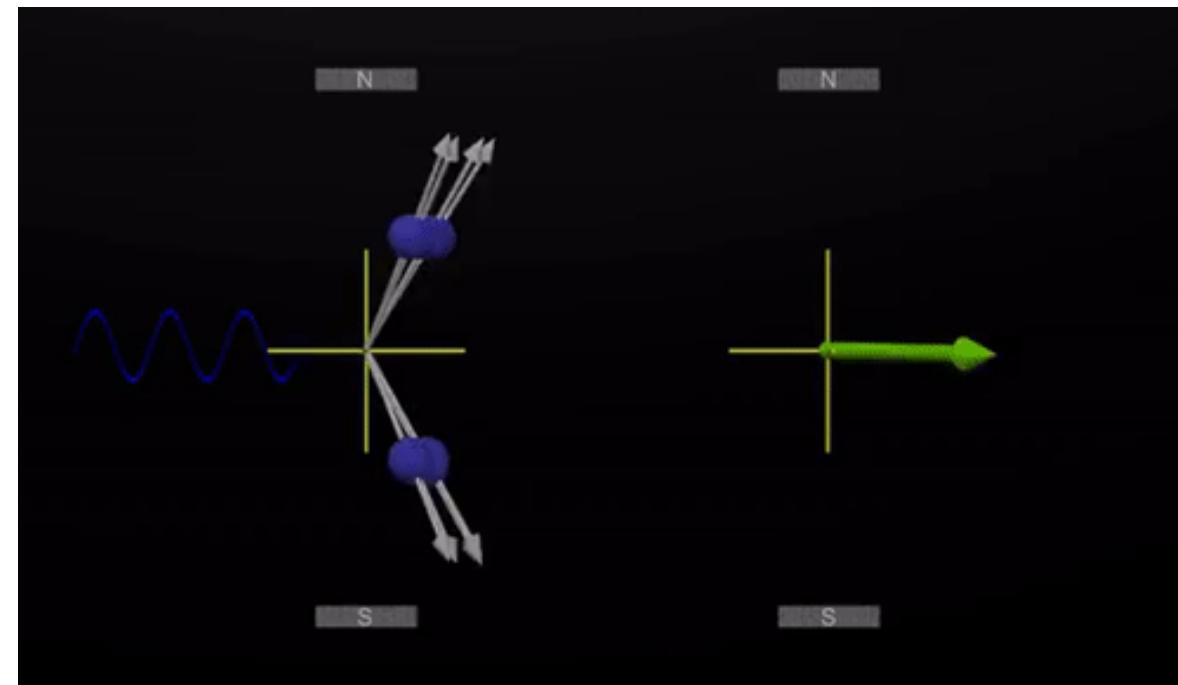
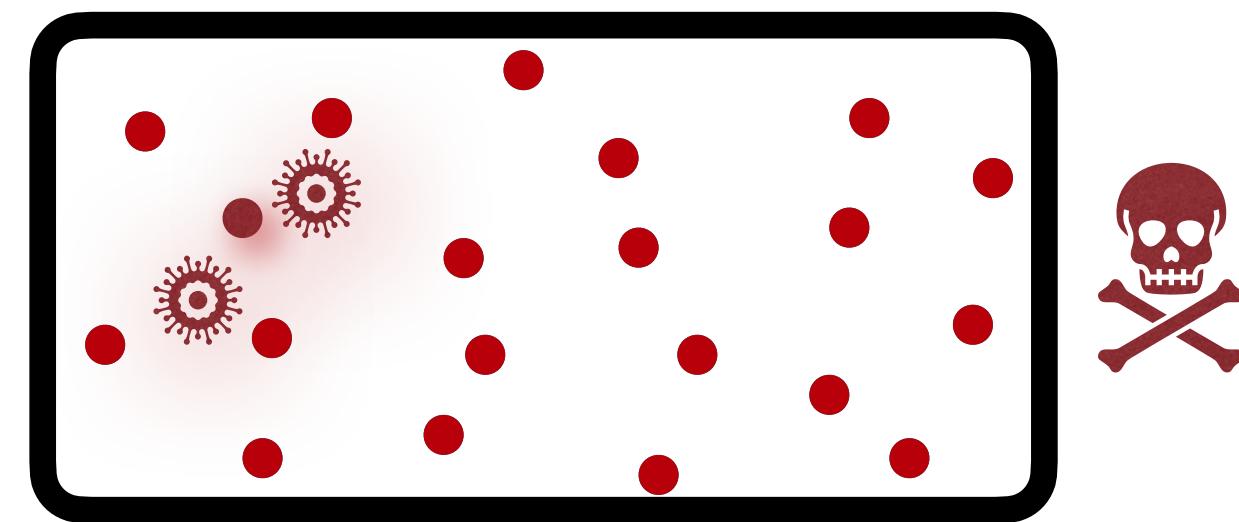


qubit-environment



T_1

qubit-qubit

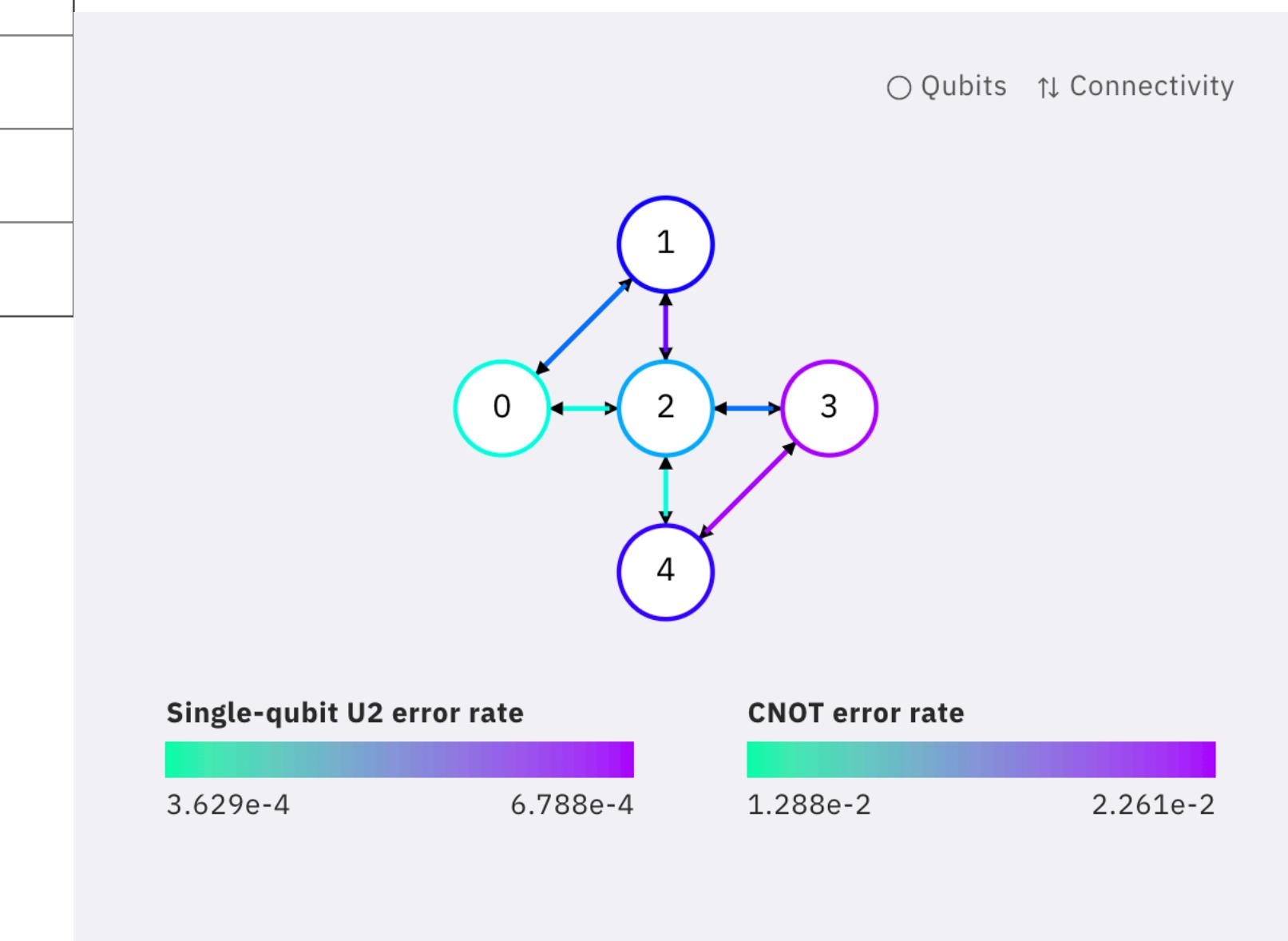


T_2

NUTRITION FACT OF QUBITS

EXAMPLE: IBMQ_5_YORKTOWN - IBMQX2

#	T1 (μs)	T2 (μs)	Frequency (GHz)	Readout error	Single-qubit U2 error rate
0	73.38	95.40	5.286	8.500E-03	3.629E-04
1	72.95	77.21	5.238	3.050E-02	5.608E-04
2	60.03	76.74	5.030	2.100E-02	4.458E-04
3	40.19	39.87	5.296	3.750E-02	6.788E-04
4	60.25	56.50	5.084	1.500E-02	5.997E-04
#	CNOT error rate				
0	cx0_1: 1.615E-02, cx0_2: 1.380E-02				
1	cx1_0: 1.615E-02, cx1_2: 2.076E-02				
2	cx2_0: 1.380E-02, cx2_1: 2.076E-02, cx2_3: 1.628E-02, cx2_4: 1.288E-02				
3	cx3_2: 1.628E-02, cx3_4: 2.261E-02				
4	cx4_2: 1.288E-02, cx4_3: 2.261E-02				



March 24, 2020 21:23:06 GMT +0800



IBM

YOUR FIRST QUANTUM CIRCUIT

IBM QUANTUM EXPERIENCE

IBM Q
System One

EXAMPLE - ENTANGLED STATE

STRUCTURE

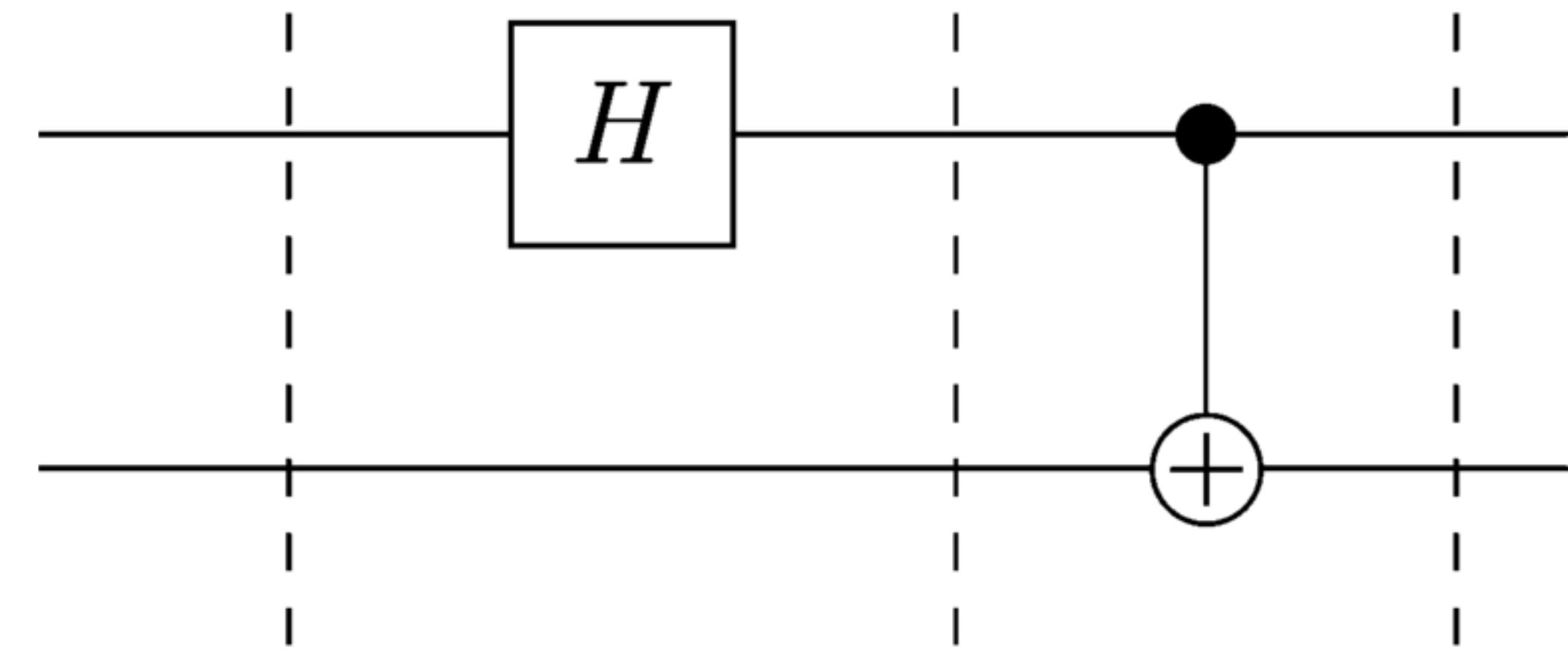
Bell states

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

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}} (|00\rangle - |11\rangle)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle)$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle)$$



$|\psi_0\rangle$

$|\psi_1\rangle$

$|\psi_2\rangle$

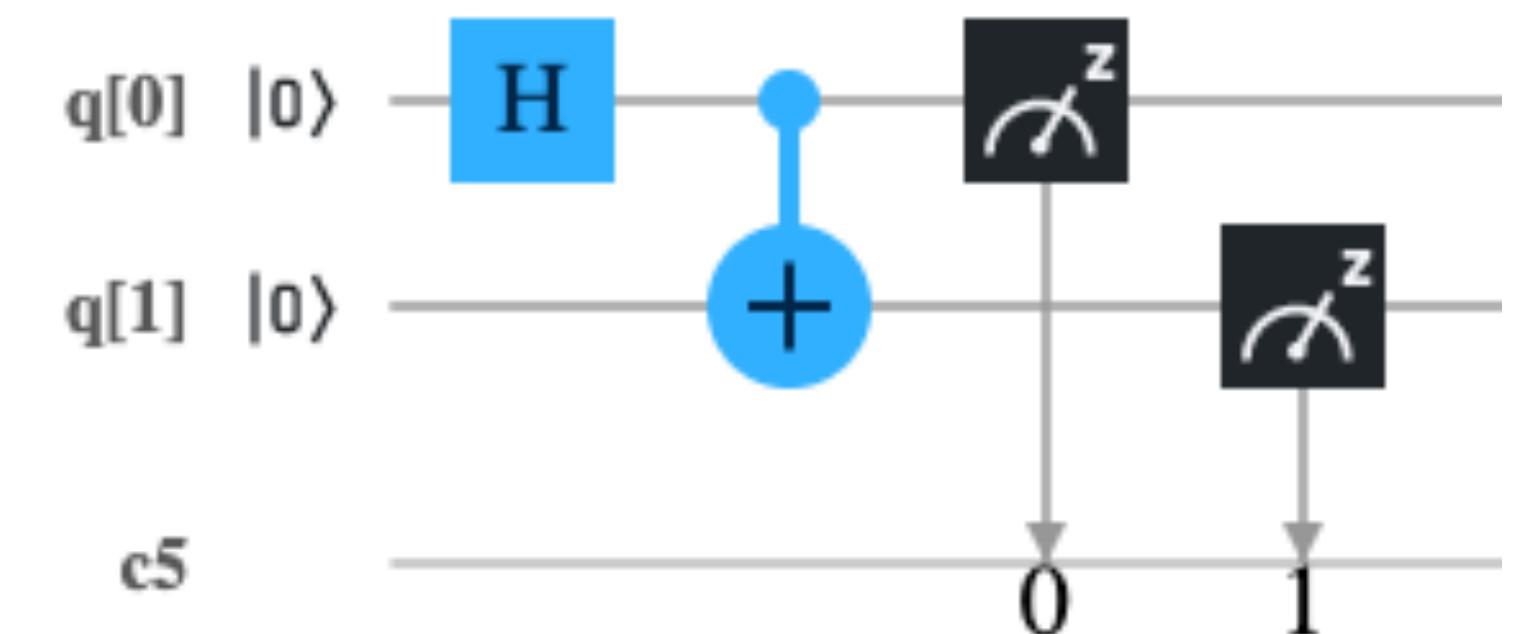
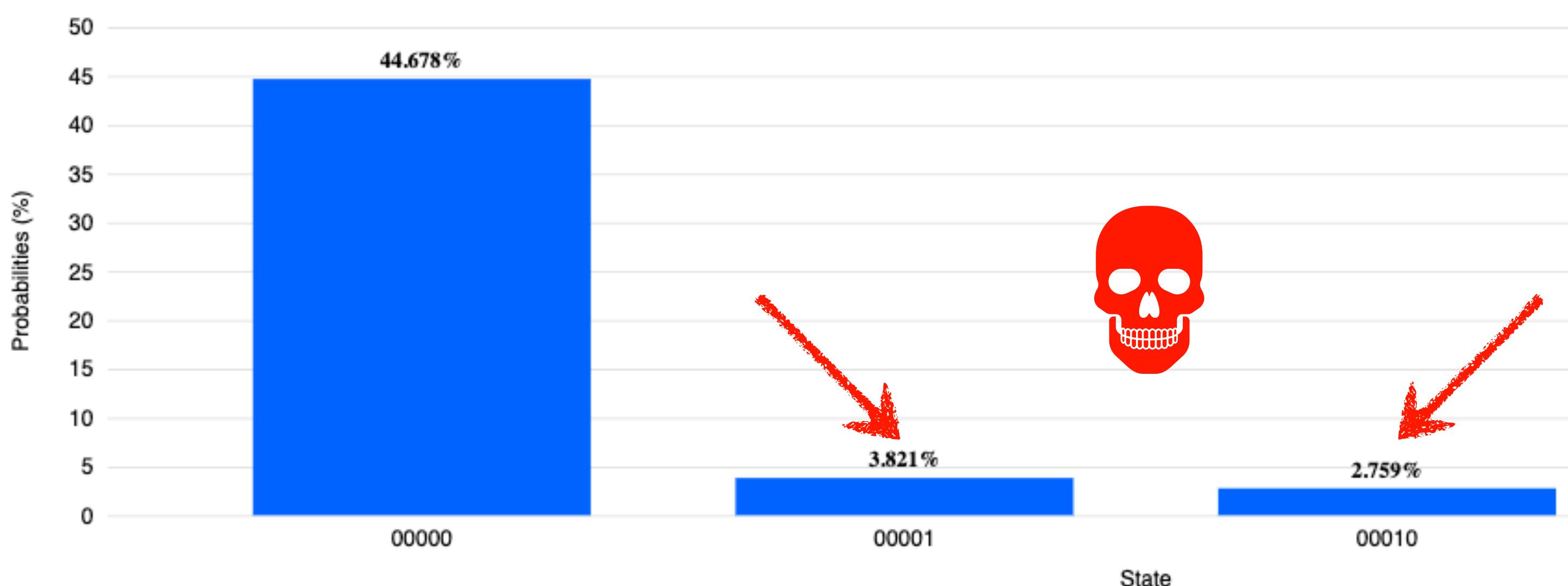
$$|\psi_2\rangle = CNOT \cdot (H \otimes I) |\psi_0\rangle$$

EXAMPLE - ENTANGLED STATE

RESULTS

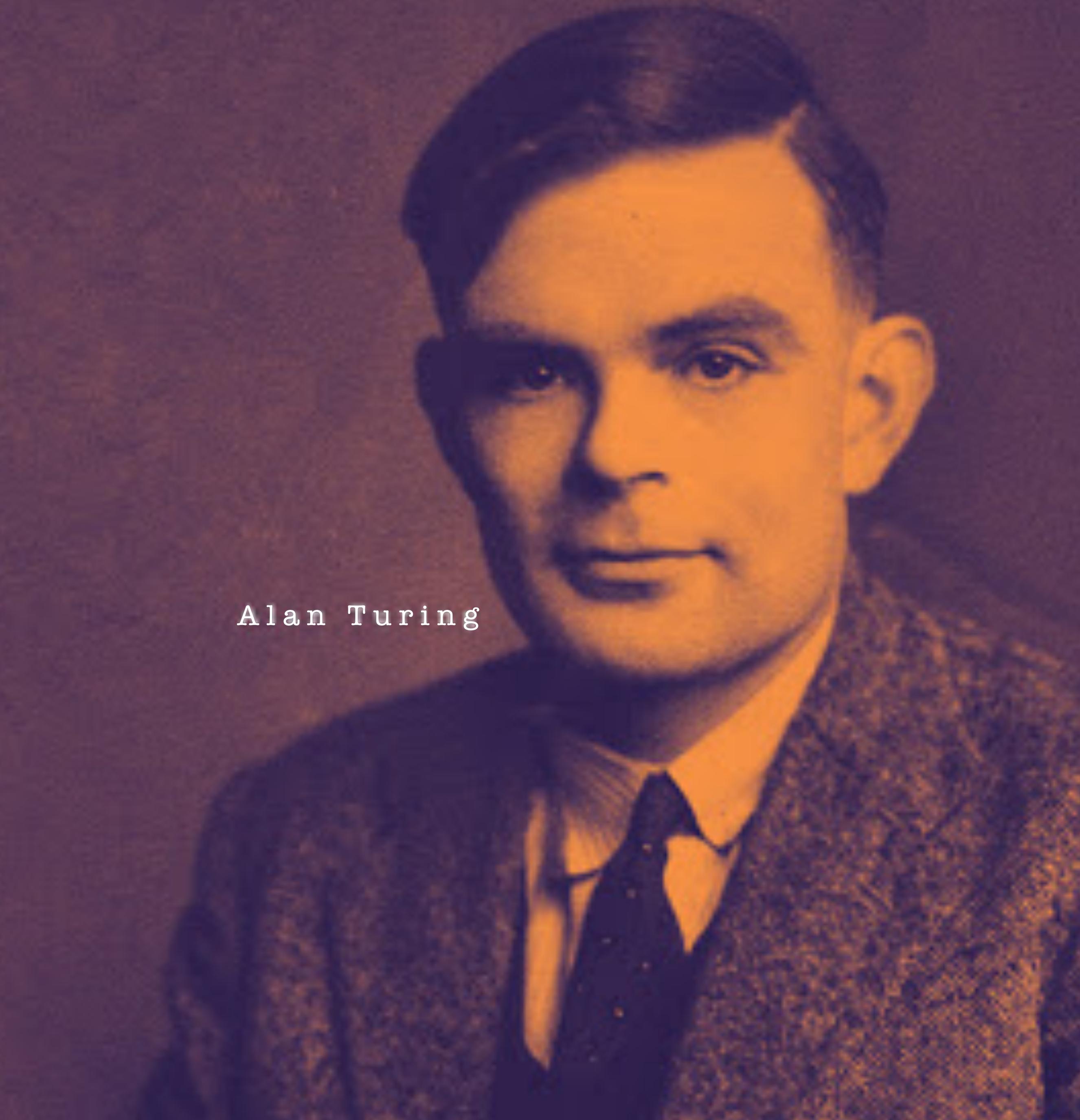
State: $|\Phi^+\rangle = \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)$

Histogram



QUESTION?

Alan Turing



SUPPLEMENTARY

TOOLS

VECTORS & MATRICES

ket-vector

$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$$

bra-vector

$$\langle\psi| = [\alpha^* \ \beta^* \ \gamma^*]$$

Hermitian conjugate

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

MATRICES OPERATIONS

Kronecker product (tensor product)

$$|\psi_1\rangle \otimes |\psi_2\rangle = \begin{bmatrix} 1 \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} & -1 \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} \\ 0 \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} & i \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} \\ (-1+i) \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} & (1-i) \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} \end{bmatrix} = \begin{bmatrix} i & -i \\ -1 & 1 \\ 0 & -1 \\ 0 & -i \\ -1-i & 1+i \\ 1-i & -1+i \end{bmatrix}$$

Matrices multiplication

$$\langle\psi| U |\psi\rangle = \langle\psi| U^\dagger |\psi\rangle = [\alpha^* \ \beta^* \ \gamma^*] \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$$

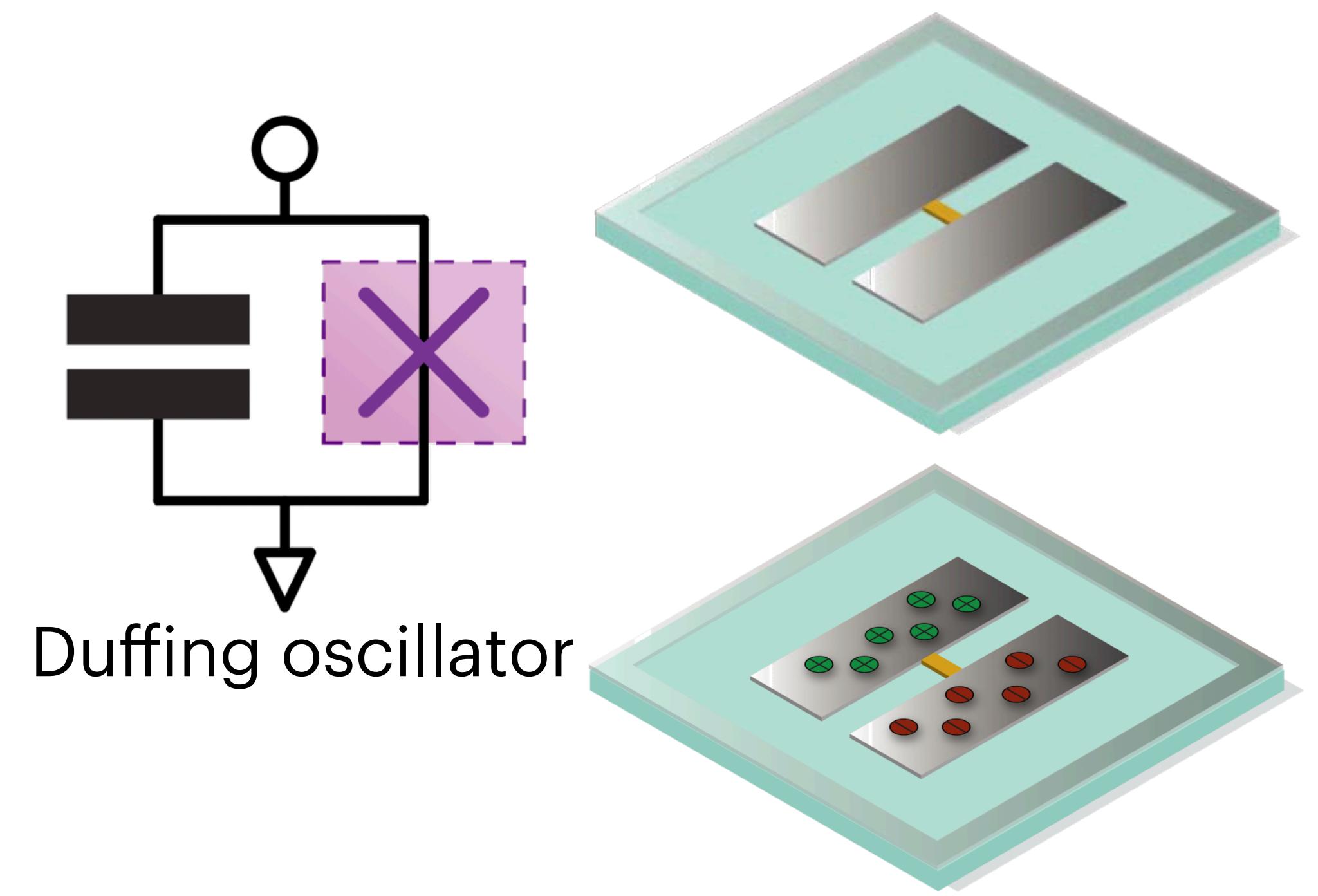
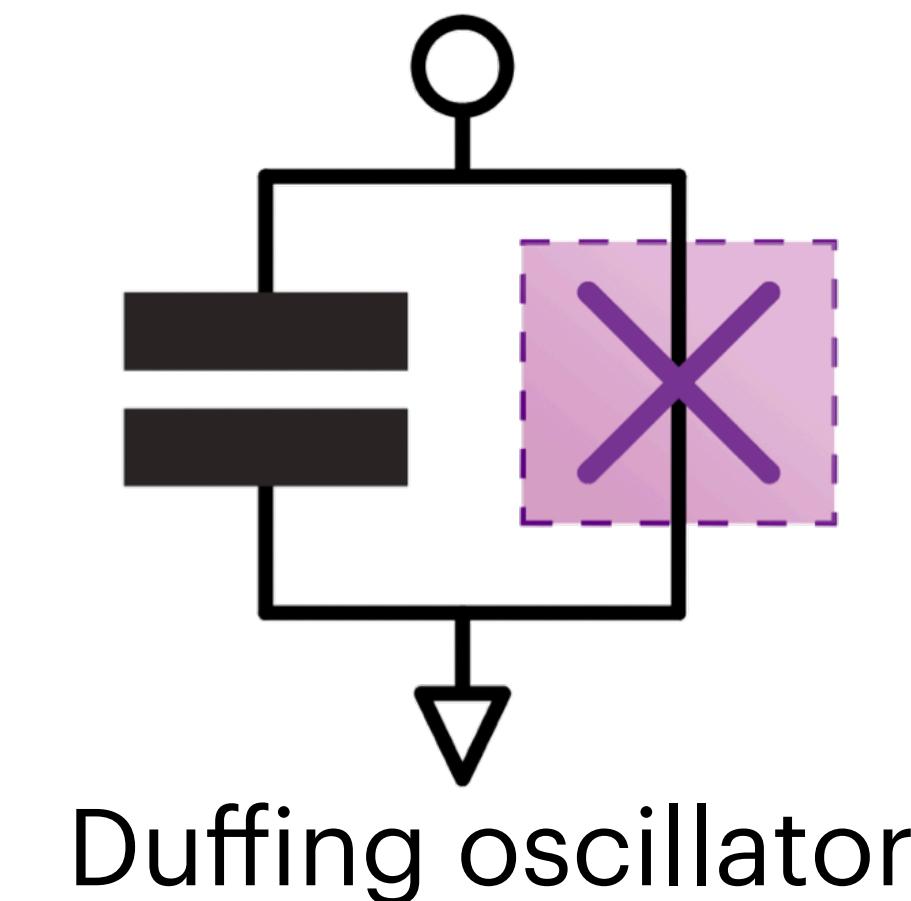
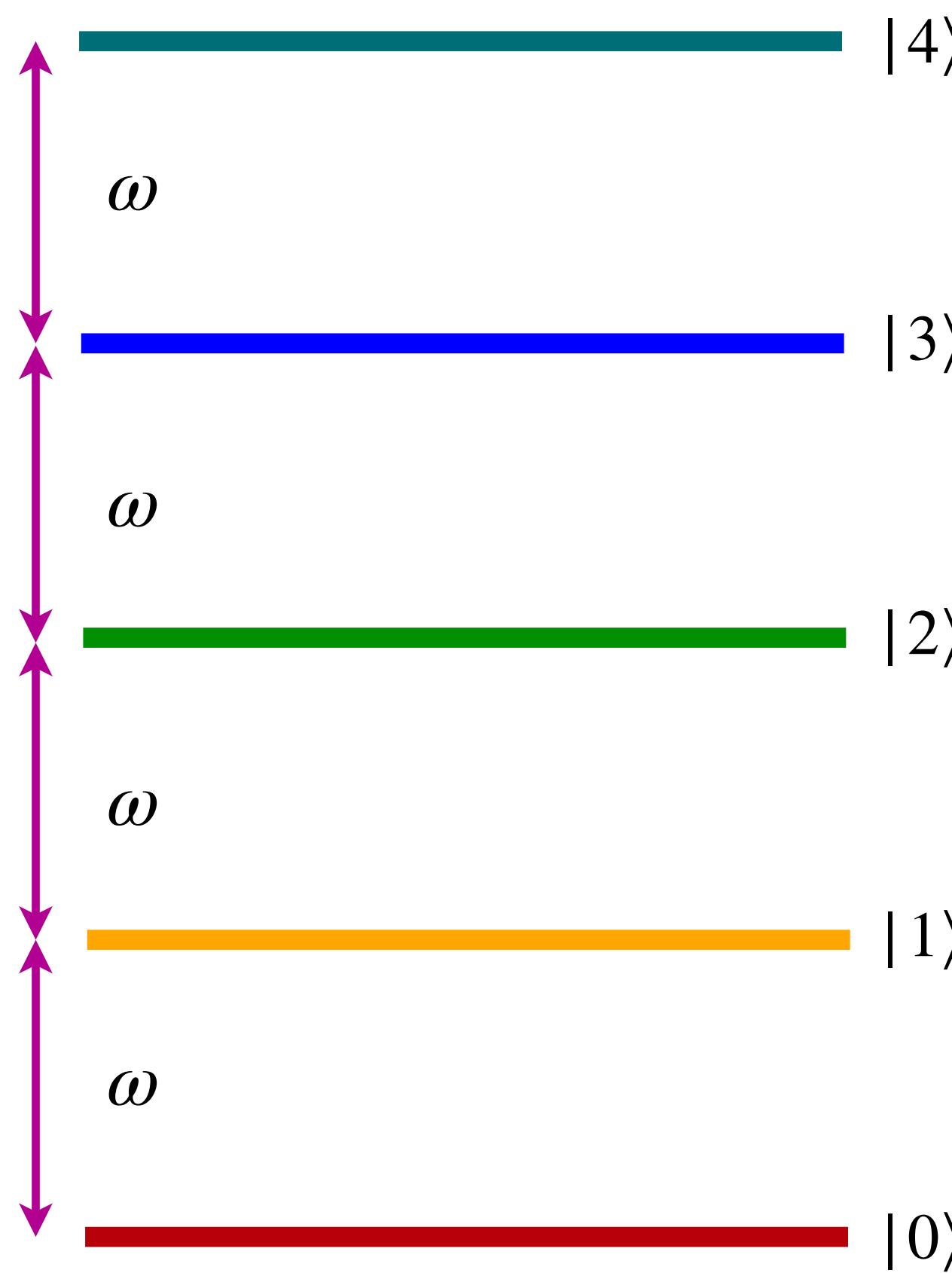
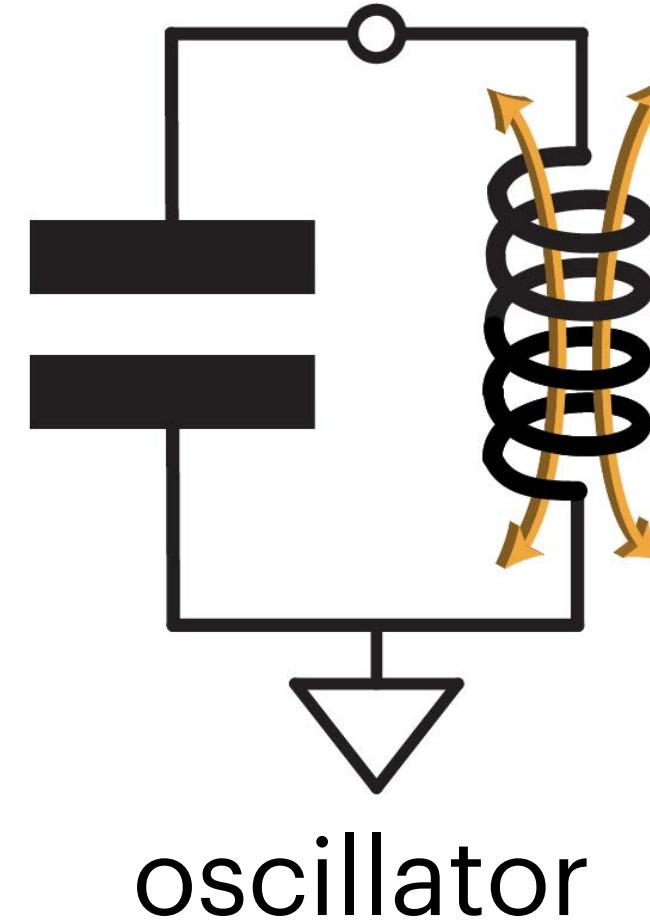
$$|\psi_1\rangle = \begin{bmatrix} 1 & -1 \\ 0 & i \\ -1+i & 1-i \end{bmatrix}$$

$$|\psi_2\rangle = \begin{bmatrix} i \\ -1 \end{bmatrix}$$

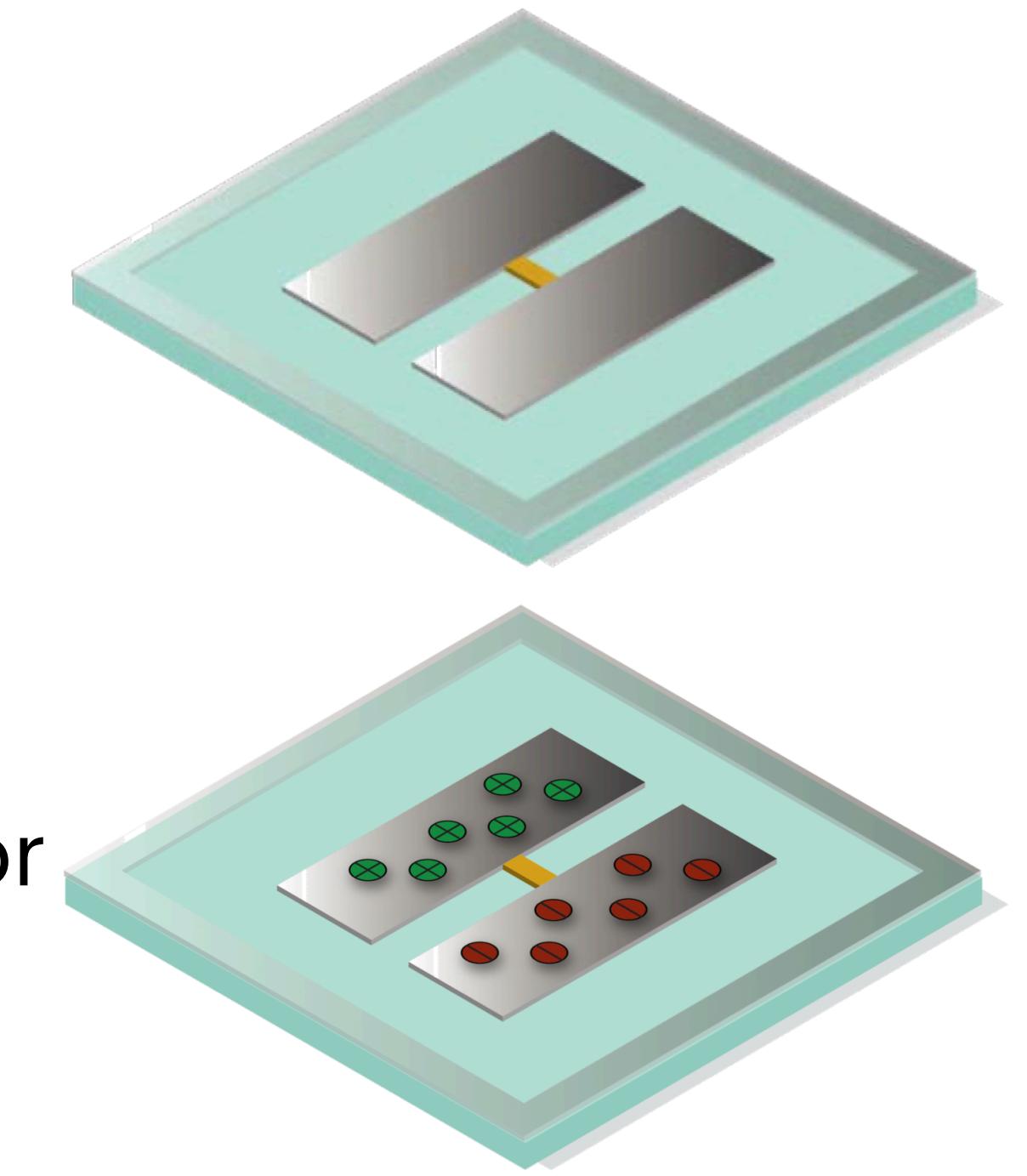
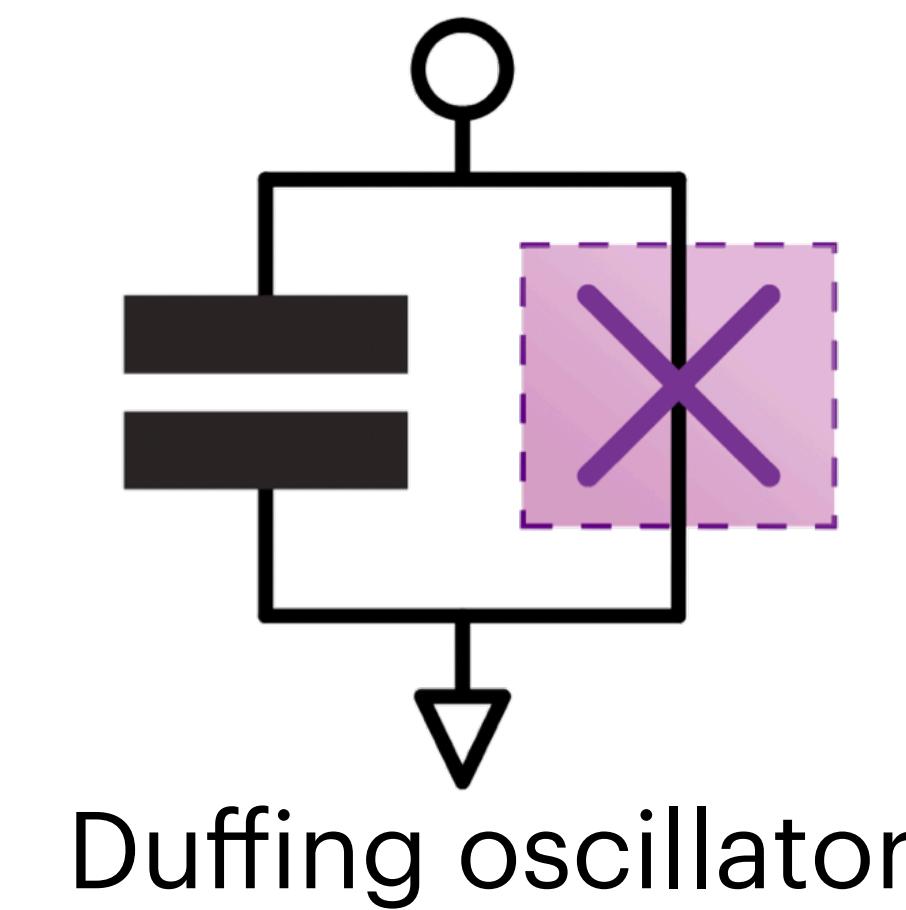
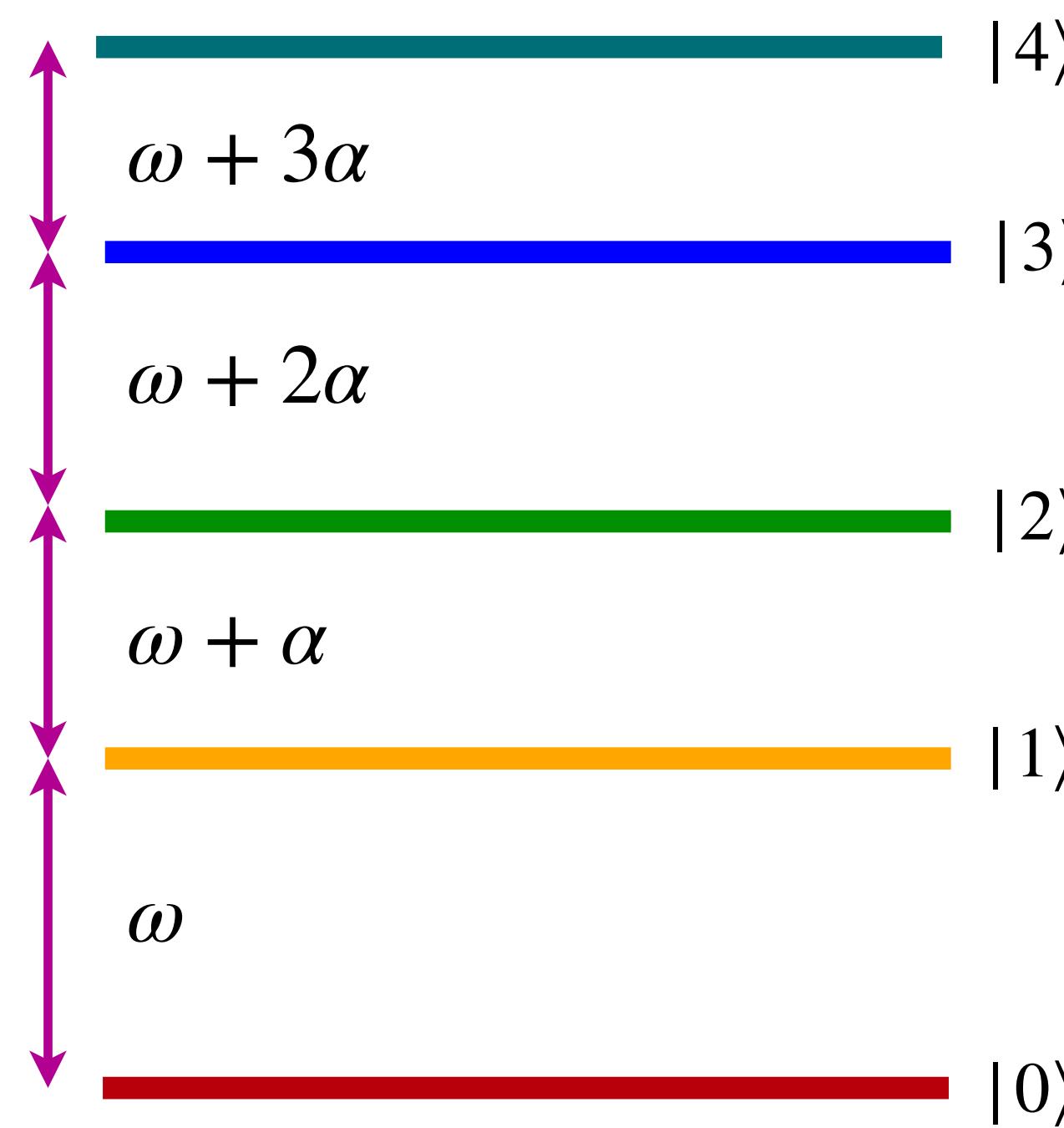
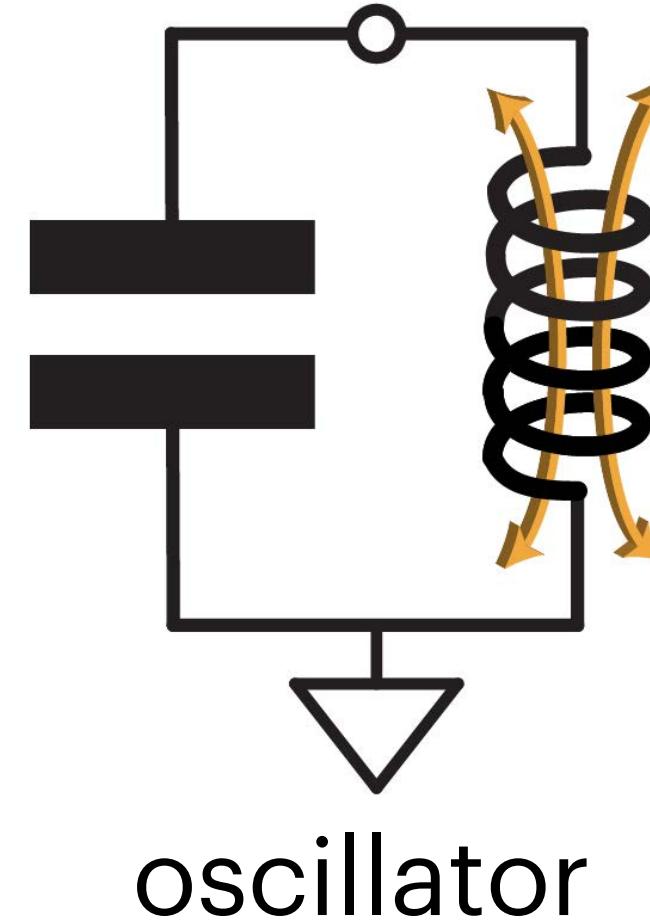
$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \quad U = \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix}$$

SUPERCONDUCTING QUBITS

BUILD QUBIT FROM OSCILLATOR

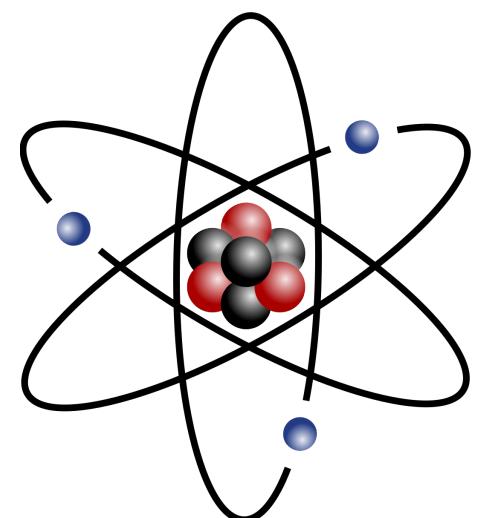


BUILD QUBIT FROM OSCILLATOR

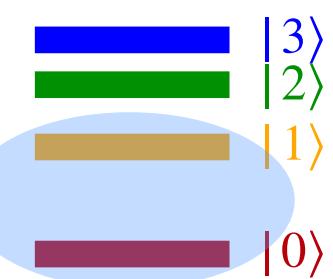


ROADMAP

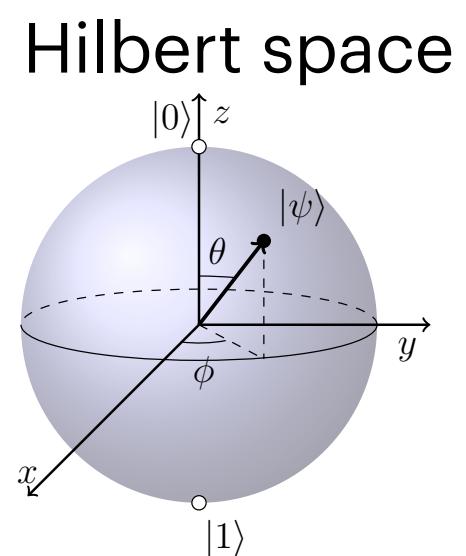
realization



energy levels

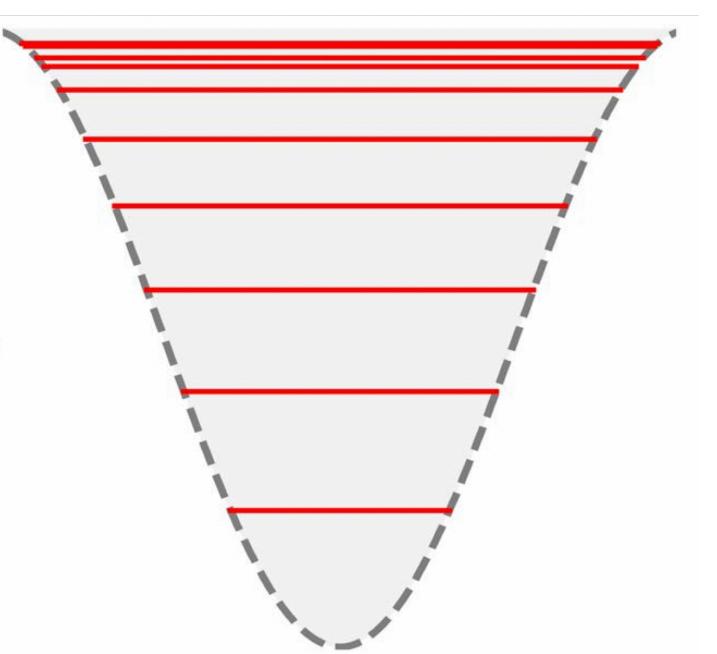


idealization
of qubit

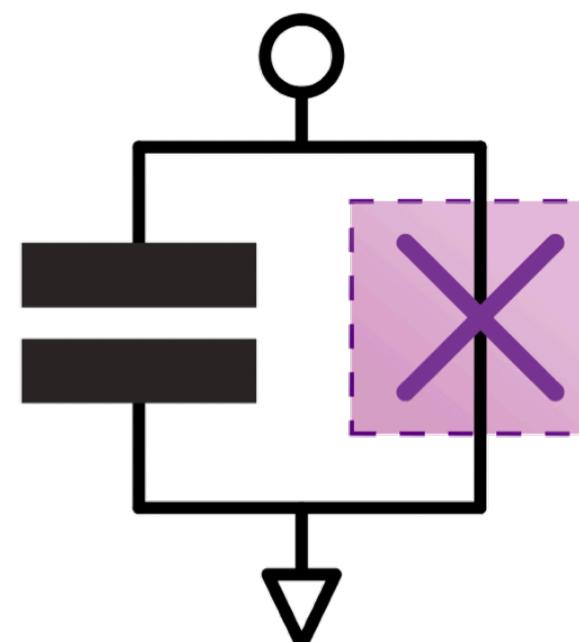


idealization

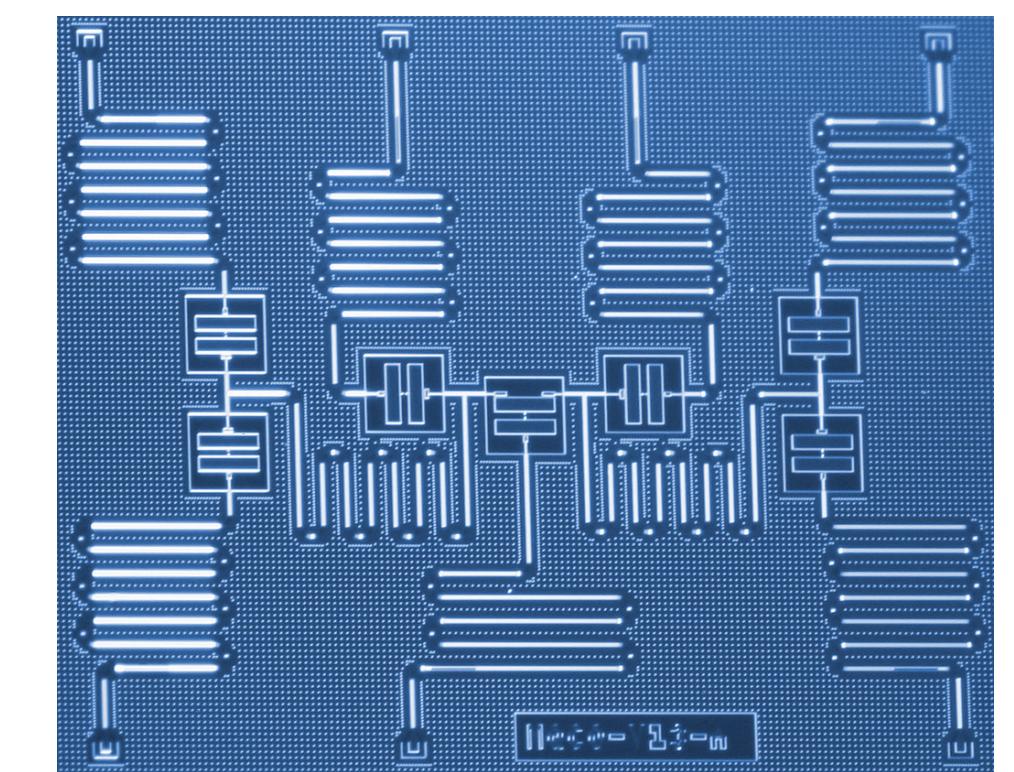
anharmonic oscillator



physical circuit model



physical layout



physical reality

"Quantum phenomena do not occur in a Hilbert space, they occur in a laboratory."

—Asher Peres

ERRORS

- Classical errors
 - Readout error
 - Pulse error
- Quantum errors
 - Depolarizing: energy transitions, dephasing, ...
 - Thermal relaxation: due to T_1, T_2

