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

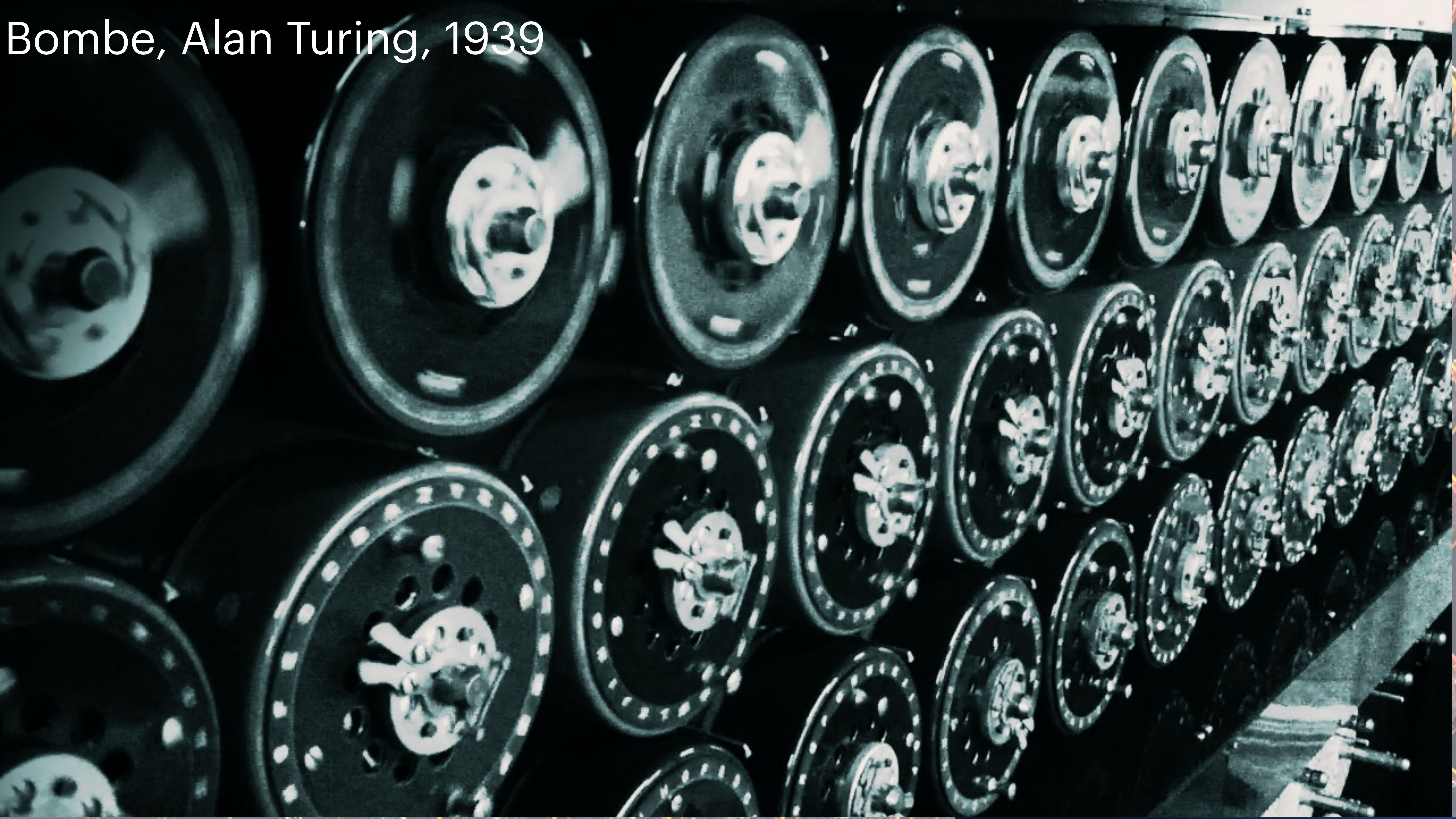
Advanced: Superconducting Qubits

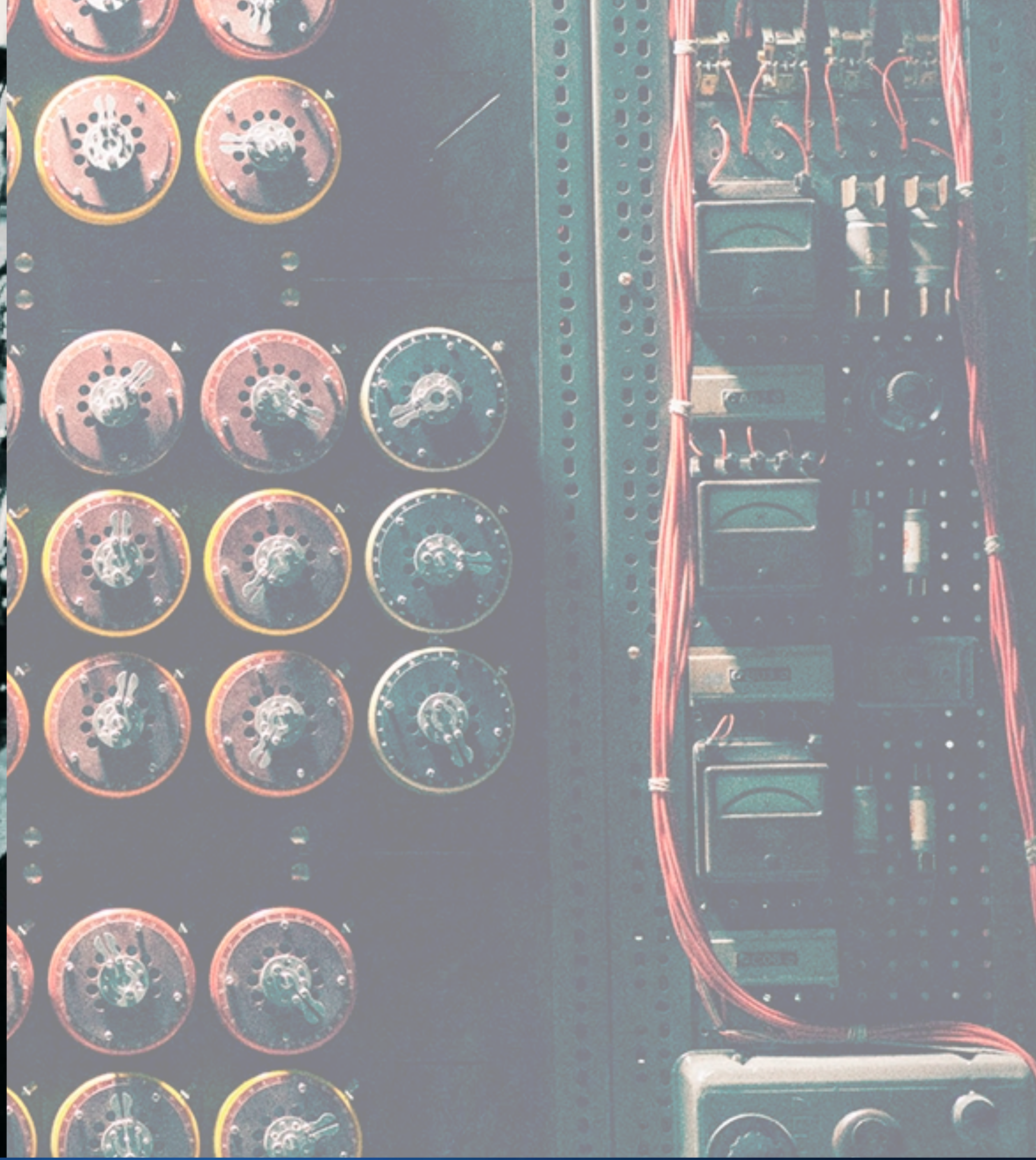
https://github.com/ycldingo/QuantumComputer_tw

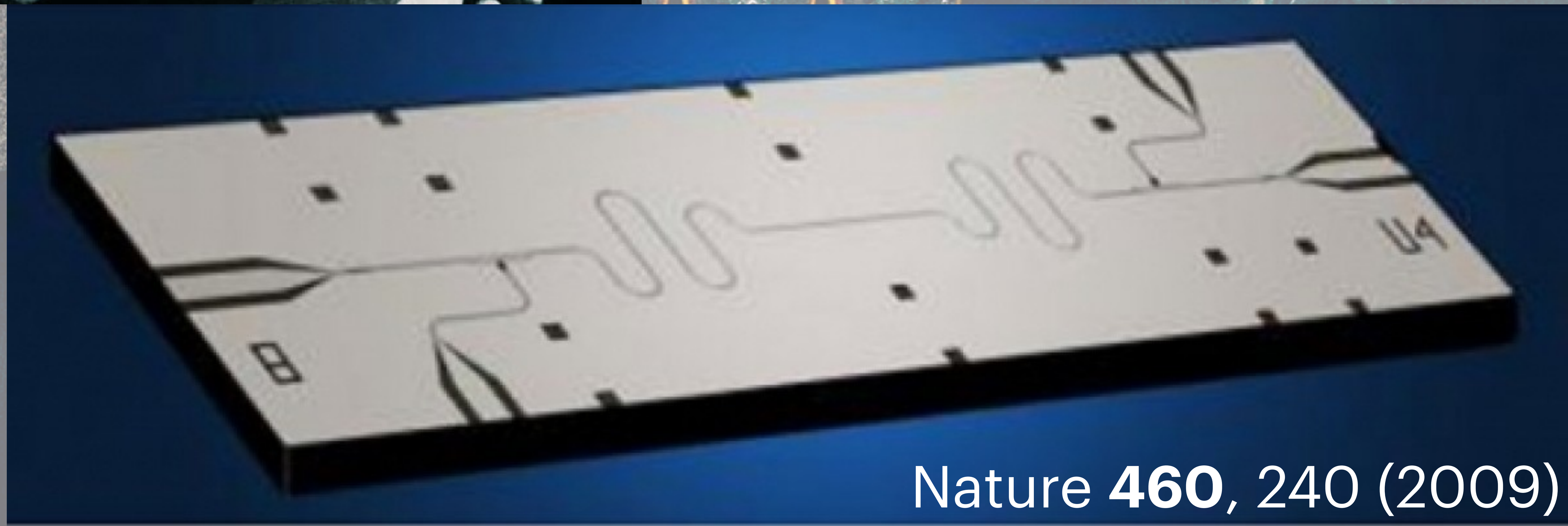
https://github.com/ycldingo/QuantumComputing_2020Summer

FROM CLASSICAL TO QUANTUM

Bombe, Alan Turing, 1939







Nature **460**, 240 (2009)

HISTORY

1980

Paul Benioff

Proposes quantum Turing machine model

1985

Paul Deutsch

Theoretical universal quantum computer

1993

Dan Simon

Quantum computer would be exponentially faster than conventional computer

1994

Peter Shor

Shor 's algorithm

1995

NIST & CalTech

Cools and traps ion to a quantum state

1997

MIT

First quantum computer (based on NMR)

2001

Emanuel Knill, Raymond Laflamme & Gerard Milburn

Shows that optical quantum computing is possible

2009

Yale University

First electronic quantum processor

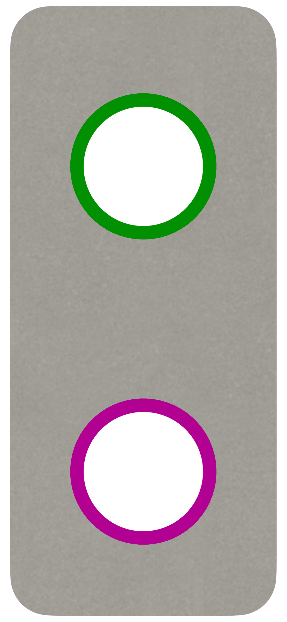
2016

IBM

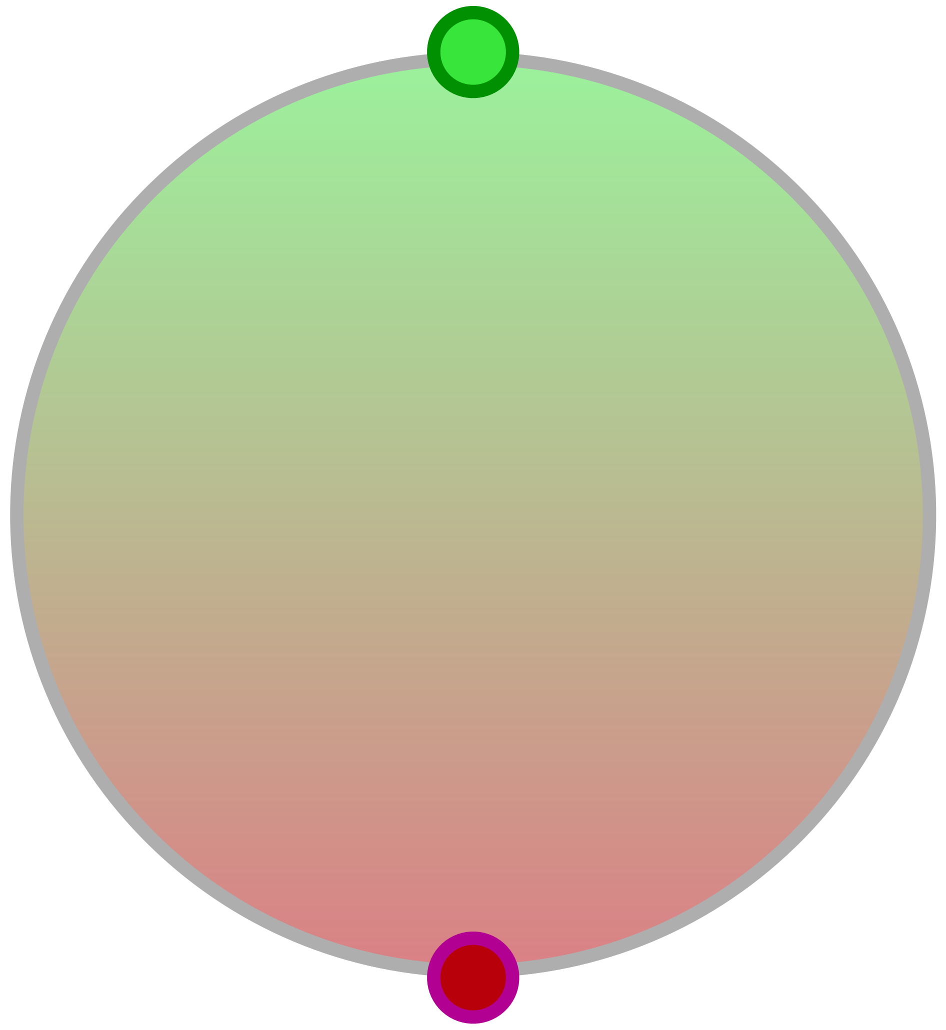
Releases Quantum Experience

CLASSICAL V.S. QUANTUM

Bit

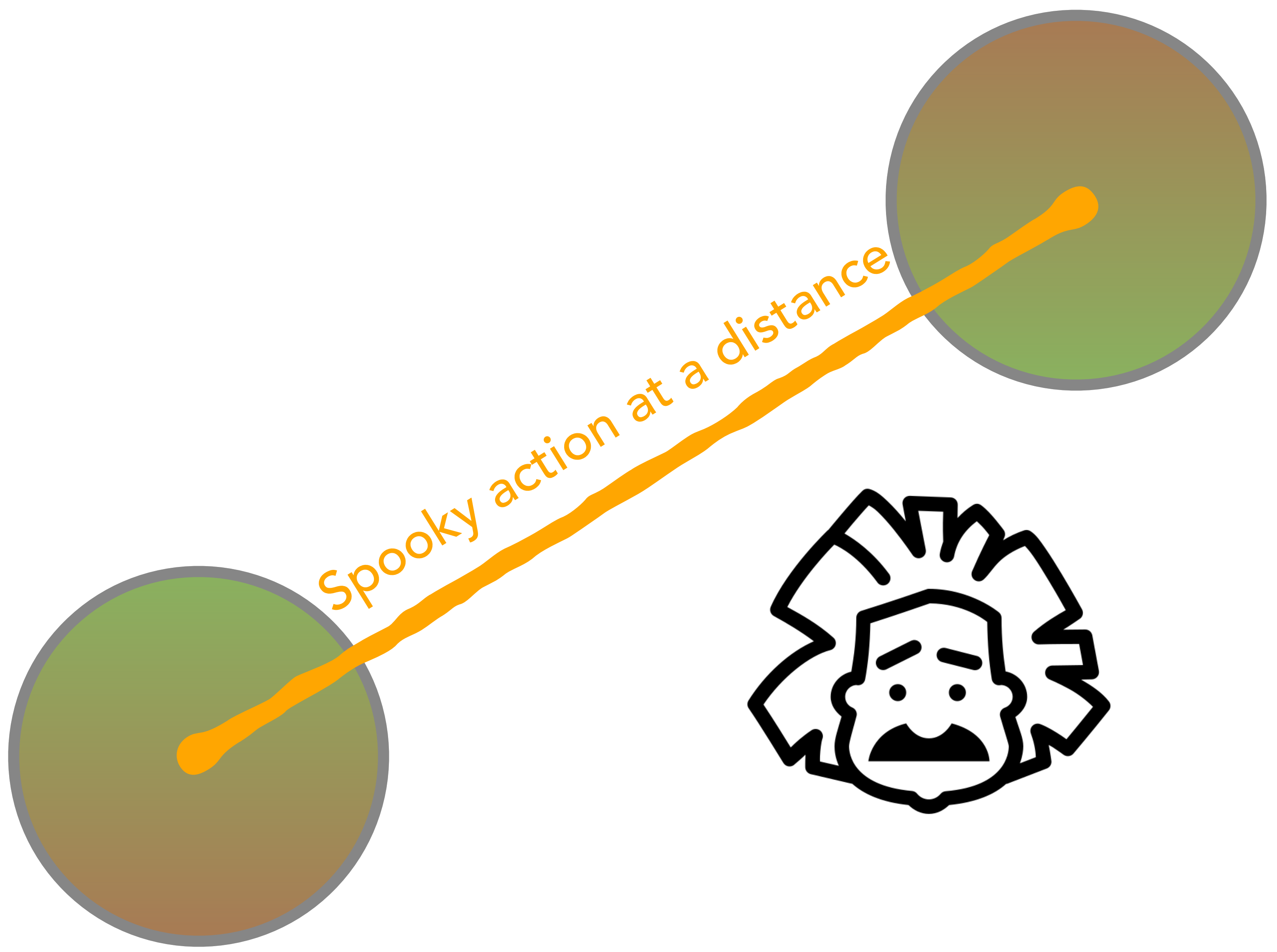


Qubit

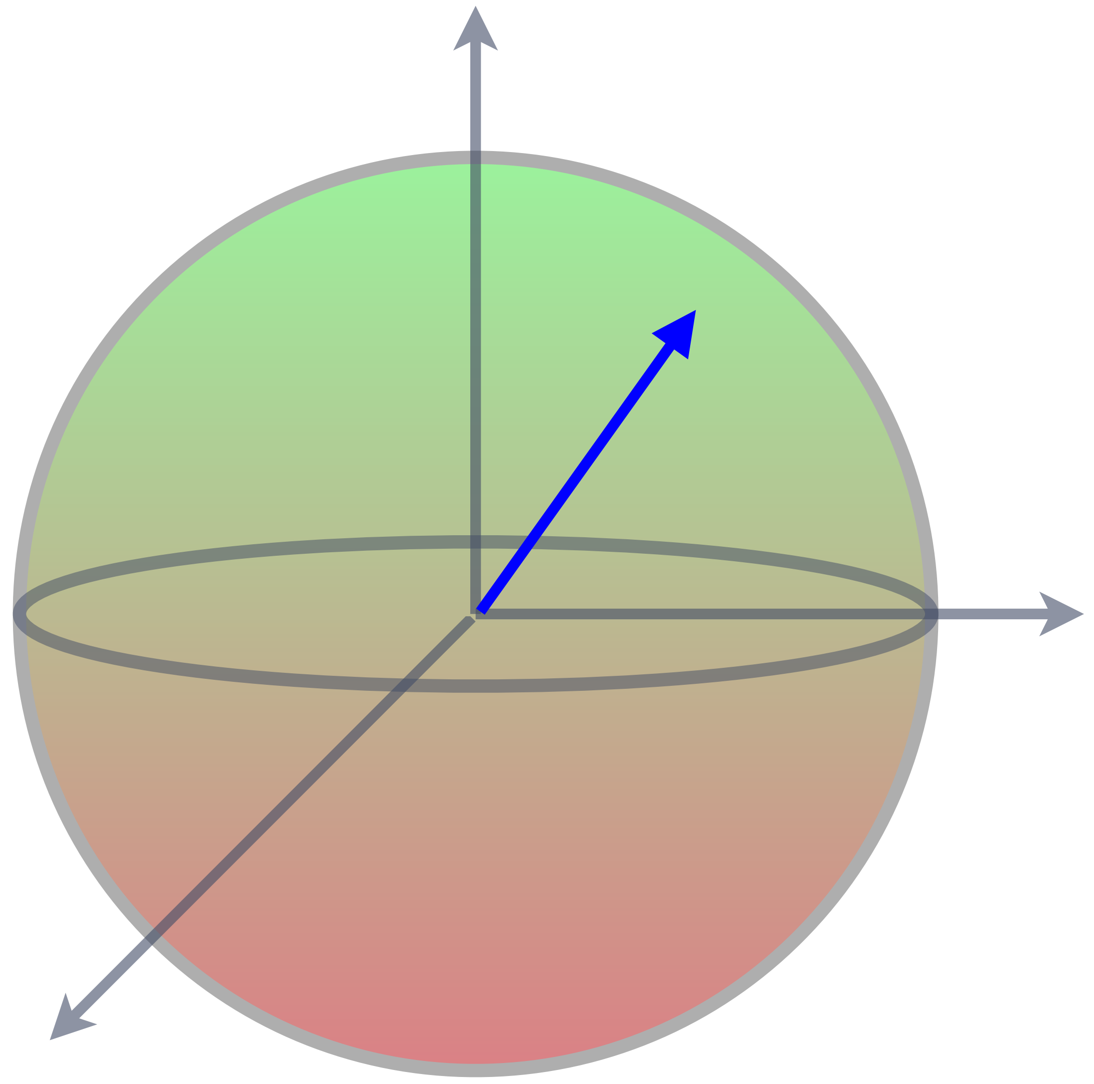


WHY SO POWERFUL ?

Entanglement



Superposition

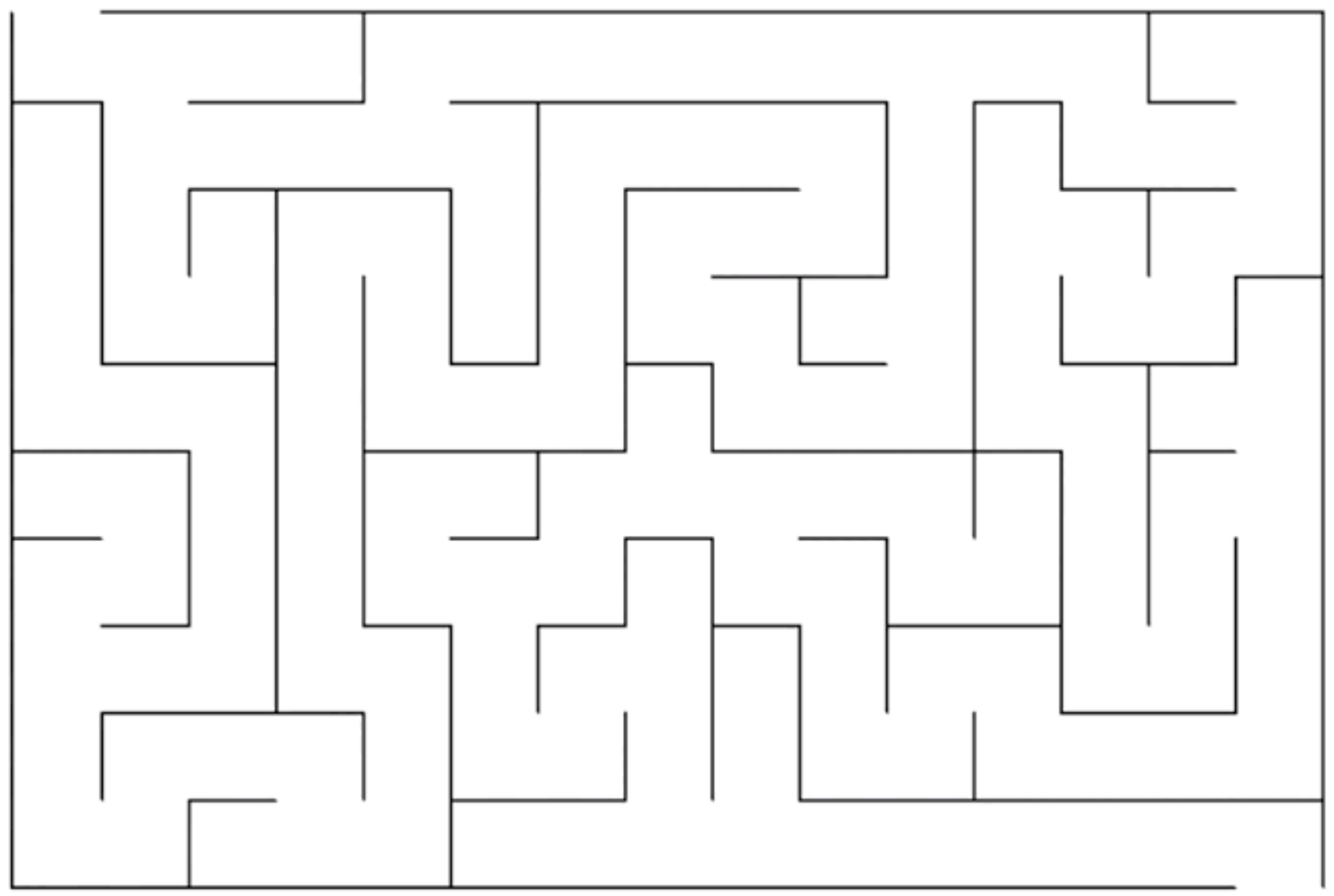


$$\alpha\,|0\rangle + \beta\,|1\rangle$$

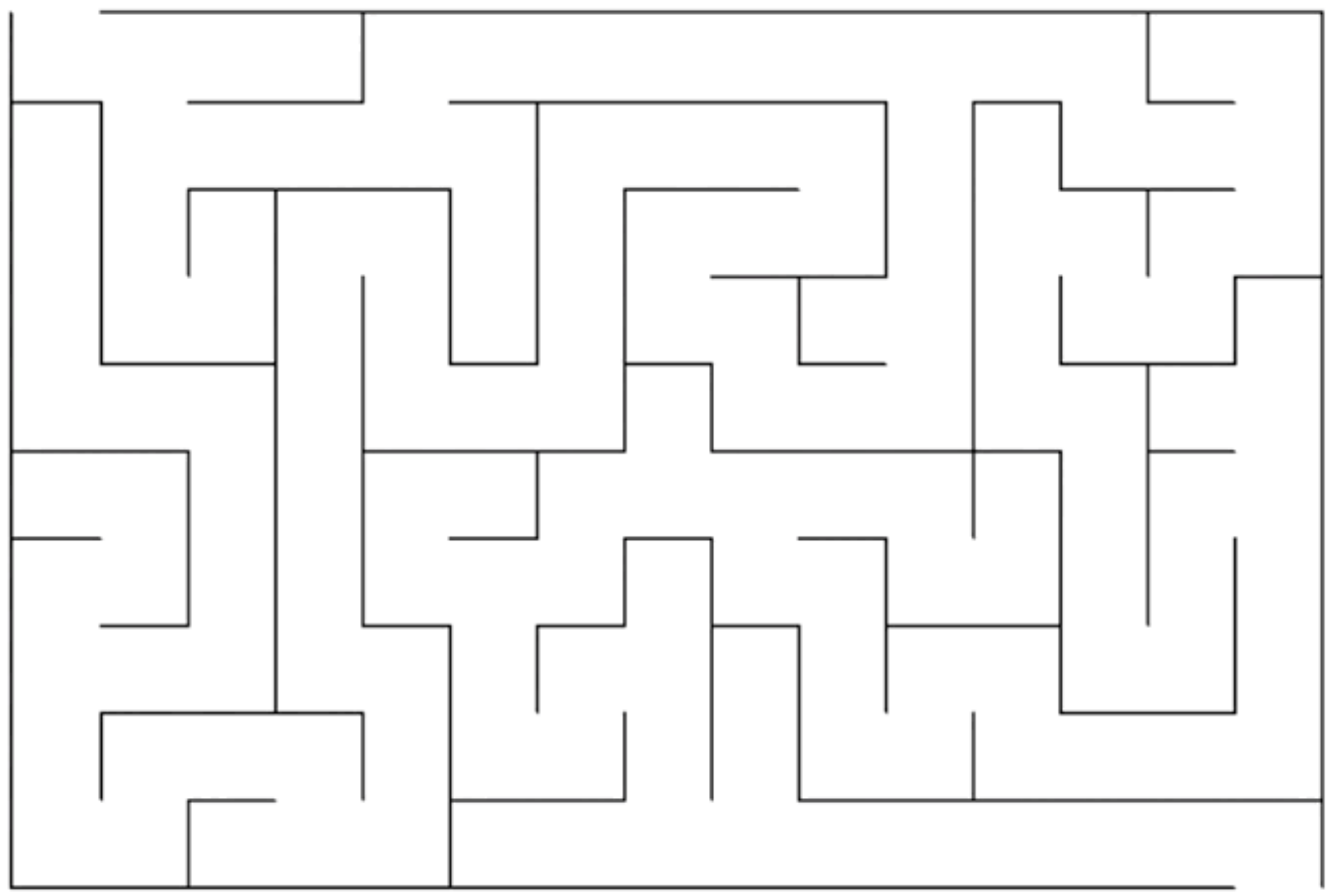

SUPERPOSITION
0
1
Natasha Hanacek/NIST

FIND A WAY OUT

Conventional



Quantum



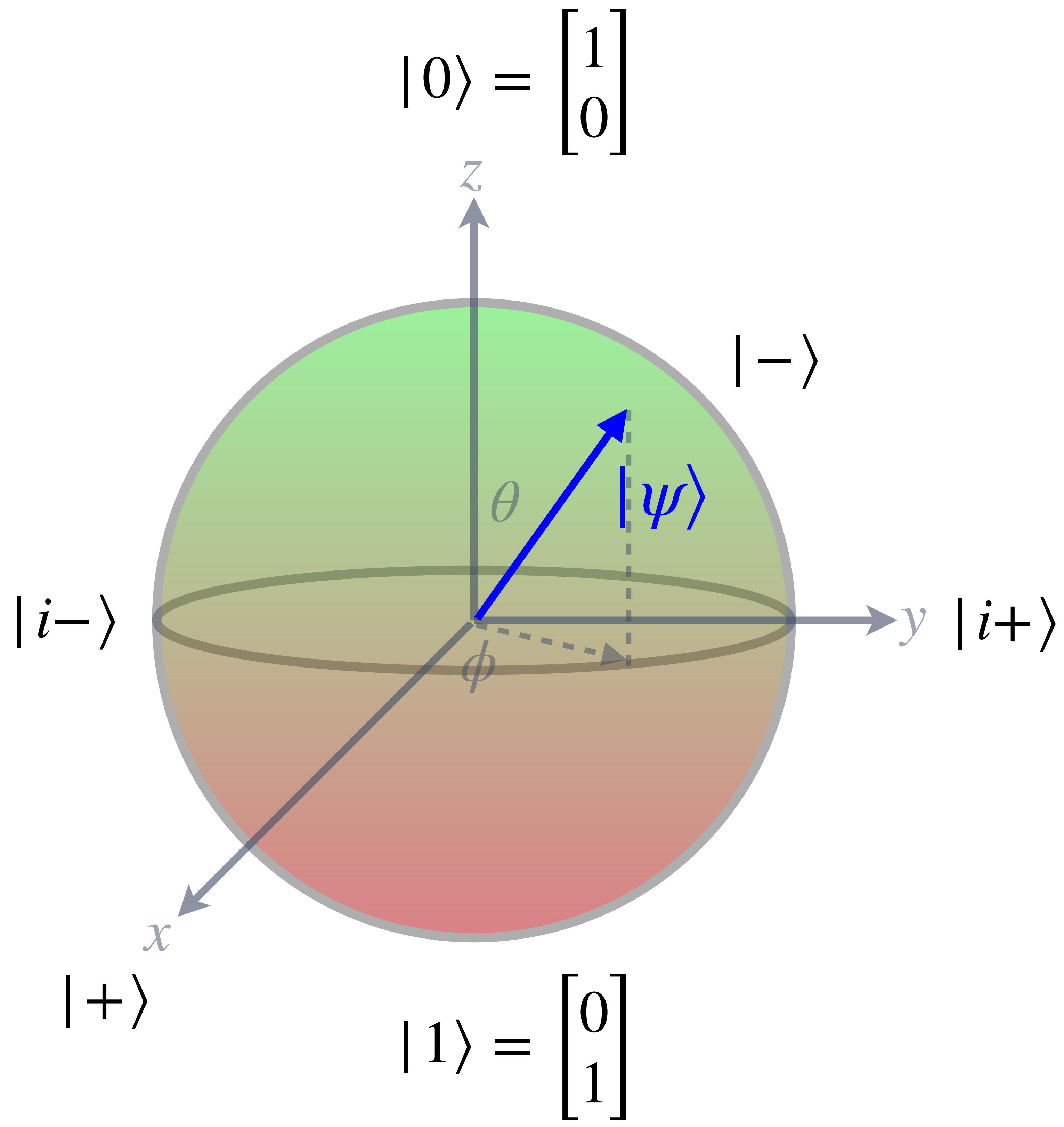
QUANTUM LANGUAGE

STATES

BLOCH SPHERE

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$
$$= \begin{bmatrix}\alpha \\ \beta\end{bmatrix}$$

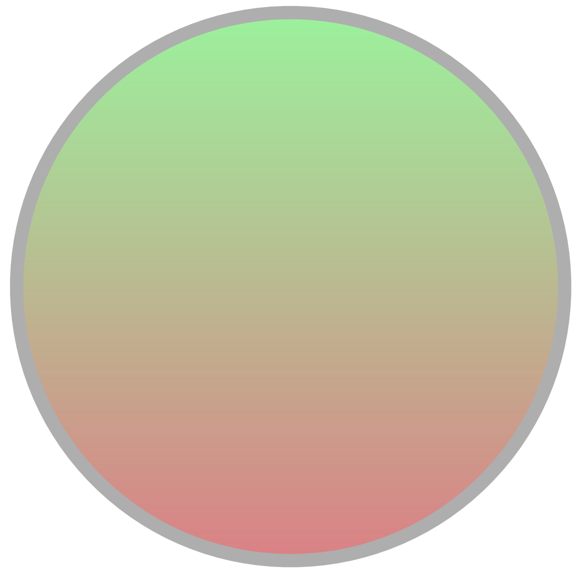
Basis: $\{\,|0\rangle, |1\rangle\,\}$



DIRAC NOTATION

Single qubit state

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



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

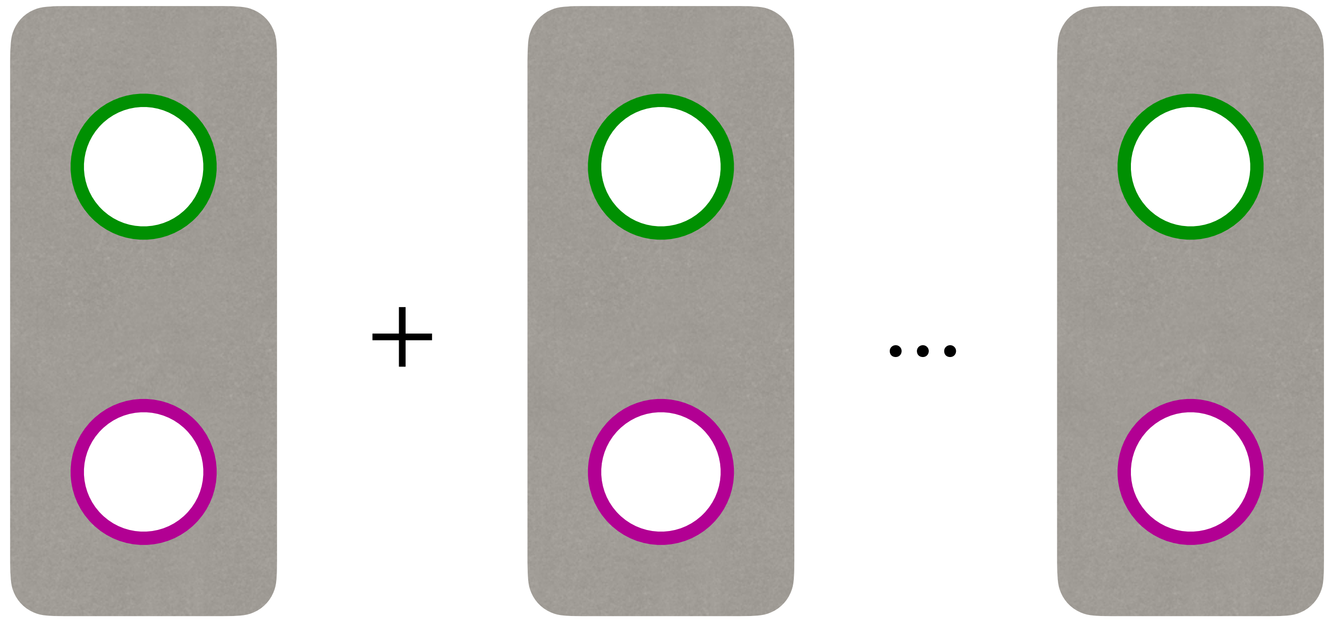
Bipartite quantum state

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

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

STATES FOR MORE THAN ONE ?

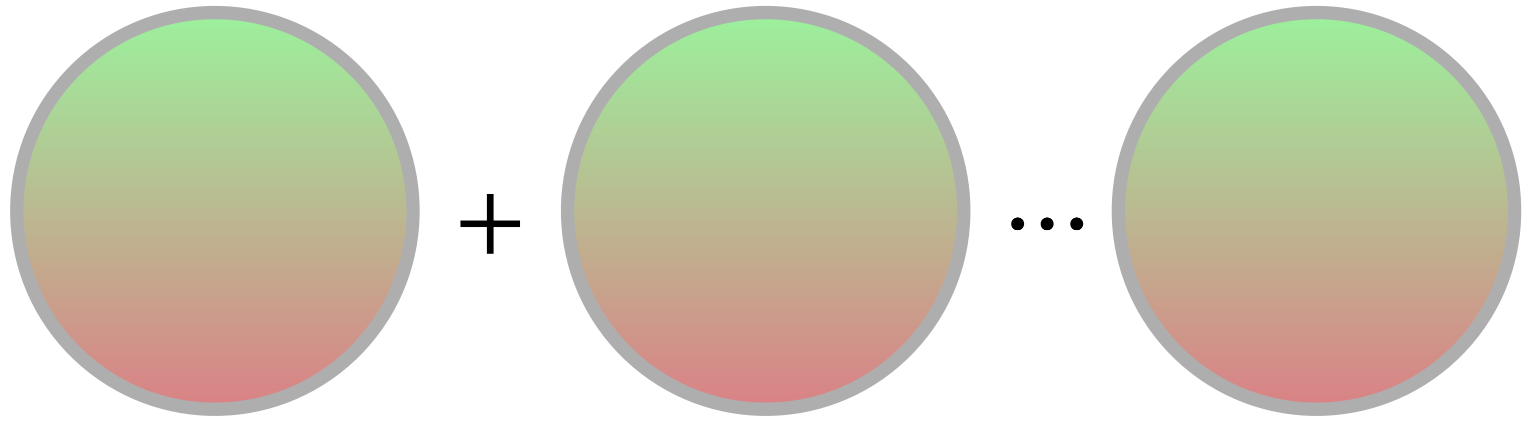
Classical



$1 \quad + \quad 1 \quad \cdots \quad 1$

N

Quantum



$2 \quad \times \quad 2 \quad \cdots \quad 2$

2^N

Exponentially speedup!

OPERATIONS - QUANTUM GATES

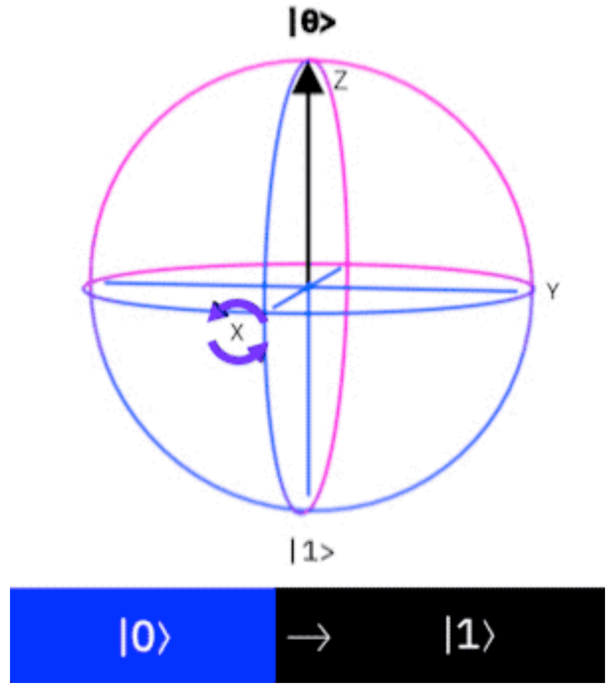
REVERSIBLE!

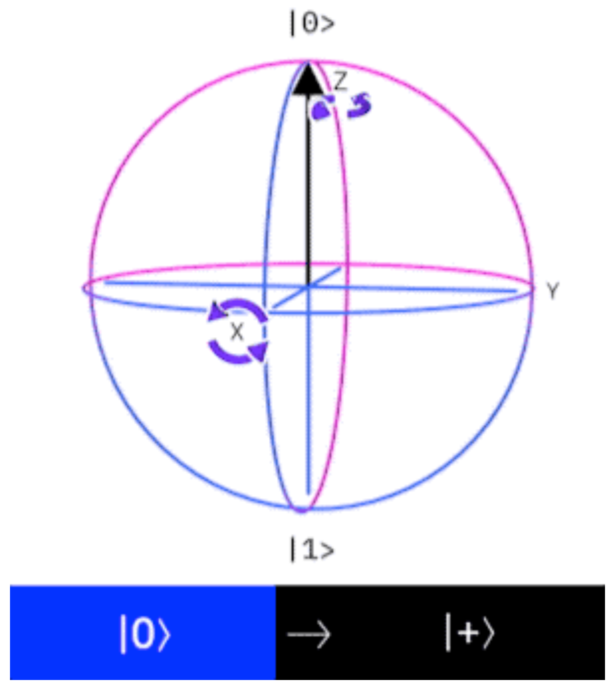
Single-qubit gates

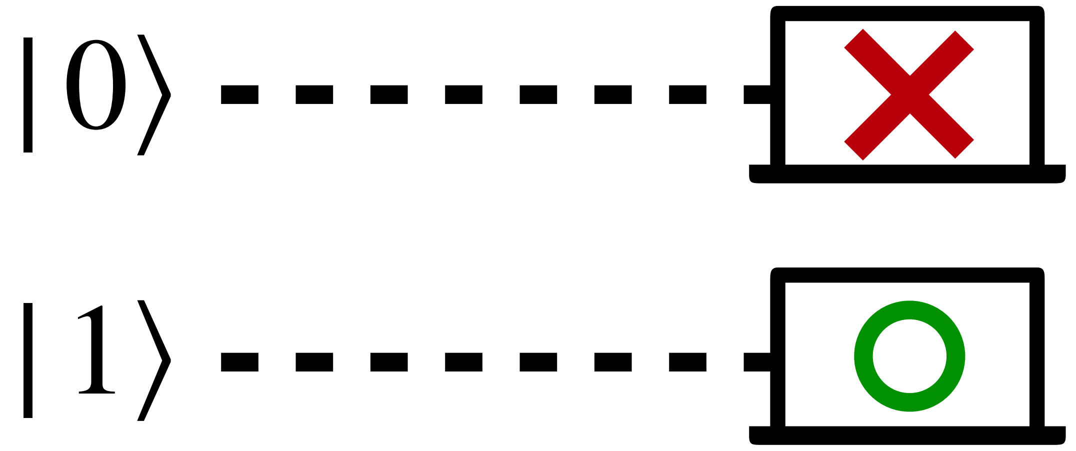
1. **Hadamard** H
2. **Rotation** X Y Z Rx Ry Rz

Two-qubit gates

1. **CNOT**
2. **Controlled-rotation** cH cRz







QUANTUM COMPUTERS

IMPLEMENTS

MONEY, MONEY, AND MONEY

Photons, electrons, nucleus

NMR

Quantum dots

Nature atoms

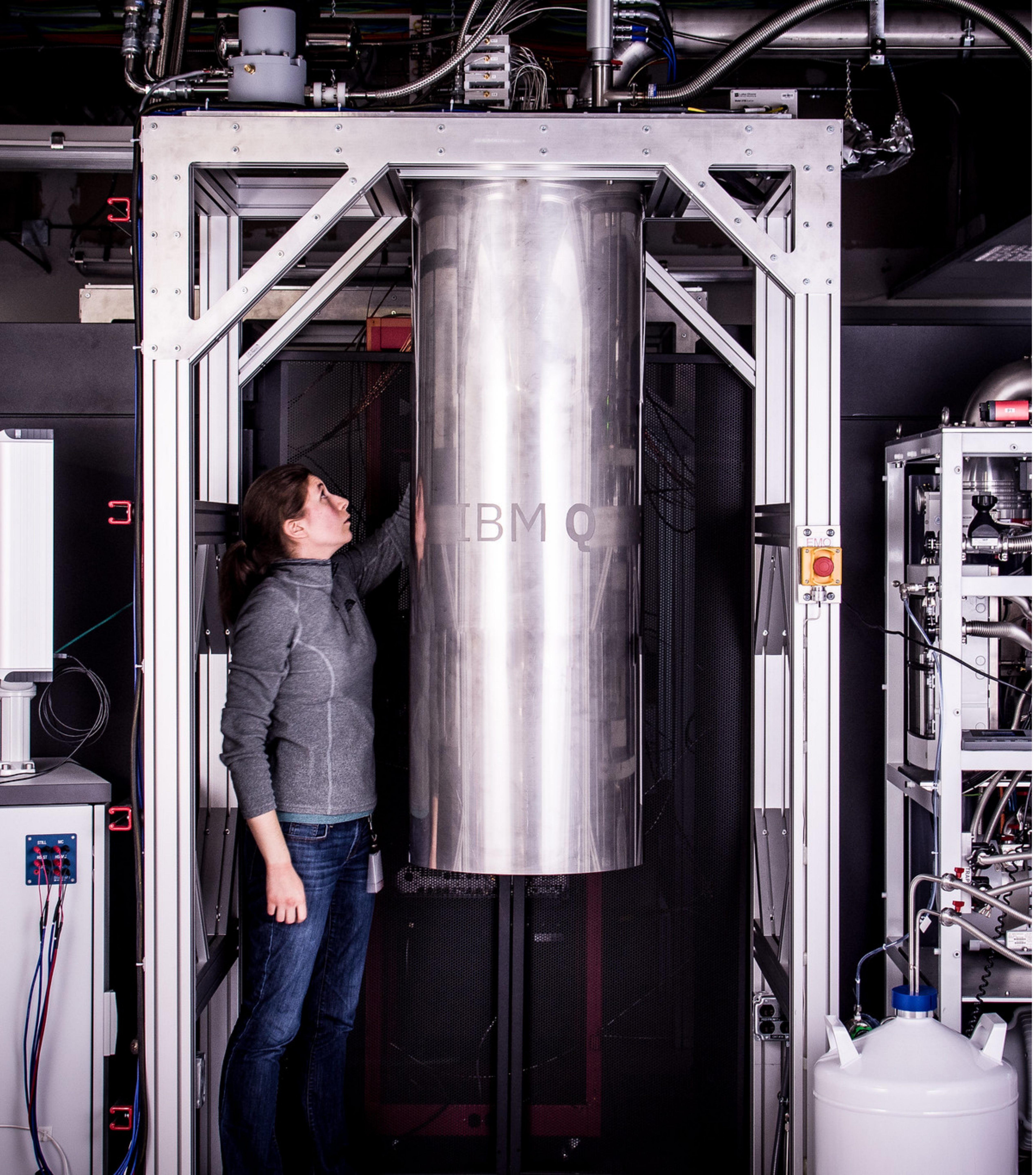
Diamonds

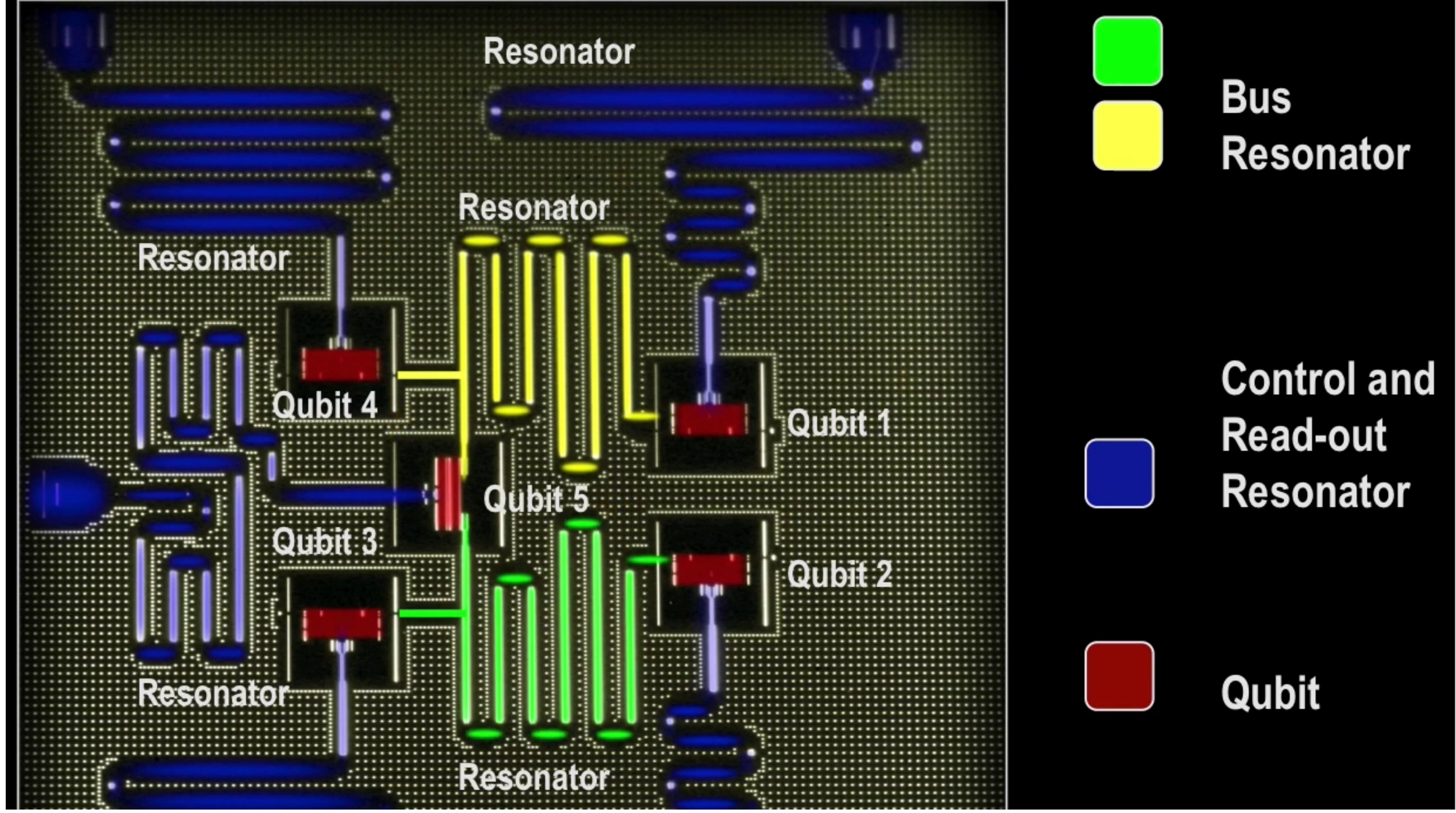
Semiconductors

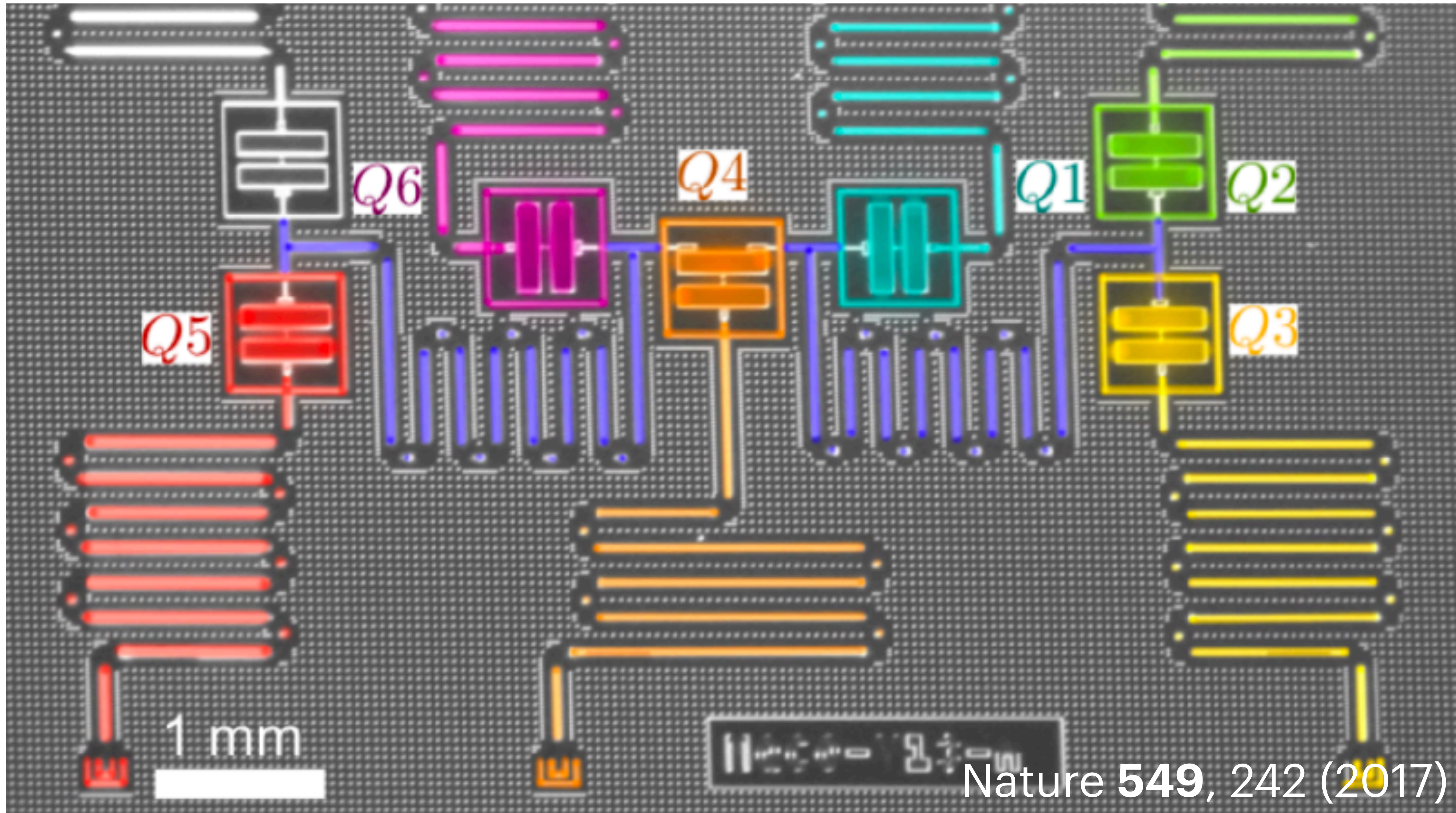
Superconductors

and so on……


Quantum Computing
Intersecting science, systems and design.
IBM Q System One
IBM



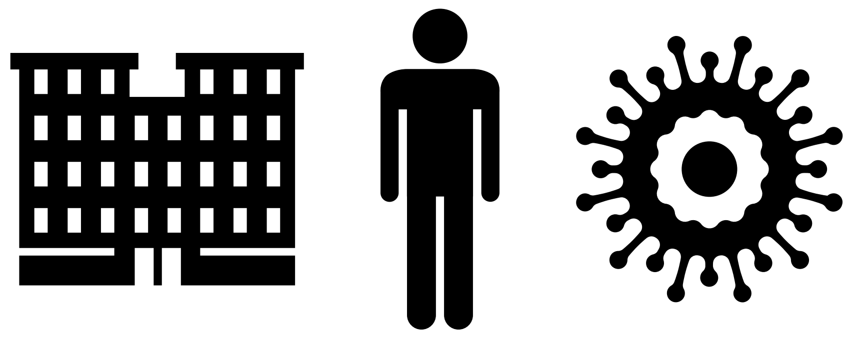




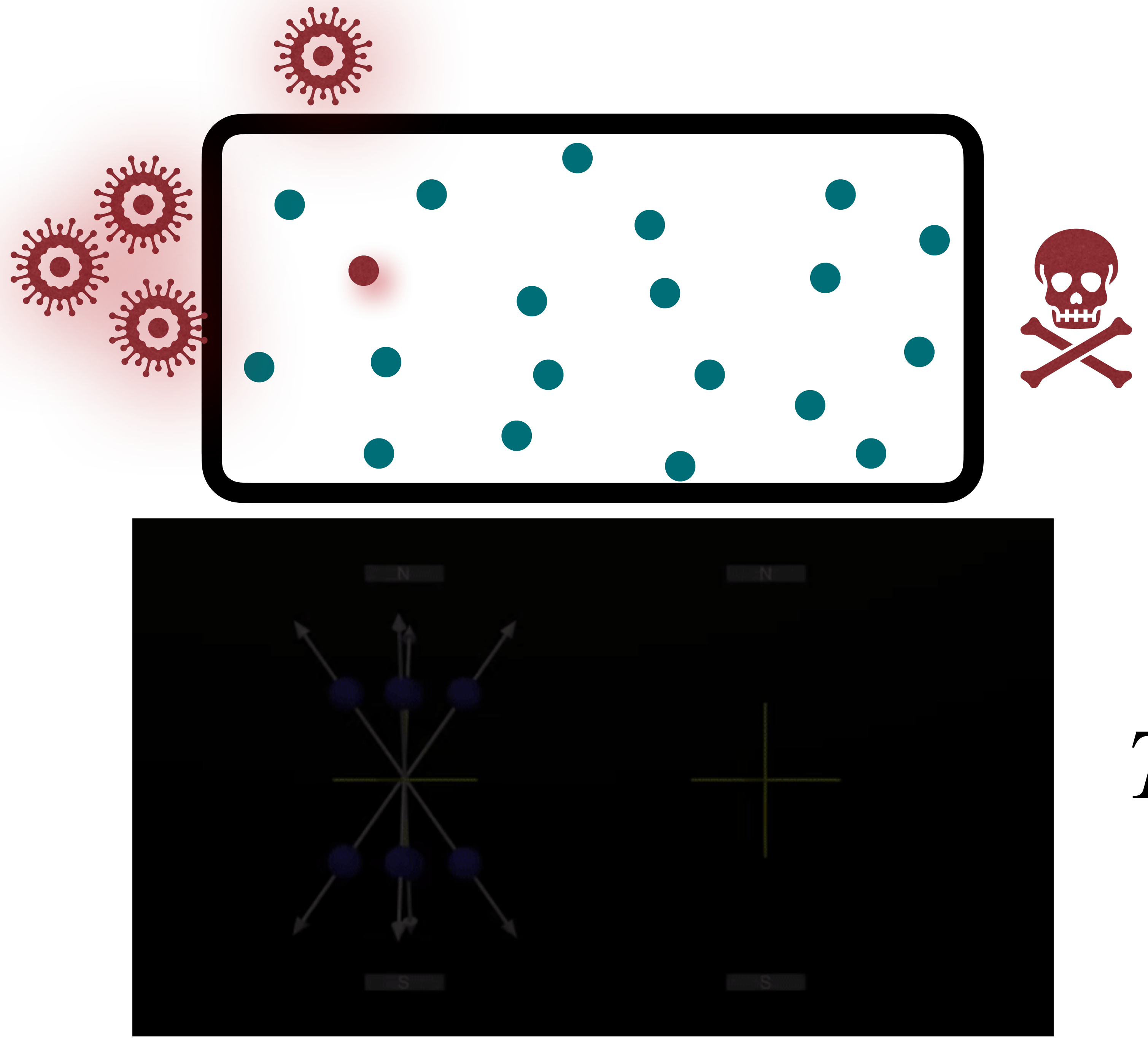
Nature **549**, 242 (2017)

RELAXATION

COVID-19 MODEL

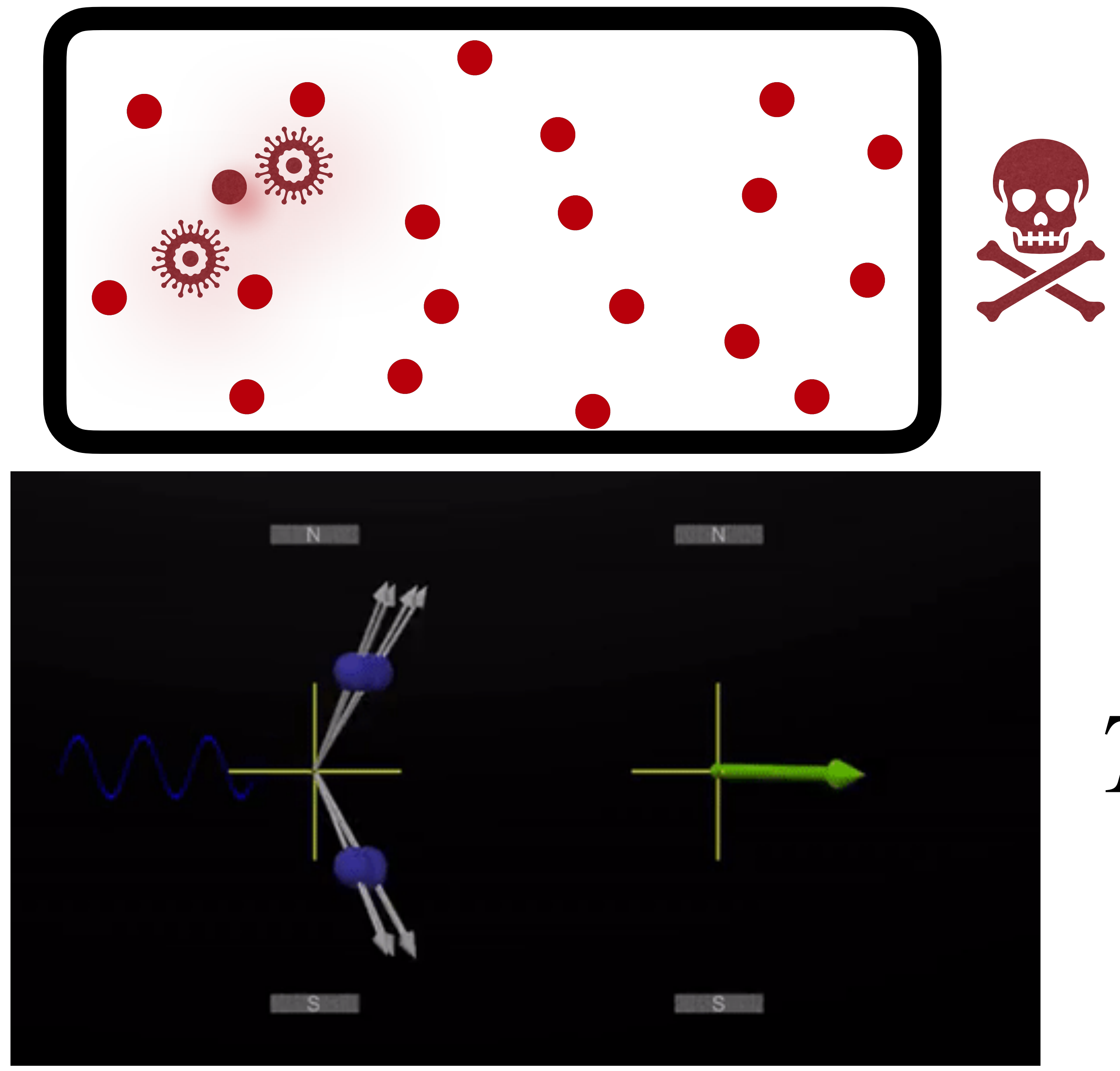


qubit-environment



T_1

qubit-qubit



T_2

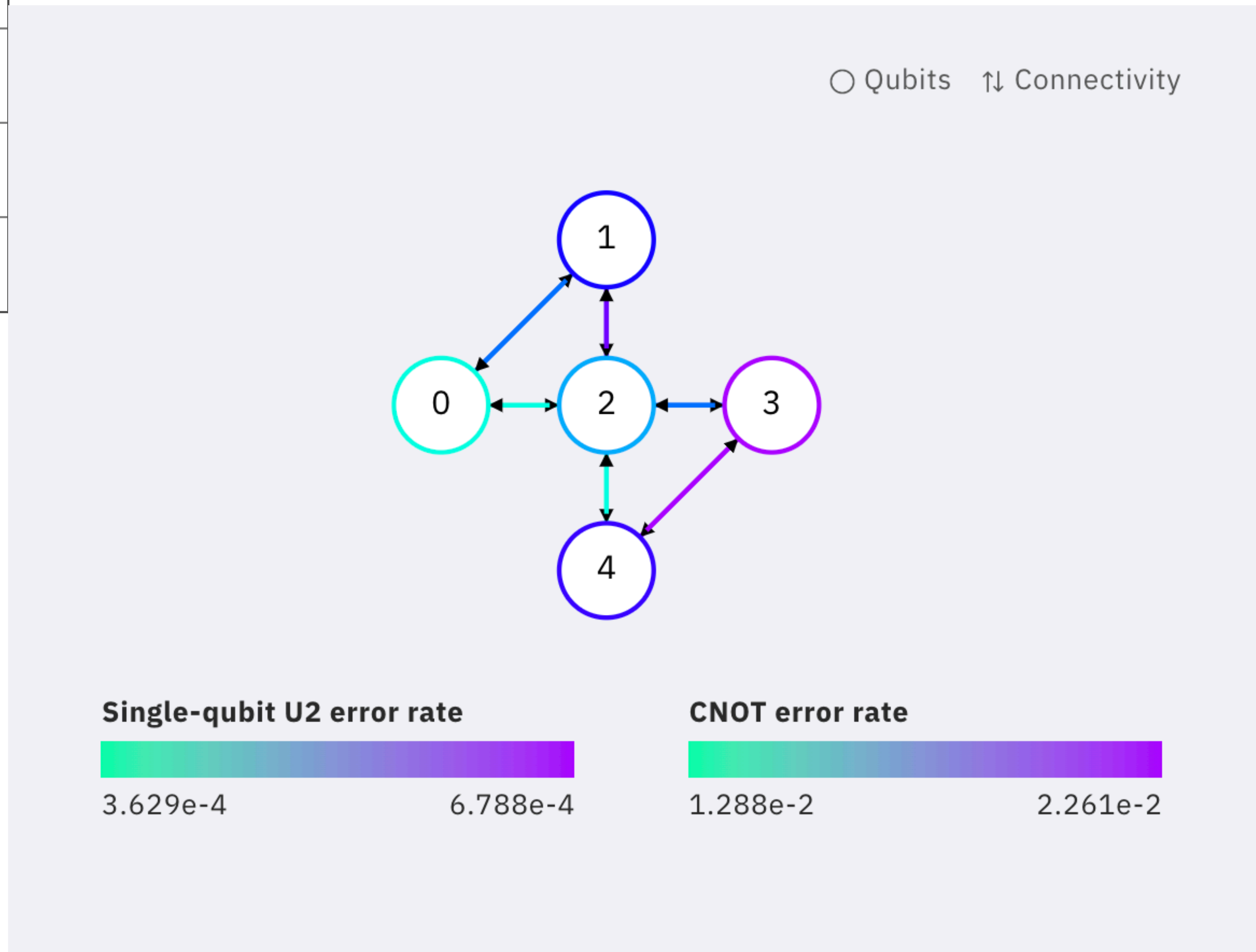
NUTRITION FACT OF QUBITS

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



YOUR FIRST QUANTUM CIRCUIT

IBM QUANTUM EXPERIENCE

EXAMPLE - ENTANGLED STATE

STRUCTURE

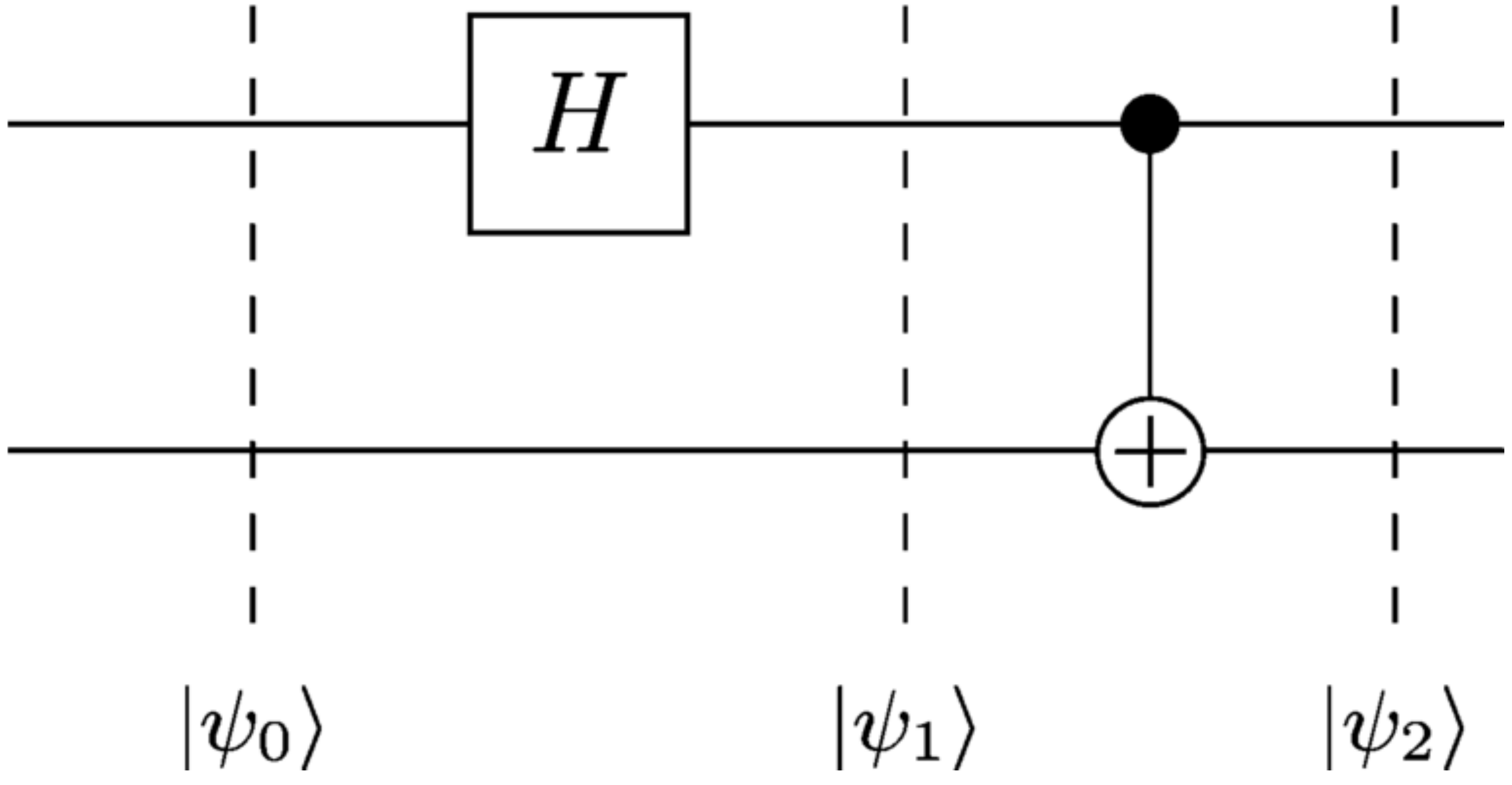
Bell states

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

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

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

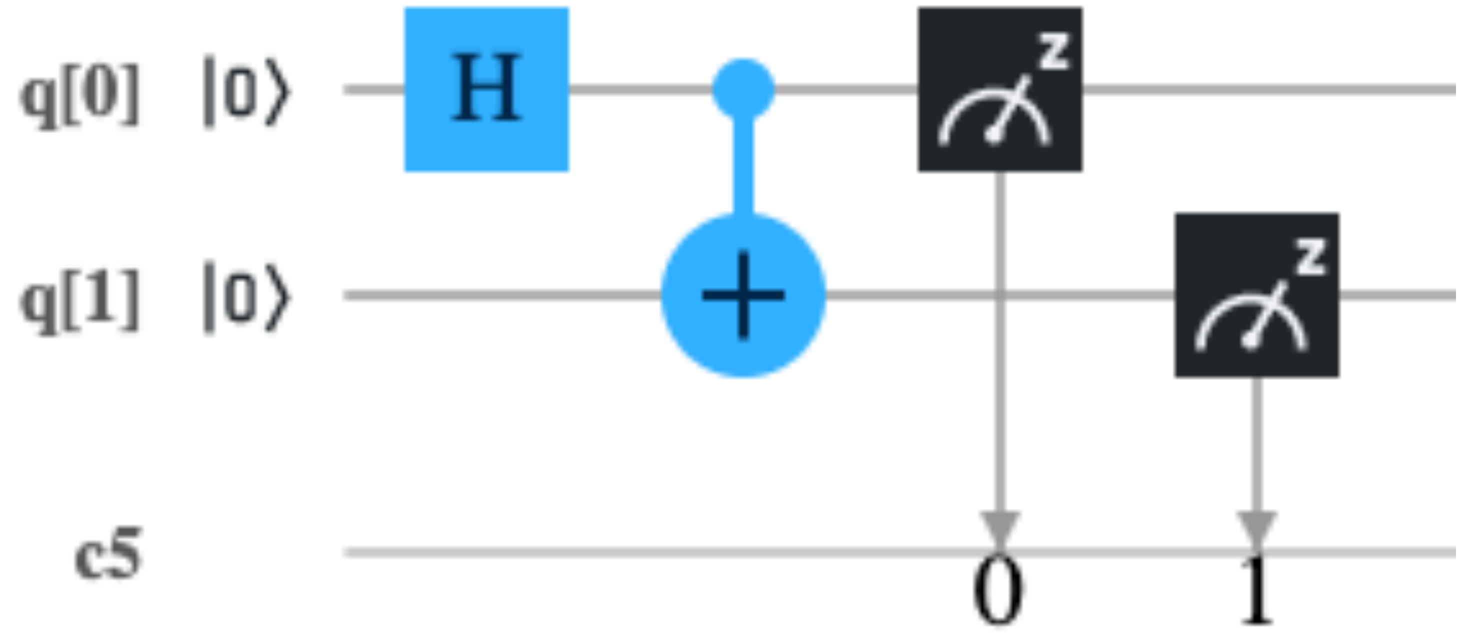
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$



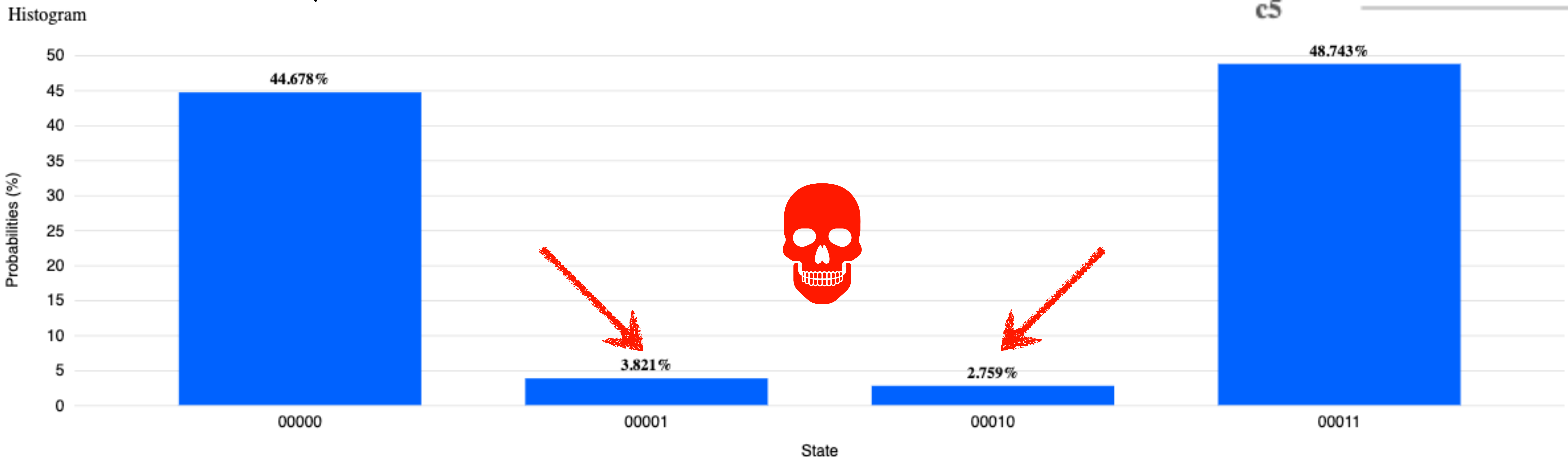
$$|\psi_2\rangle = CNOT \cdot (H \otimes I)\,|\psi_0\rangle$$

EXAMPLE - ENTANGLED STATE

RESULTS

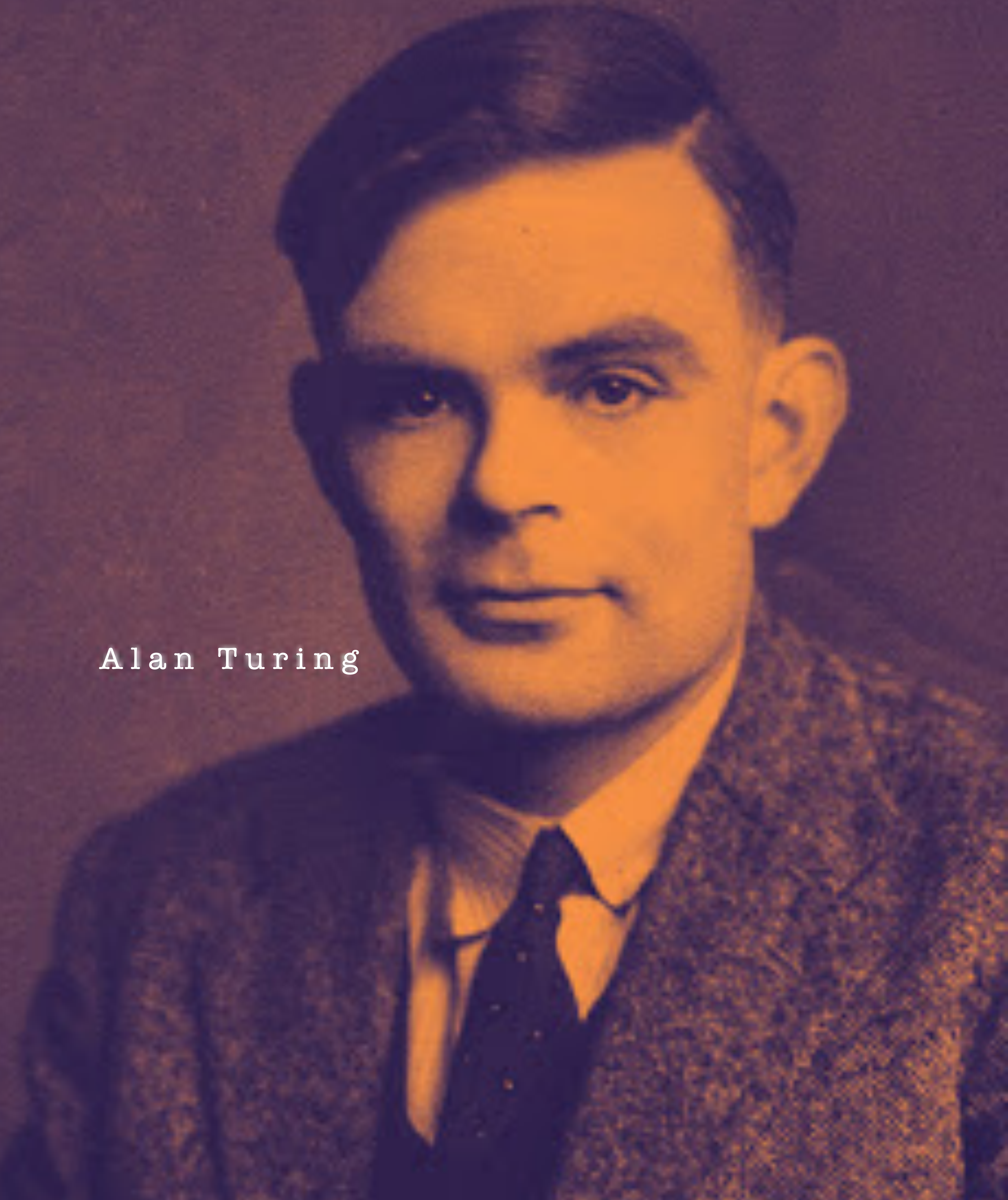


State: $|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$



Alan Turing

QUESTION?



SUPPLEMENTARY

TOOLS

VECTORS & MATRICES

ket-vector

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

bra-vector

$$\langle\psi| = \begin{bmatrix} \alpha* & \beta* & \gamma* \end{bmatrix}$$

Hermitian conjugate

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

MATRICES OPERATIONS

Kronecker product (tensor product)

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

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

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

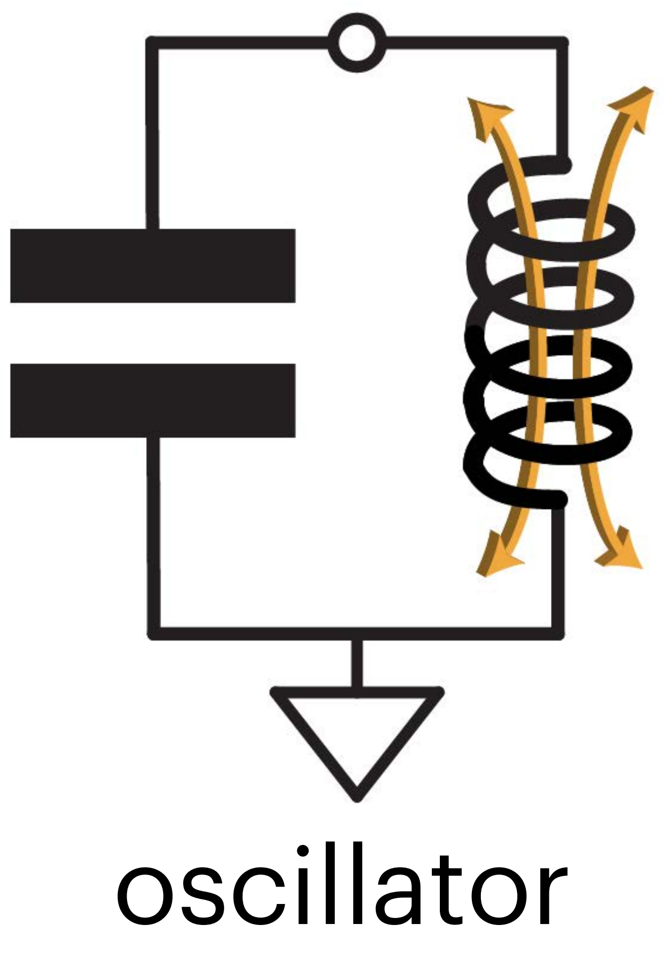
Matrices multiplication

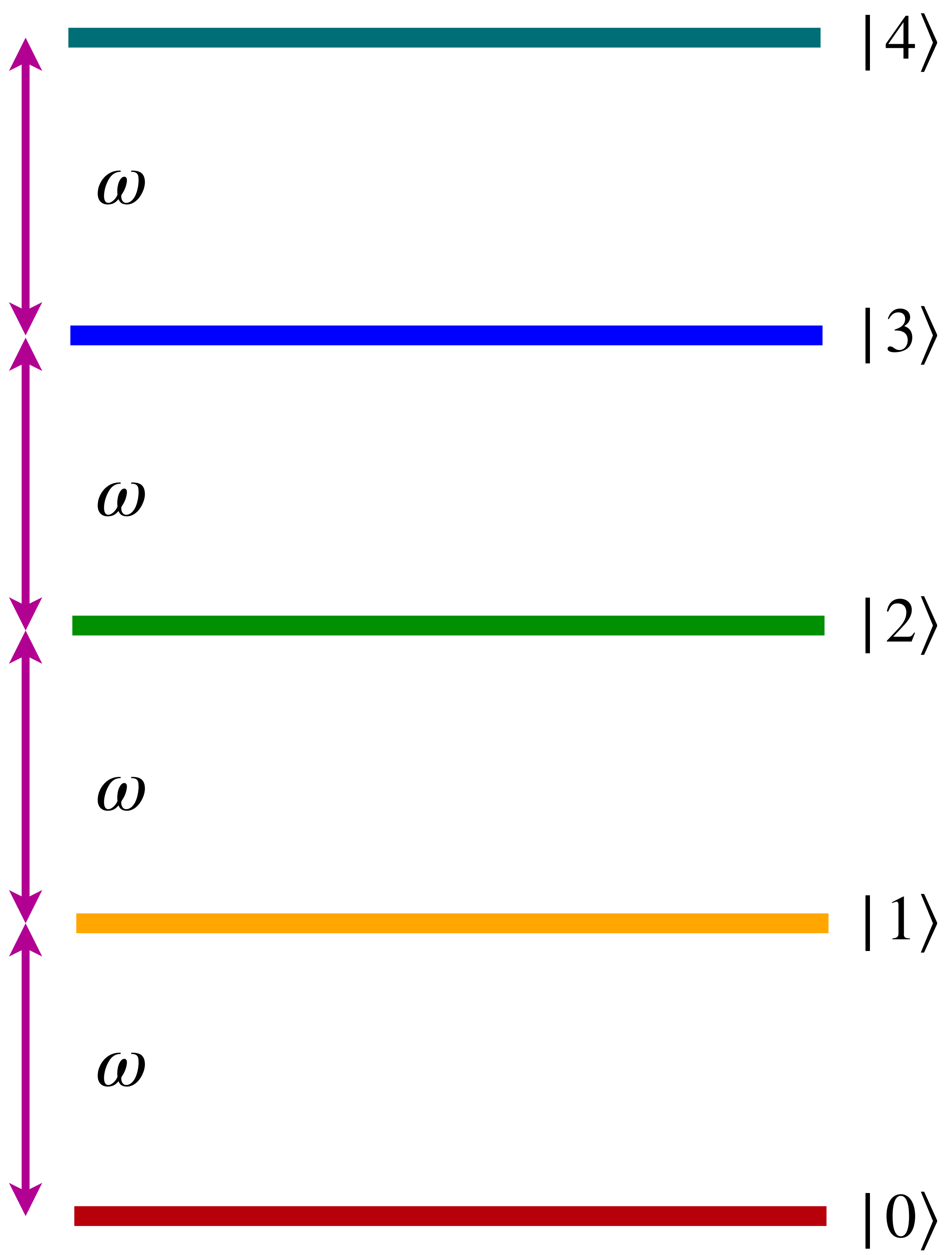
$$\langle\psi| \, U \, |\psi\rangle = \langle\psi| \, U^\dagger \, |\psi\rangle = \begin{bmatrix} \alpha* & \beta* & \gamma* \end{bmatrix} \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$$

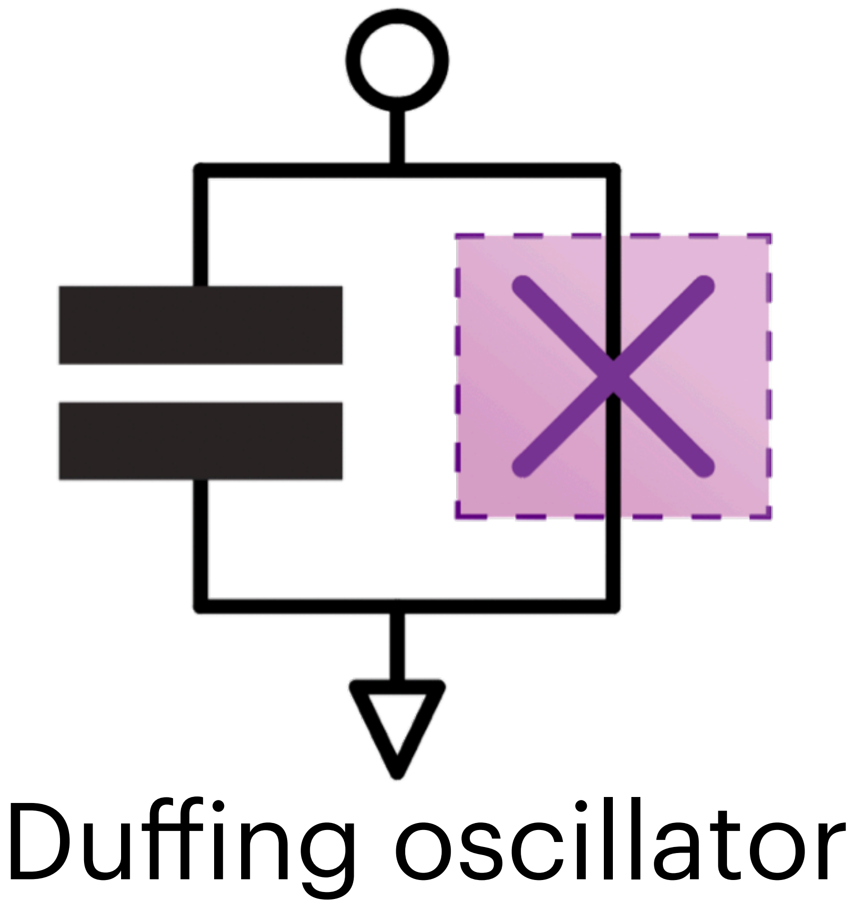
$$|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \quad U = \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix}$$

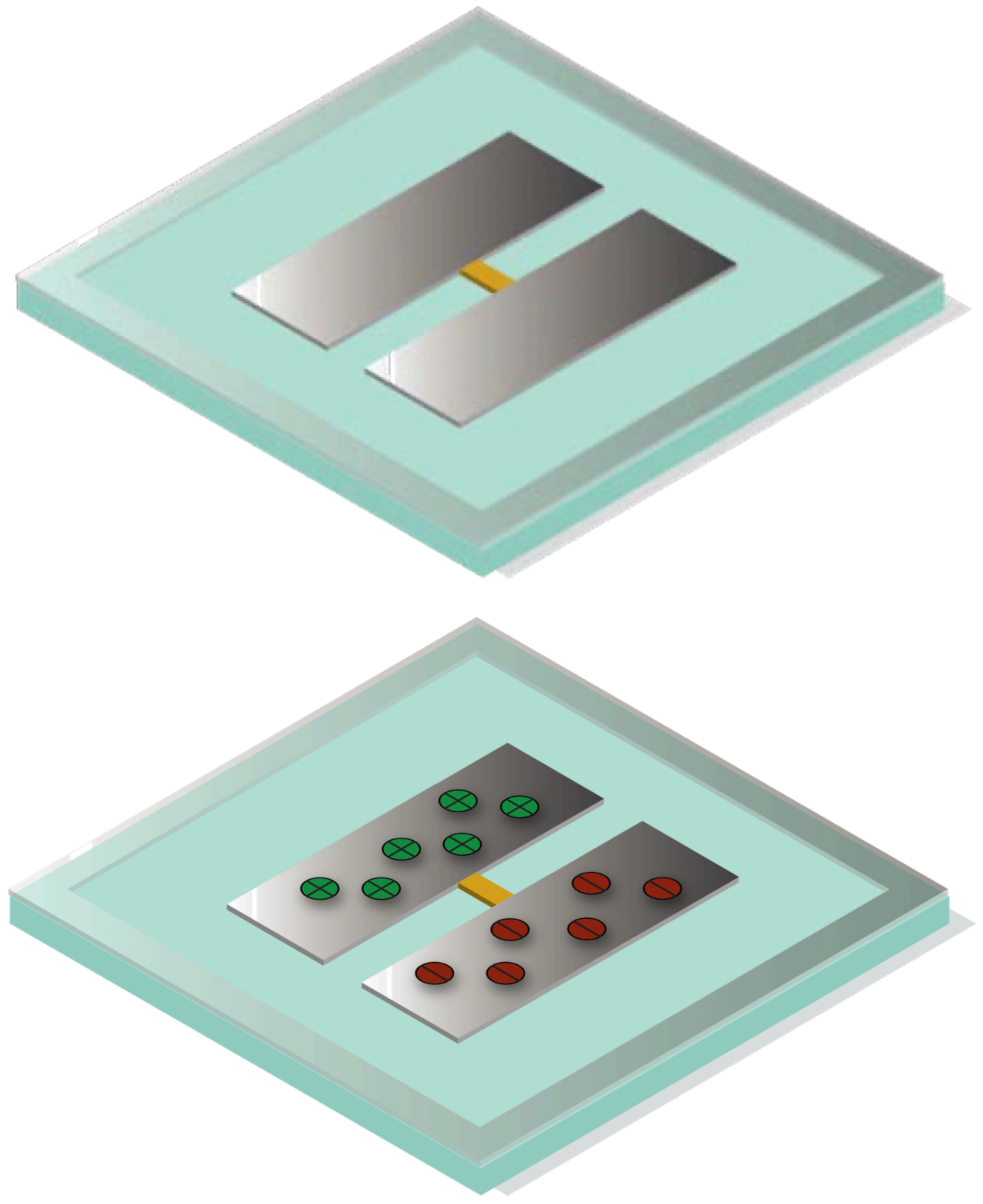
SUPERCONDUCTING QUBITS

BUILD QUBIT FROM OSCILLATOR

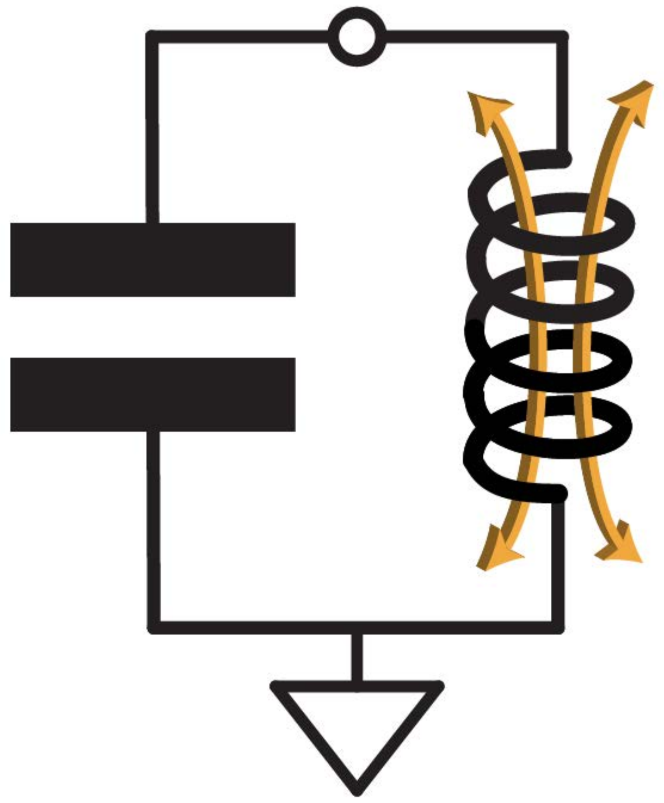




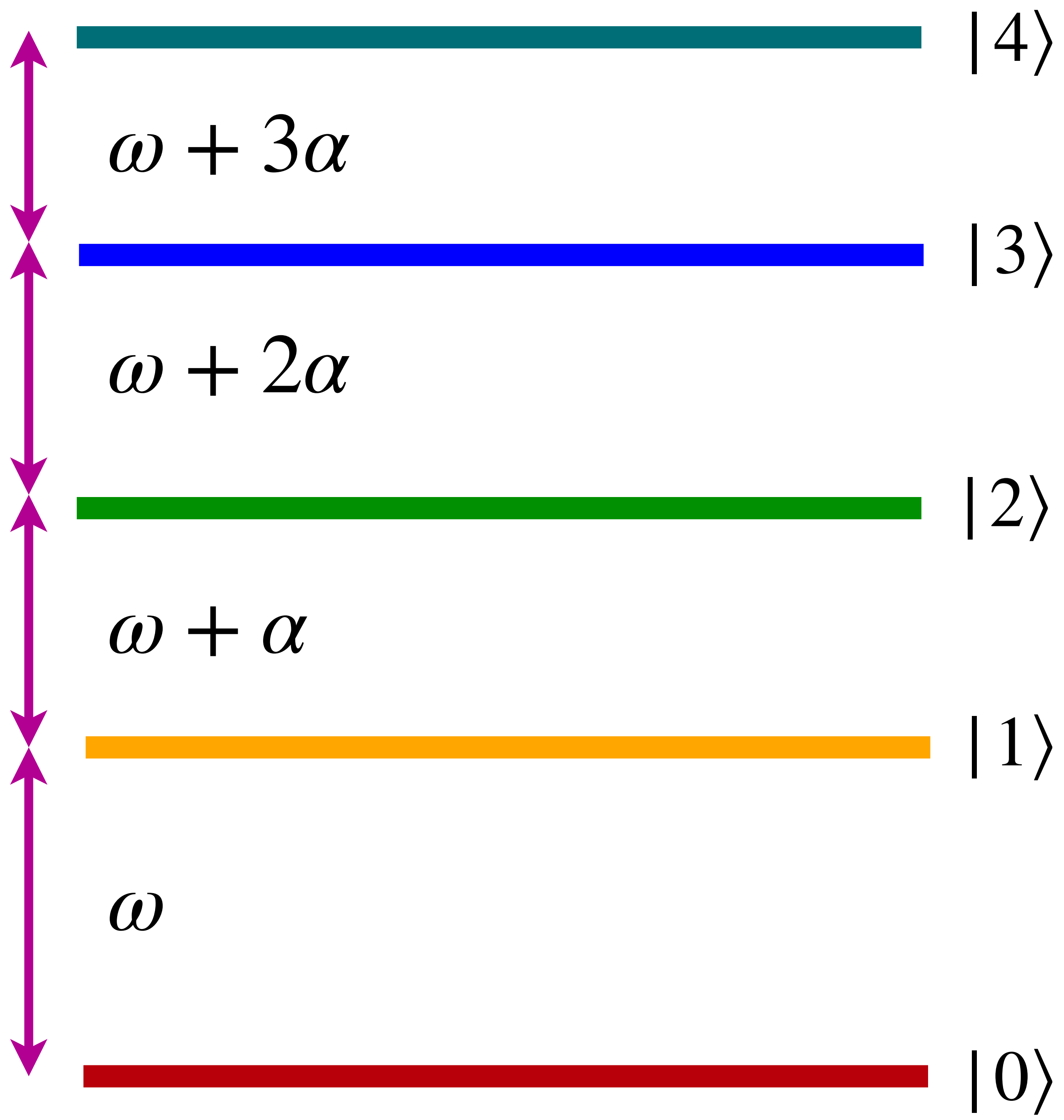


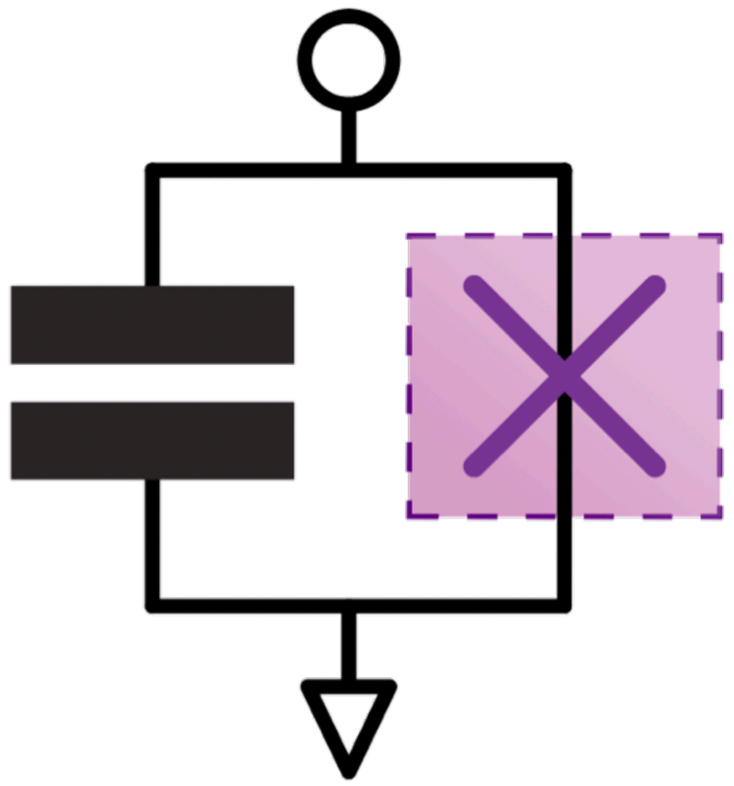


BUILD QUBIT FROM OSCILLATOR

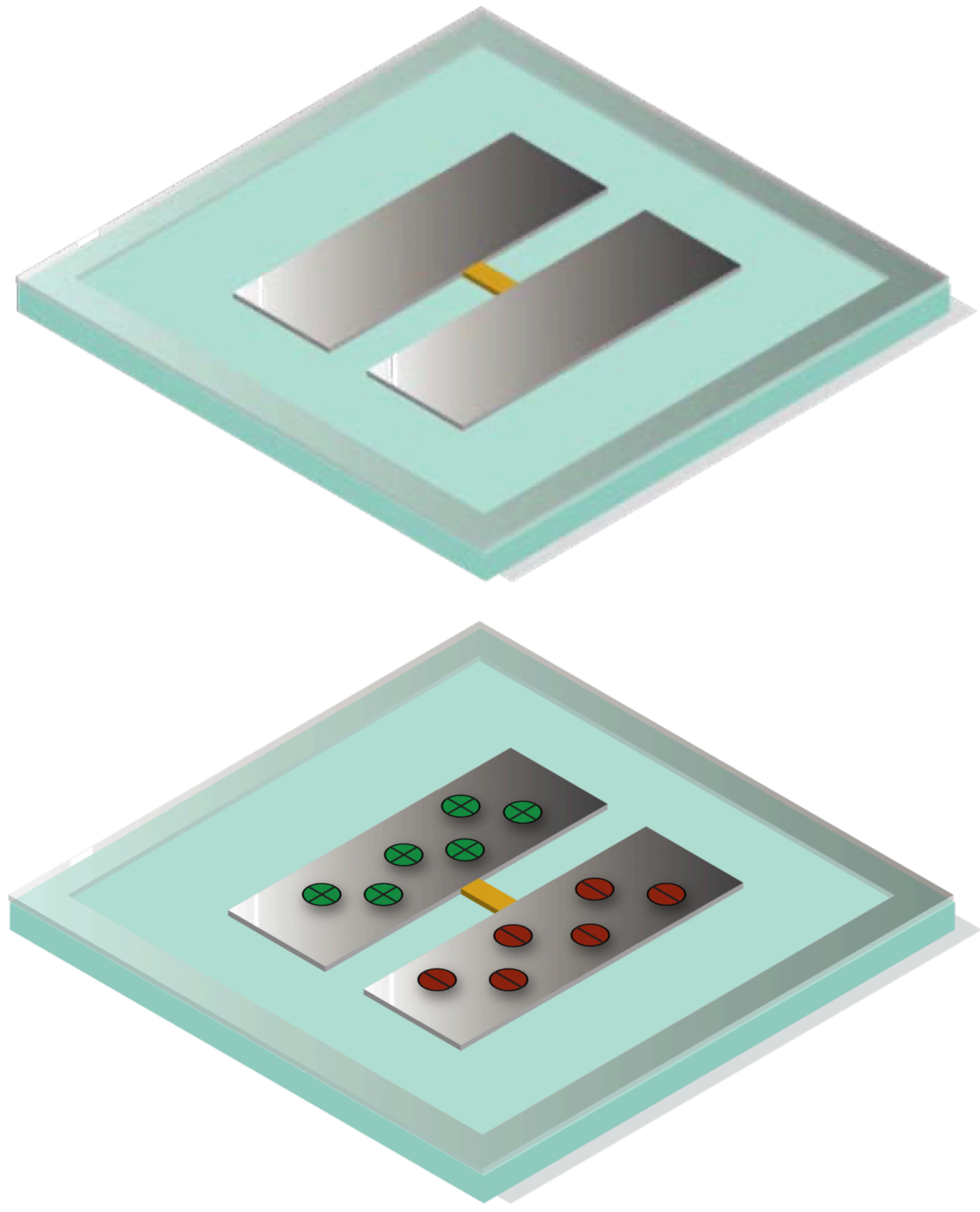


oscillator





Duffing oscillator

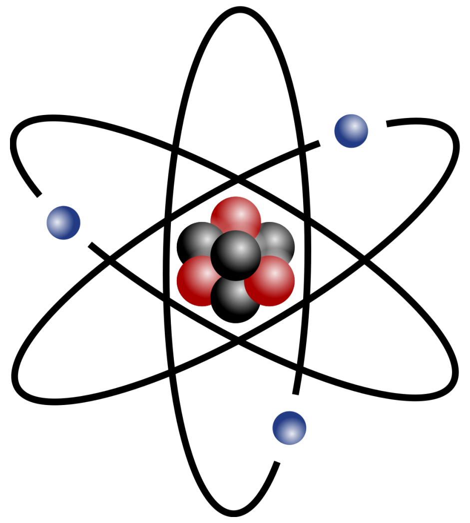


ROADMAP

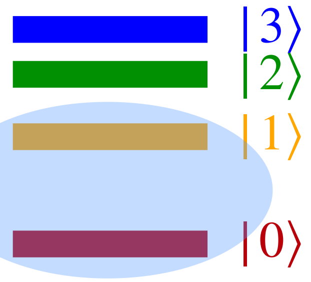
“Quantum phenomena do not occur in a Hilbert space, they occur in a laboratory.”

—Asher Peres

realization

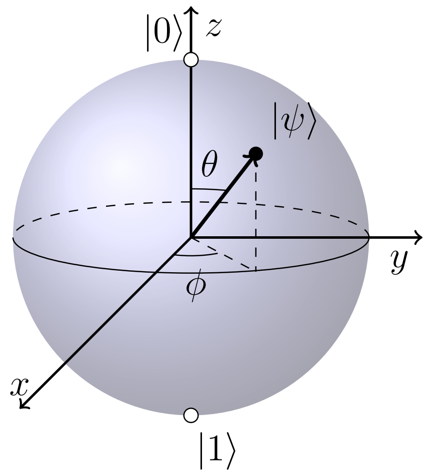


energy levels

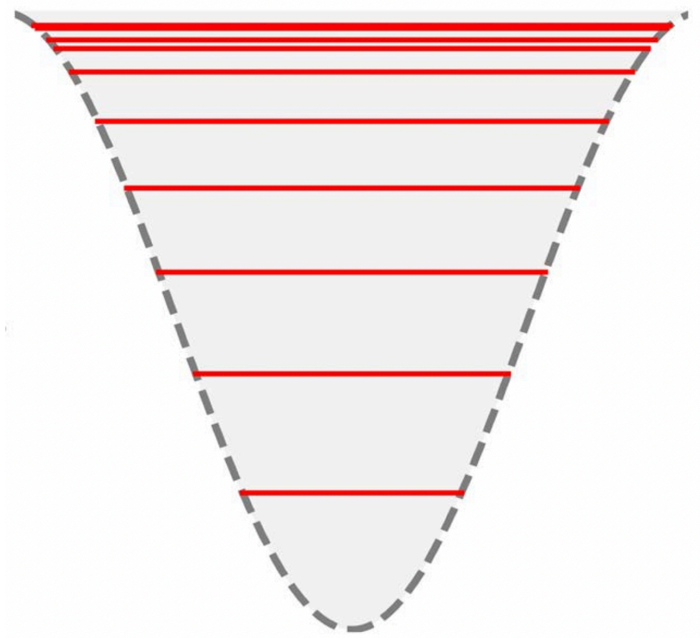


idealization of qubit

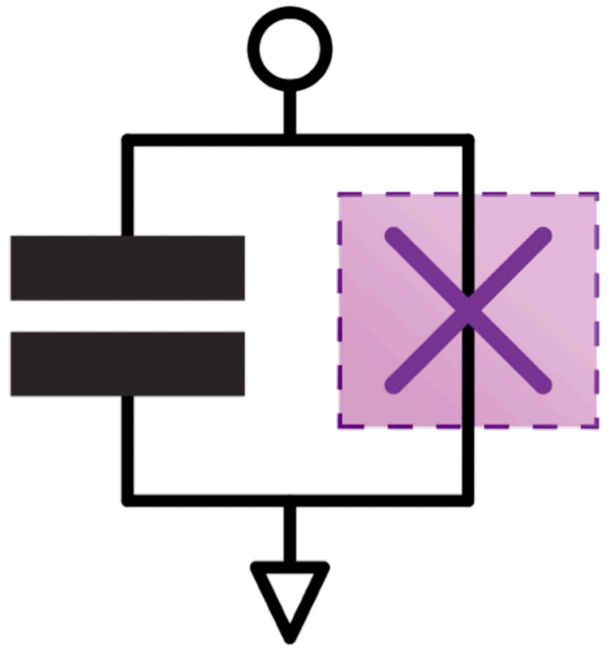
Hilbert space



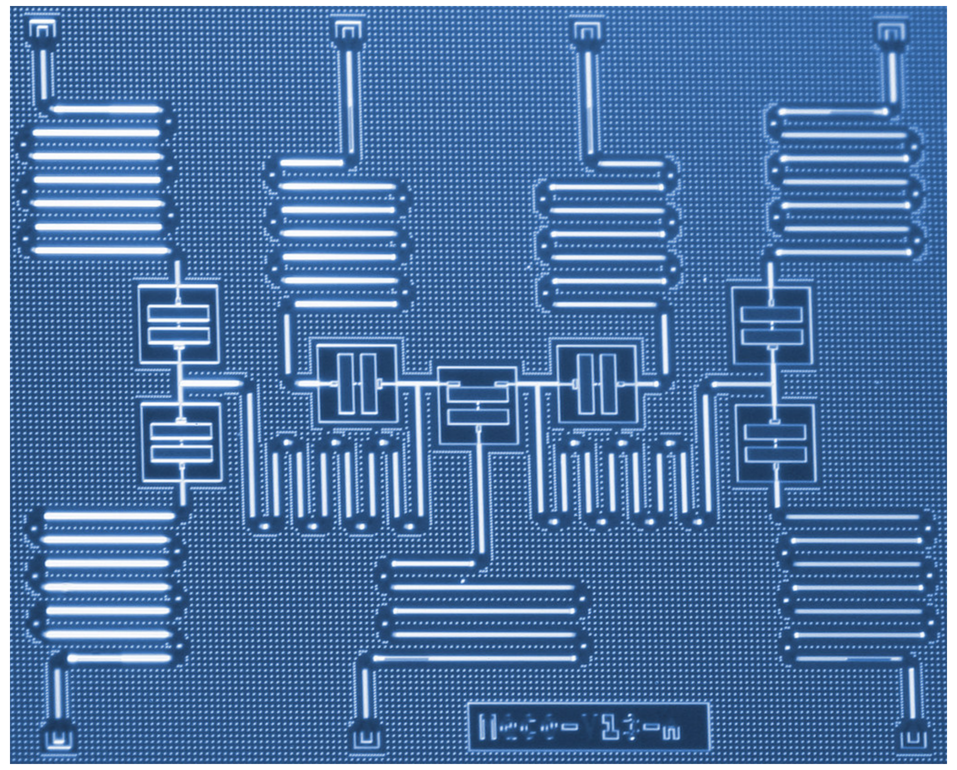
anharmonic oscillator



physical circuit model



physical layout



idealization → **physical reality**

ERRORS

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