Explore IBM Q Devices

Insight of hardwares & Quantum random walks

Sep 07, 2021

Quantum Technology Summer School

Outline

Github: https://github.com/ycldingo/QTSummerSchool2021

- Experience IBM Quantum
  - Composer - building in seconds
  - Execution via quantum processors
  - Nutrition facts of real devices
  - Advanced player: Quantum Lab
- Hardware outlook
  - From Bloch sphere to qubit
  - Gates & states
  - Errors: lifetime, leakage, and all that
  - Driving pulse
  - Janyes-Cumming model
- Quantum Random walk
  - Elements: coin & shift
  - Walking patterns
  - *Project - Randomly walks in quantum and classical*

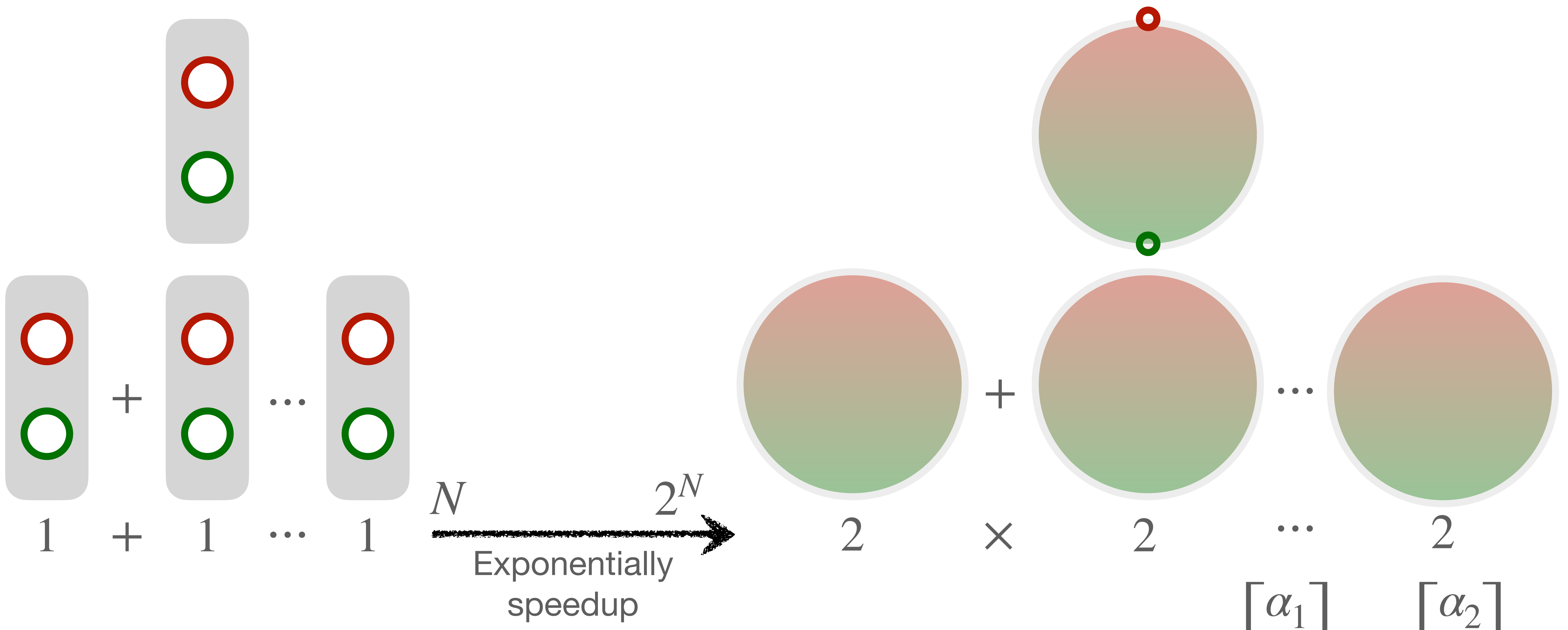
Play with Quantum

[Quantum Computers Explained - Limits of Human Technology]

[If You Don’t Understand Quantum Physics, Try This!]

Classical V.S. Quantum

- Classical
- Quantum



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

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

$$|\psi_1\rangle \otimes |\psi_2\rangle \otimes |\psi_3\rangle = \begin{bmatrix} \alpha_1 \\ \beta_1 \\ \gamma_1 \end{bmatrix} \otimes \begin{bmatrix} \alpha_2 \\ \beta_2 \\ \gamma_2 \end{bmatrix} \otimes \begin{bmatrix} \alpha_3 \\ \beta_3 \\ \gamma_3 \end{bmatrix} = |\psi_1\psi_2\psi_3\rangle$$

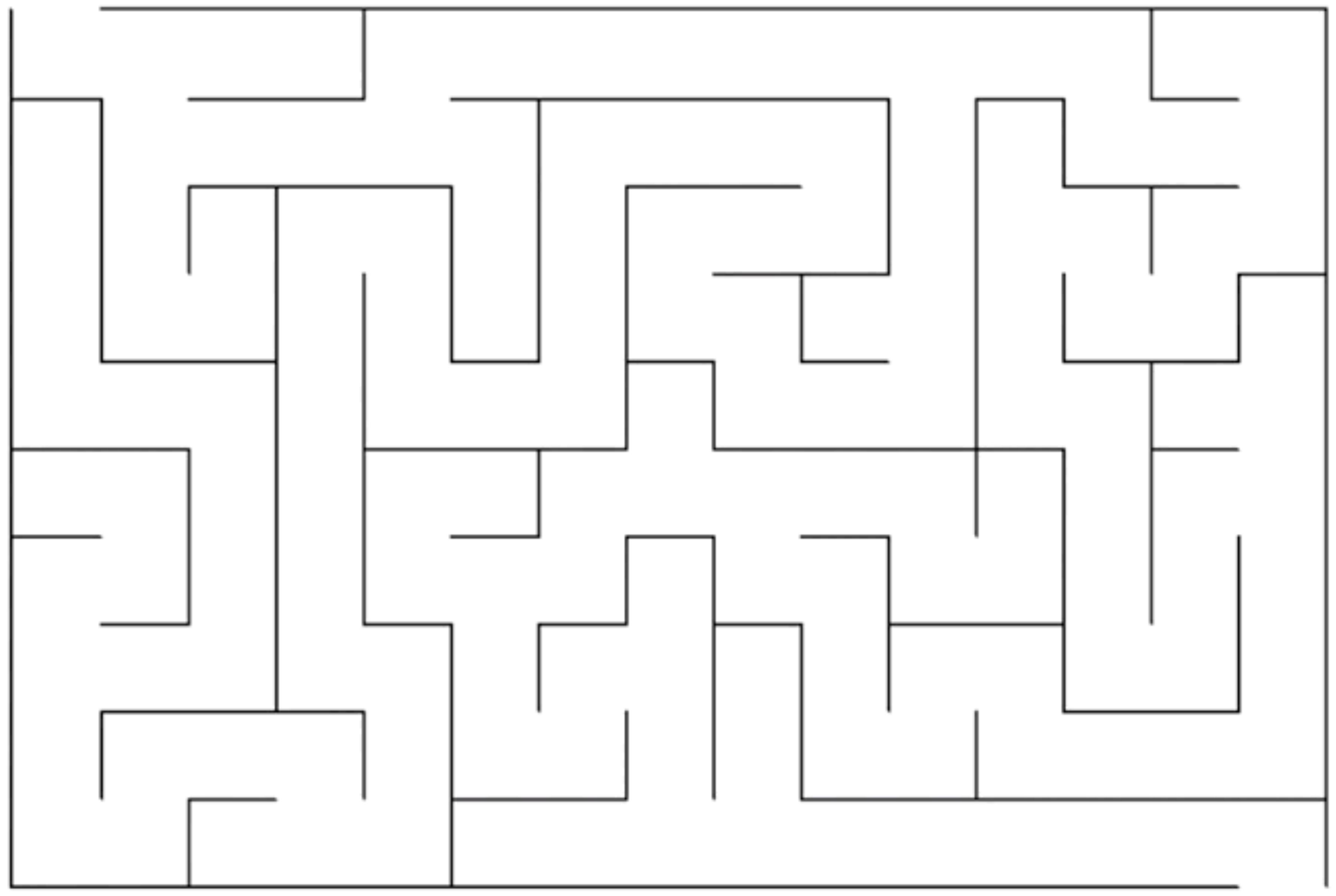
basis: $\{|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle\}$

SUPERPOSITION

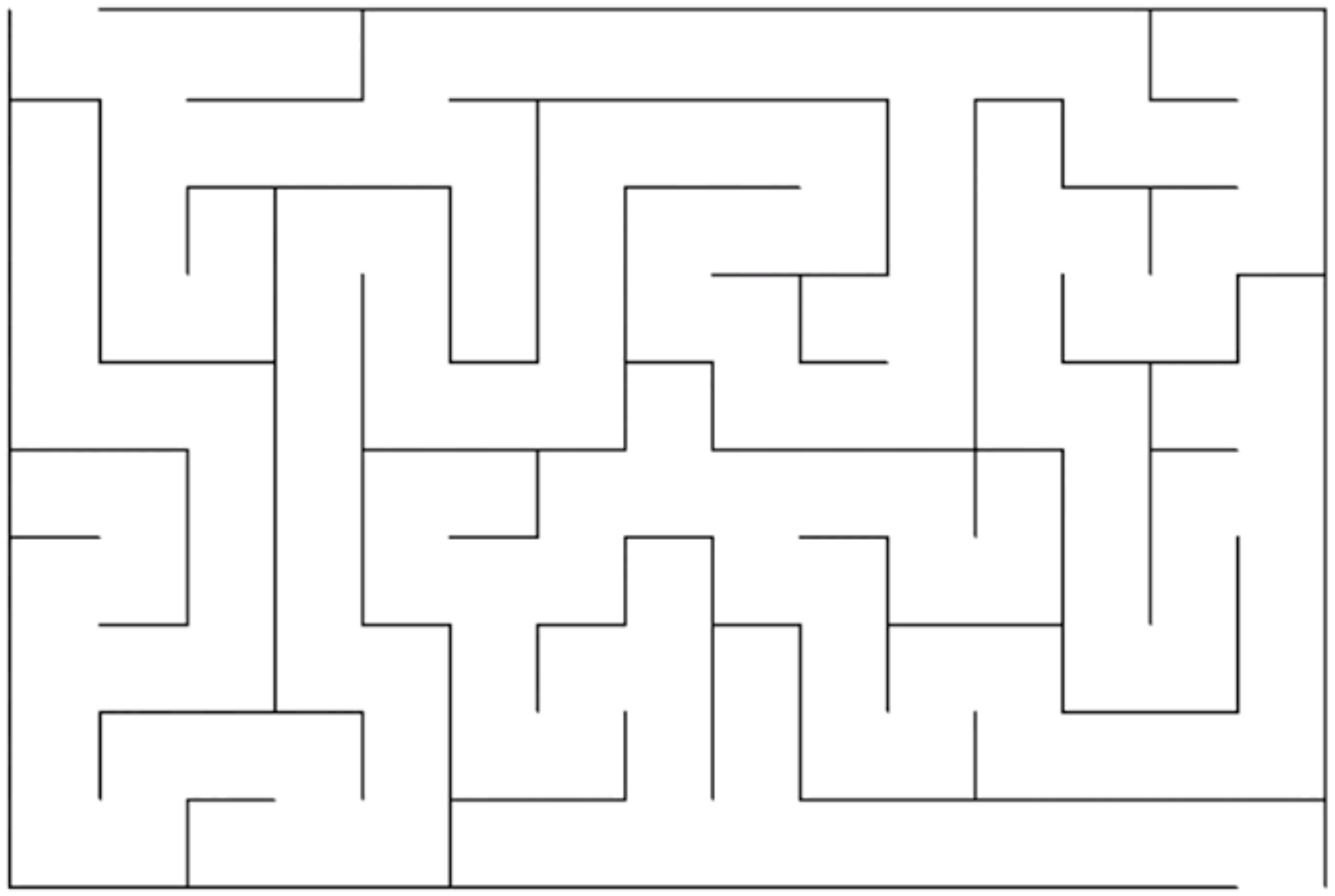
Entanglement

When we are in a complex maze……

- Conventional computer



- Quantum computer



Notations

- State
  - $|\psi\rangle$: ket-vector $\quad |\psi\rangle = \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$
  - $\langle\psi|$: bra-vector $\quad \langle\psi| = \begin{bmatrix} \alpha^* & \beta^* & \gamma^* \end{bmatrix}$
  - $|\psi_1\rangle\, |\psi_2\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$: tensor product

$$|\psi_1\rangle = \begin{bmatrix} 1 & -1 \\ 0 & i \\ -1+i & 1-i \end{bmatrix} \qquad |\psi_2\rangle = \begin{bmatrix} i \\ -1 \end{bmatrix}$$

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

- Operators
  - $U^\dagger = \left(U^T\right)^* = (U^*)^T$: Hermitian conjugate
  - $\langle\psi|\, U\, |\psi\rangle = \langle\psi|\, U^\dagger\, |\psi\rangle \equiv \langle U\rangle$: expectation value

$$= \begin{bmatrix} \alpha^* & \beta^* & \gamma^* \end{bmatrix} \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$$

$$U = \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix}$$

1. Why do we use “vectors” in quantum mechanics?
2. If the position can be continuous, who is being “quantized”?

QUANTIZATION

All the animations and explanations on
www.toutestquantique.fr

Postulates of quantum mechanics

- State vector

$$|\Psi\rangle = c_1|\psi_1\rangle + c_2|\psi_2\rangle$$

- Observable

$$\mathscr{A} : |\psi\rangle \mapsto |\psi'\rangle = \mathscr{A}|\psi\rangle$$

- Measurement

$$\mathscr{A} \to \{a\} : \mathscr{A}|\psi_a\rangle = a|\psi_a\rangle$$

- Born rule

$$P_a = |\langle\psi_a|\psi\rangle|^2$$

- Wavefunction collapse

$$\mathscr{A} : a \implies |\psi_a\rangle$$

- Time evolution

$$|\psi(t)\rangle = \mathscr{U}(t, t_0)|\psi(t_0)\rangle$$

Hardware outlook

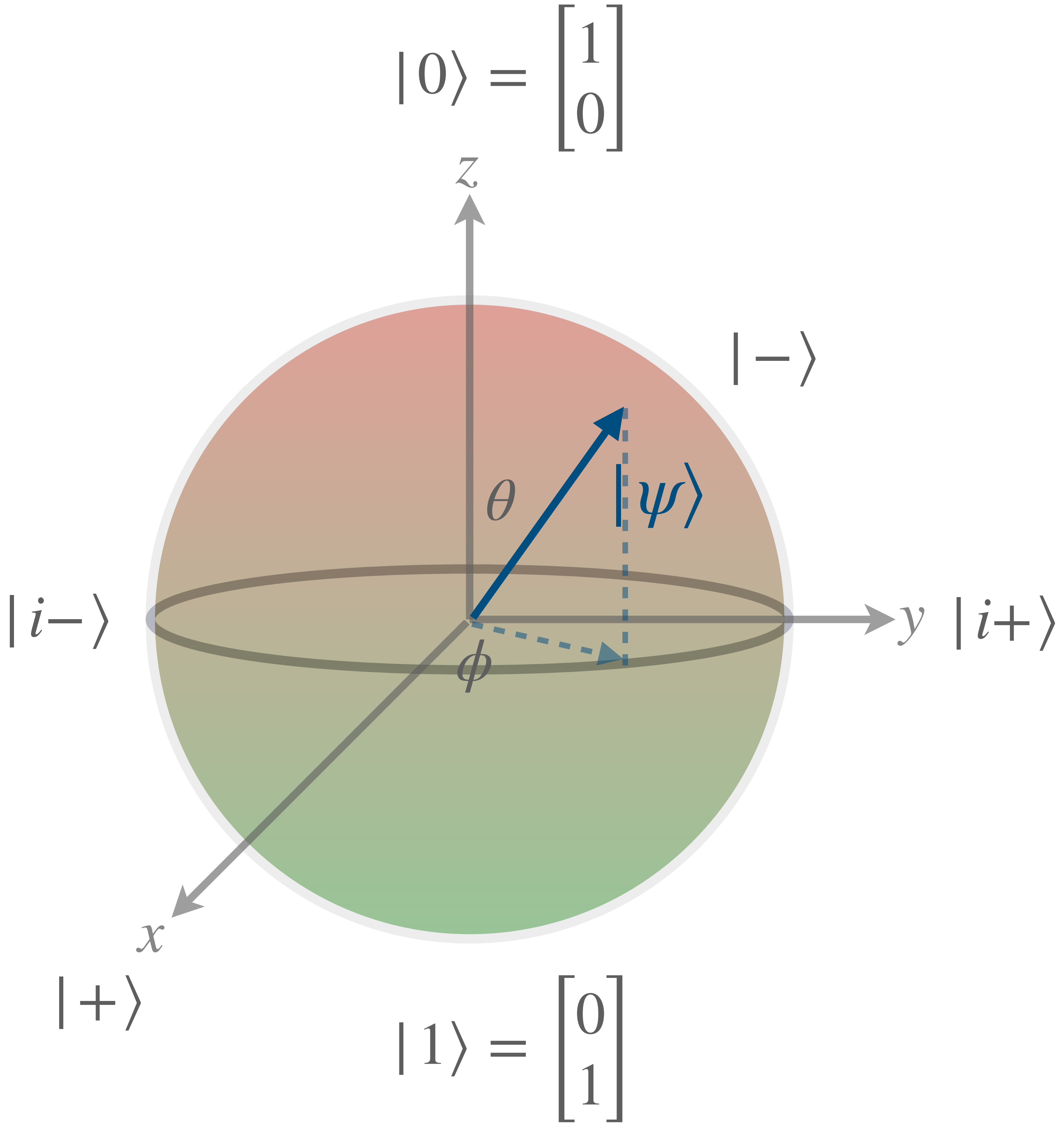
A quick wrap-up

Bloch sphere

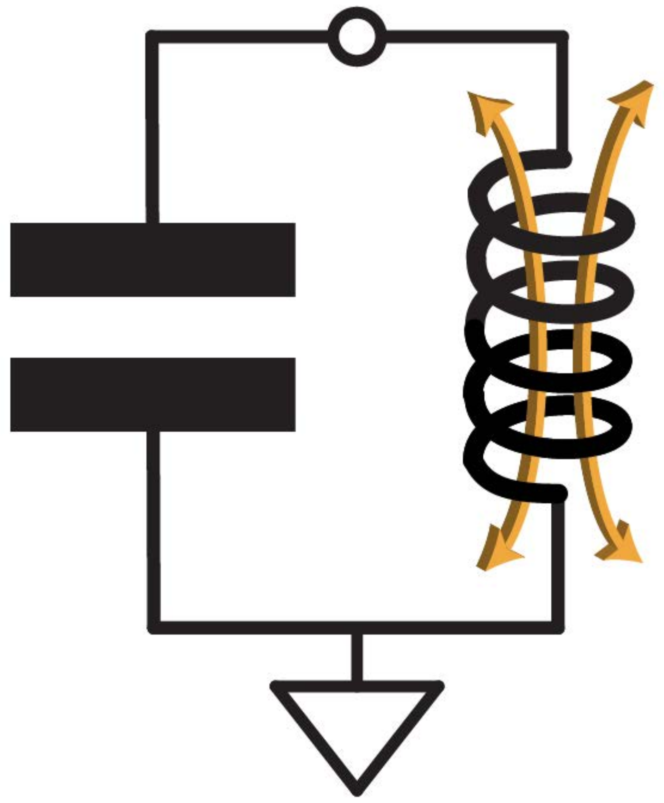
$$
\begin{aligned}
|\psi\rangle &= \alpha\,|0\rangle + \beta\,|1\rangle \\
&= e^{ir}\left(\cos\frac{\theta}{2} + e^{i\phi}\sin\frac{\theta}{2}\right)
\end{aligned}
$$

$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \pm |1\rangle\right)$$

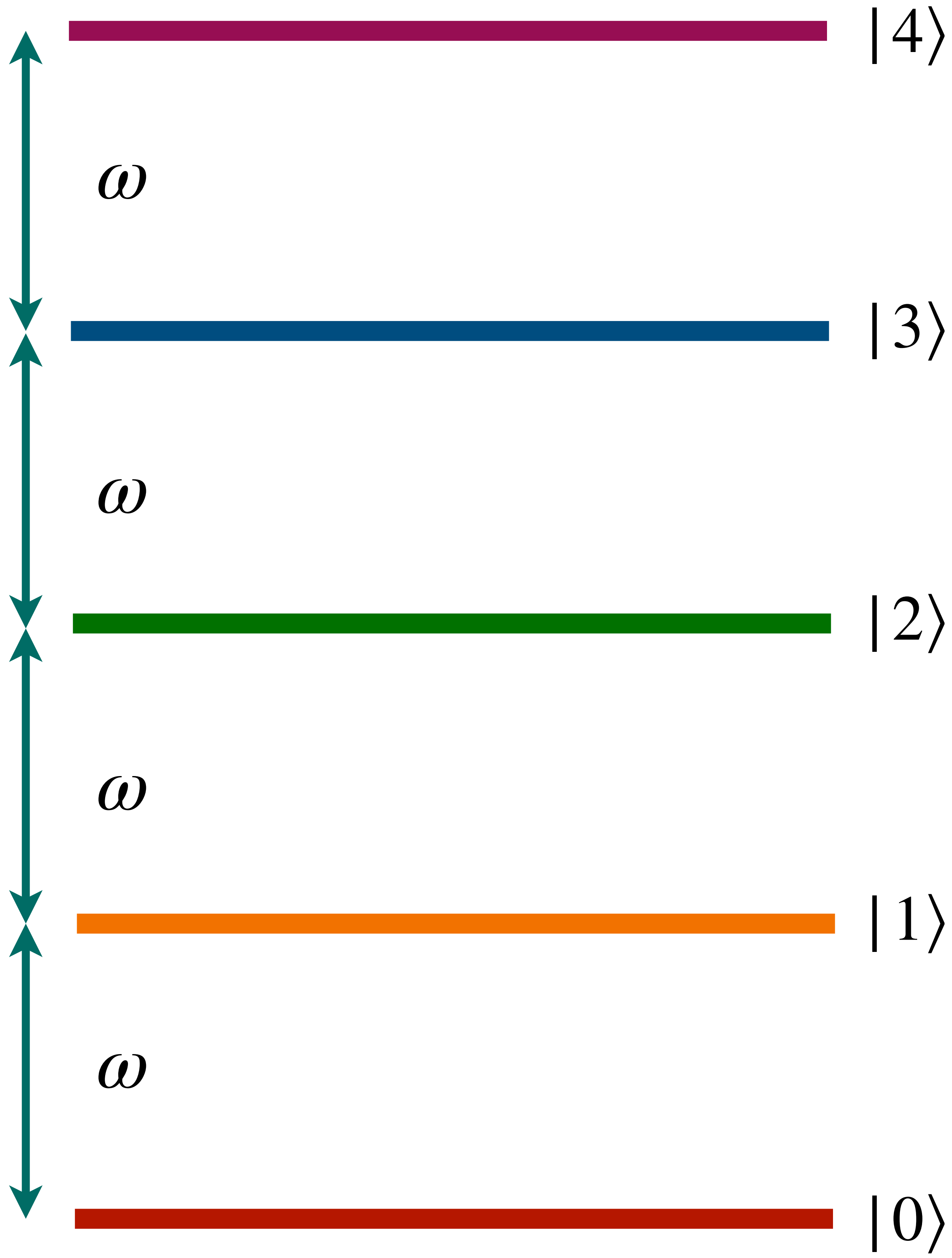
$$|i\pm\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \pm i\,|1\rangle\right)$$

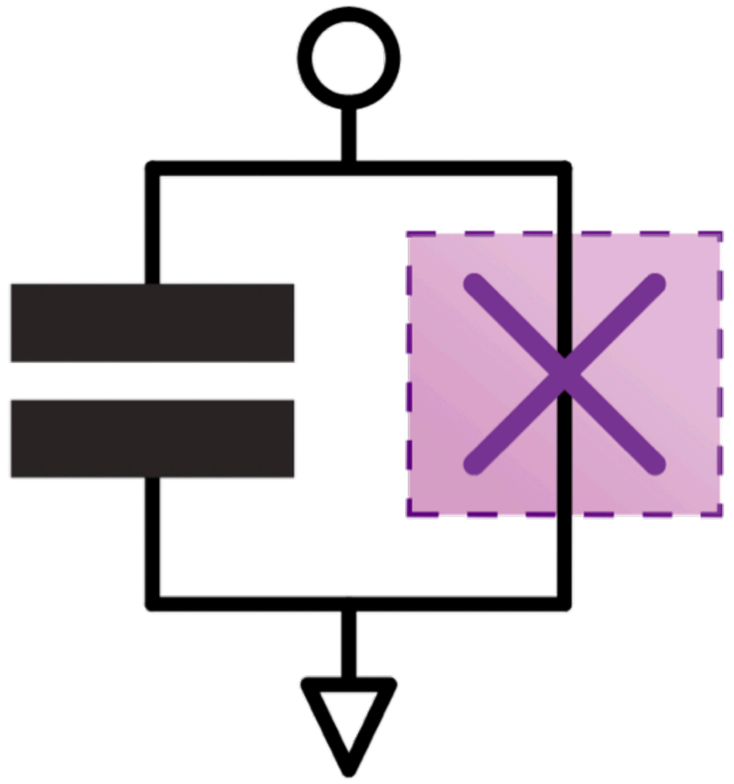


Build qubit from oscillator

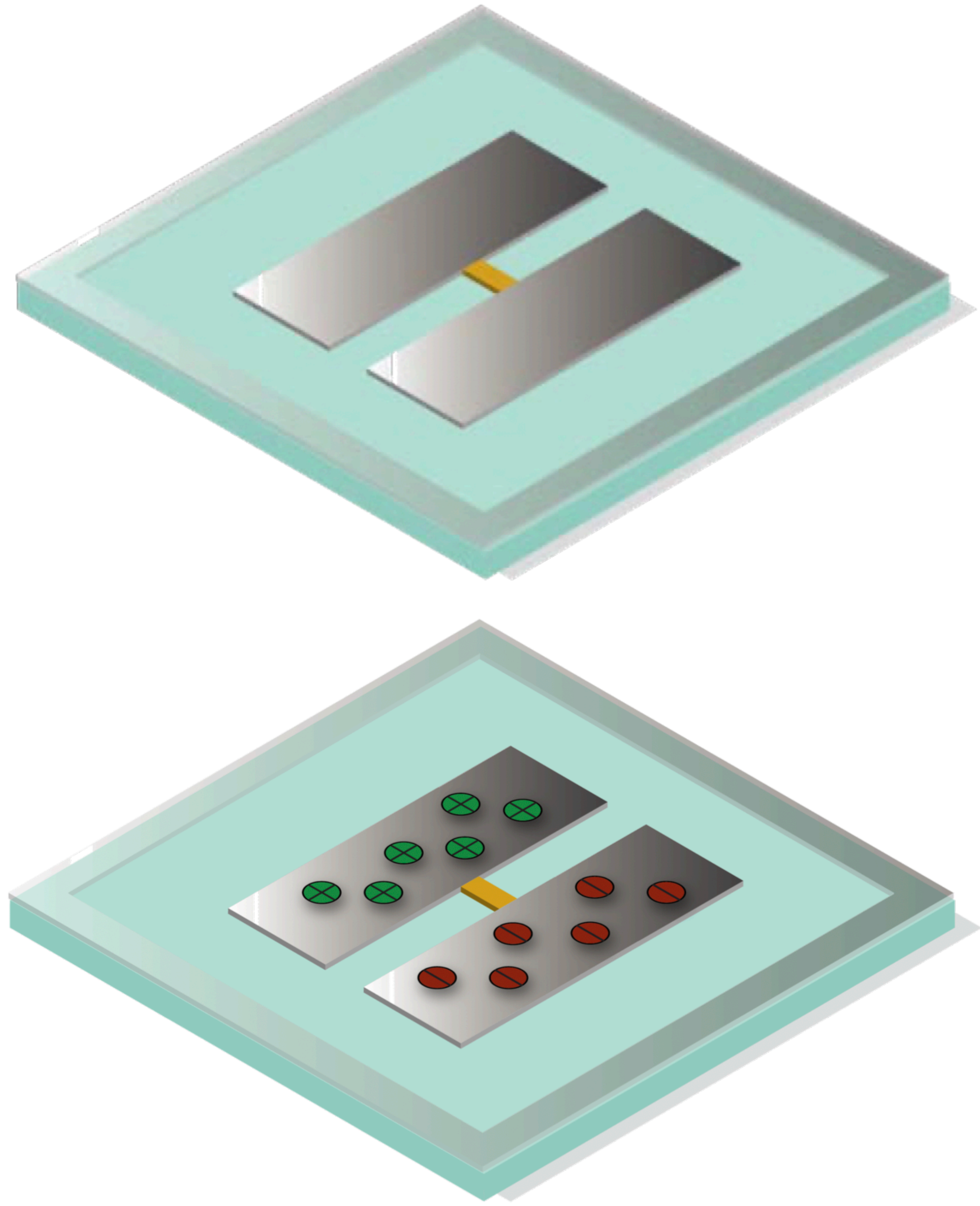


oscillator

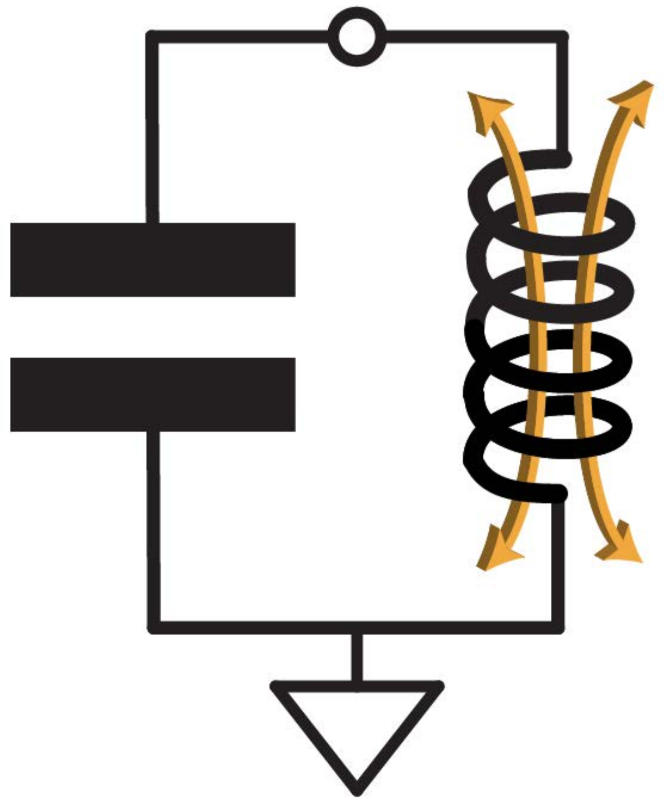




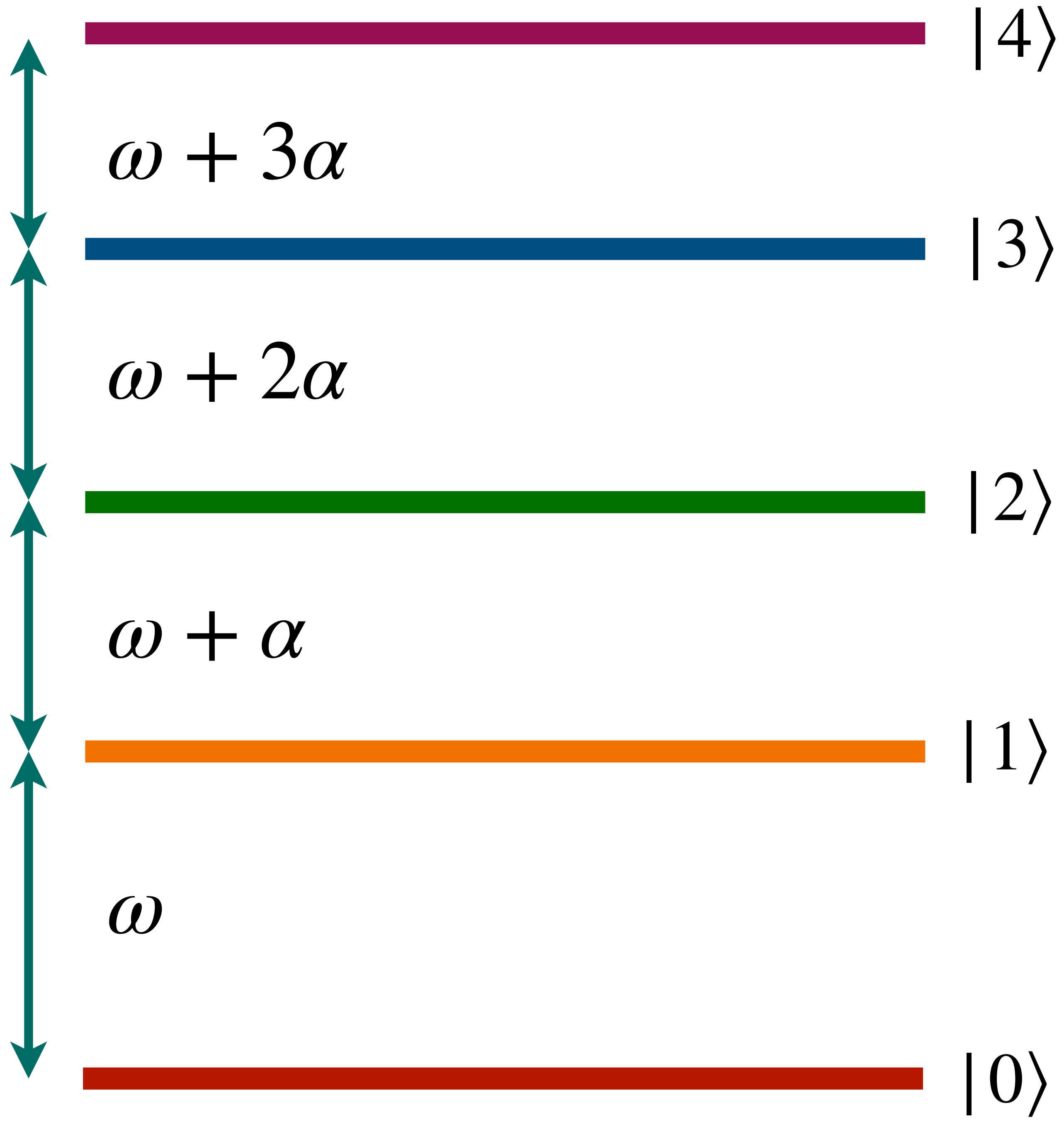
Duffing oscillator

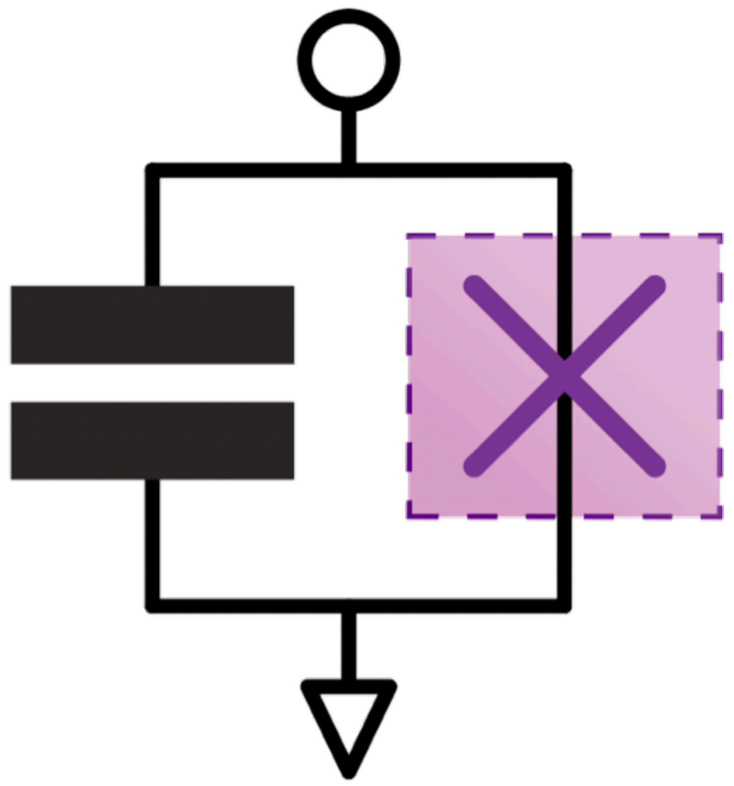


Build qubit from oscillator

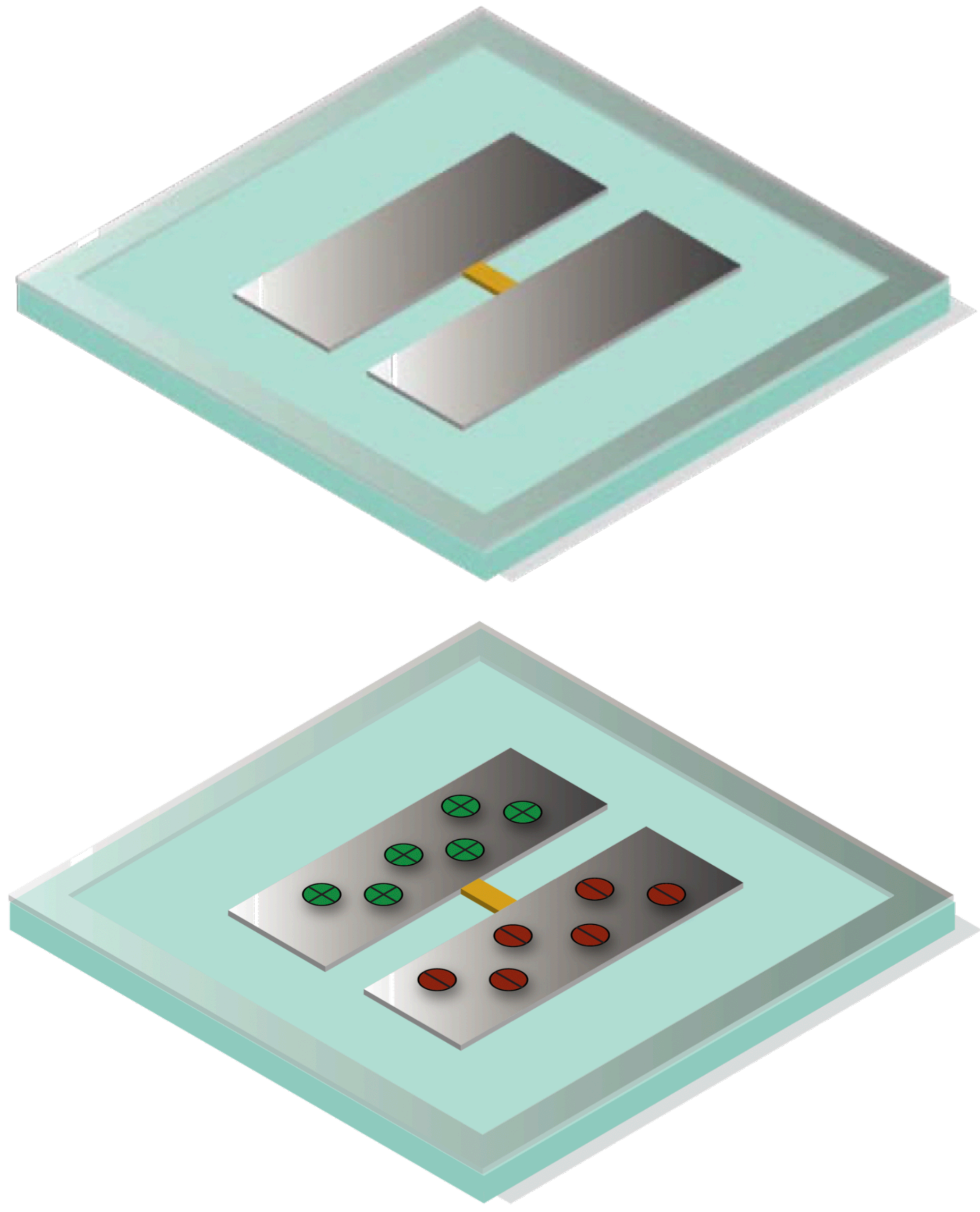


oscillator





Duffing oscillator

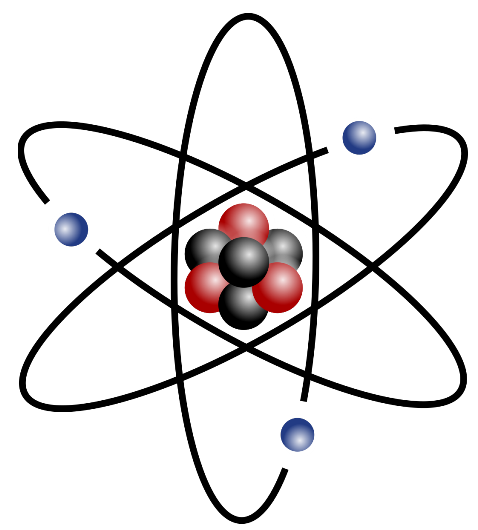


Roadmap

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

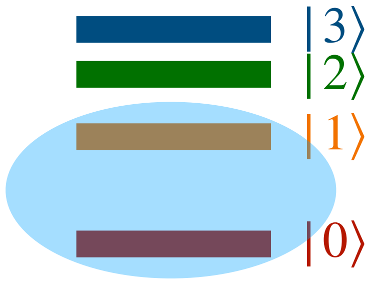
—Asher Peres

realization

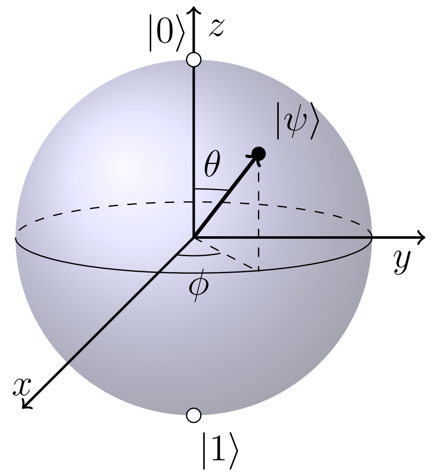


energy levels

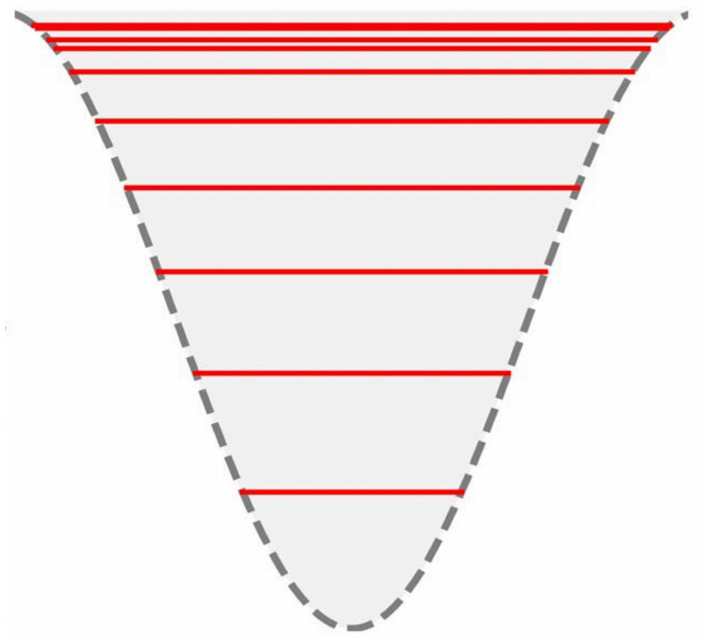
idealization of qubit



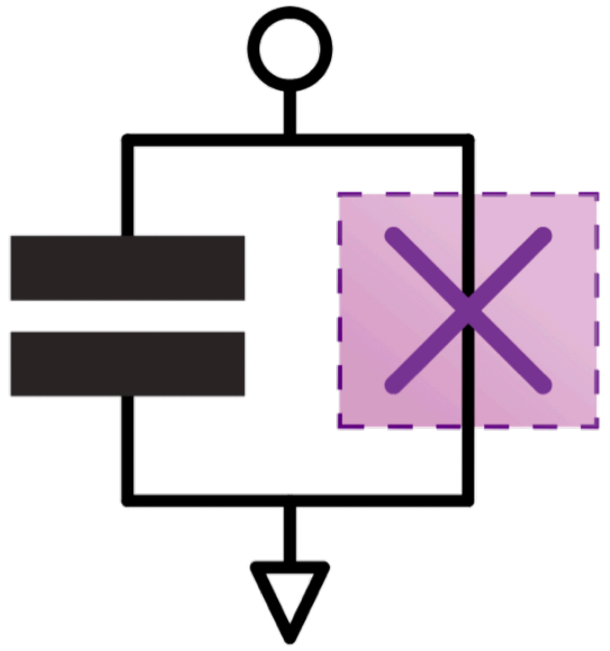
Hilbert space



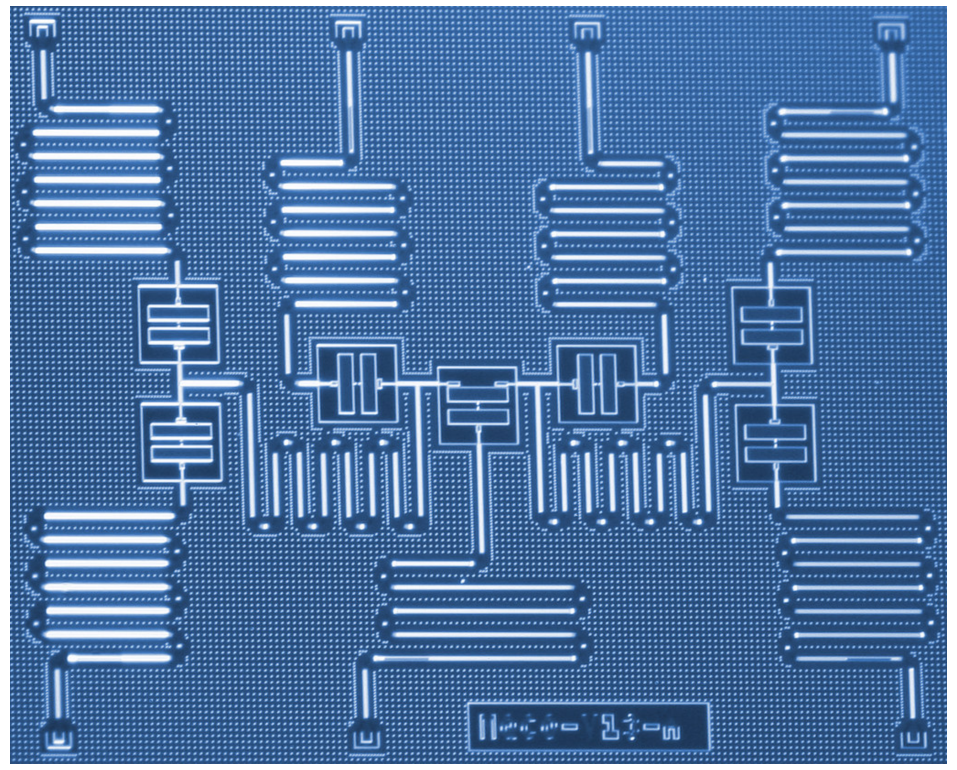
anharmonic oscillator



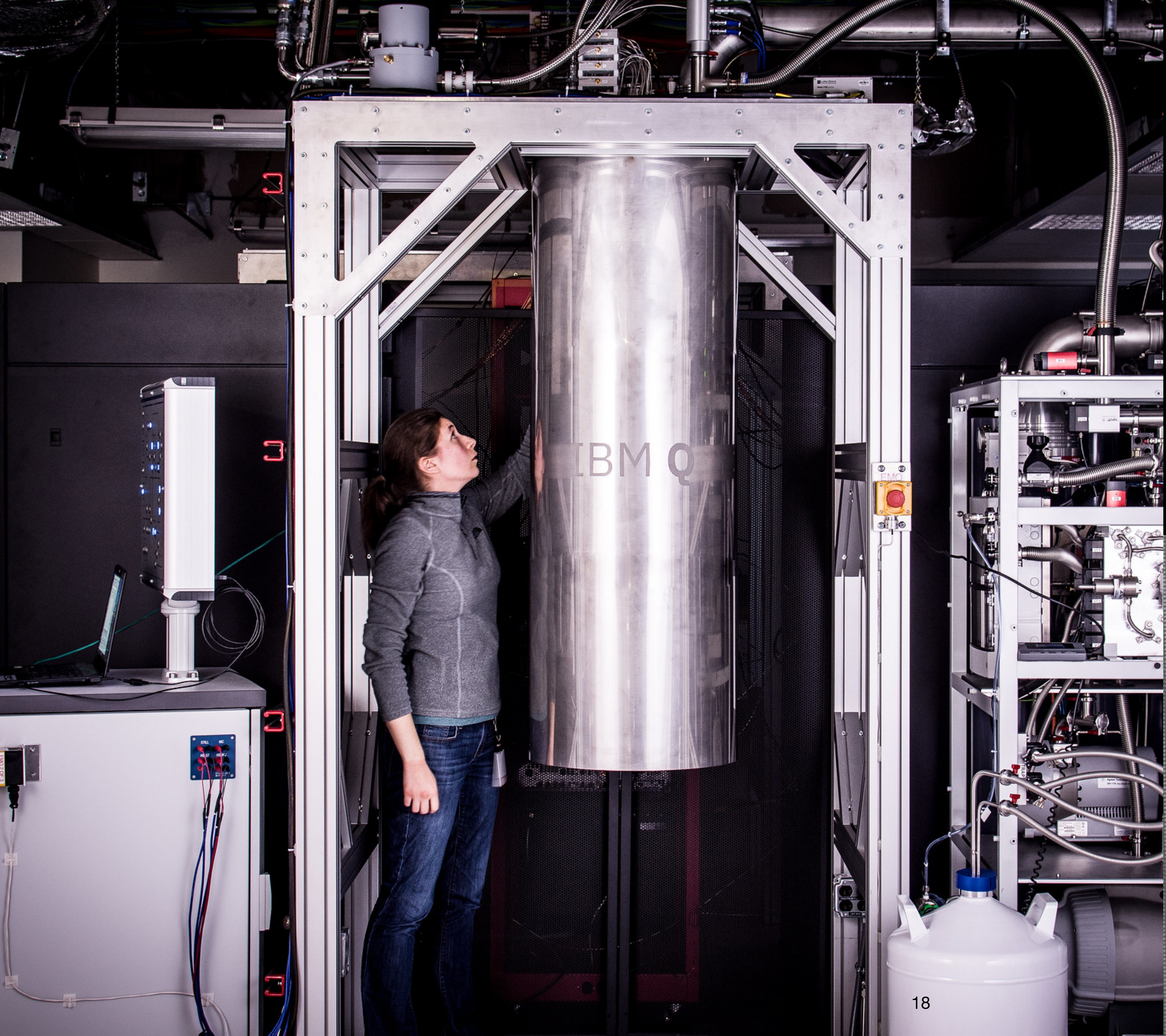
physical circuit model

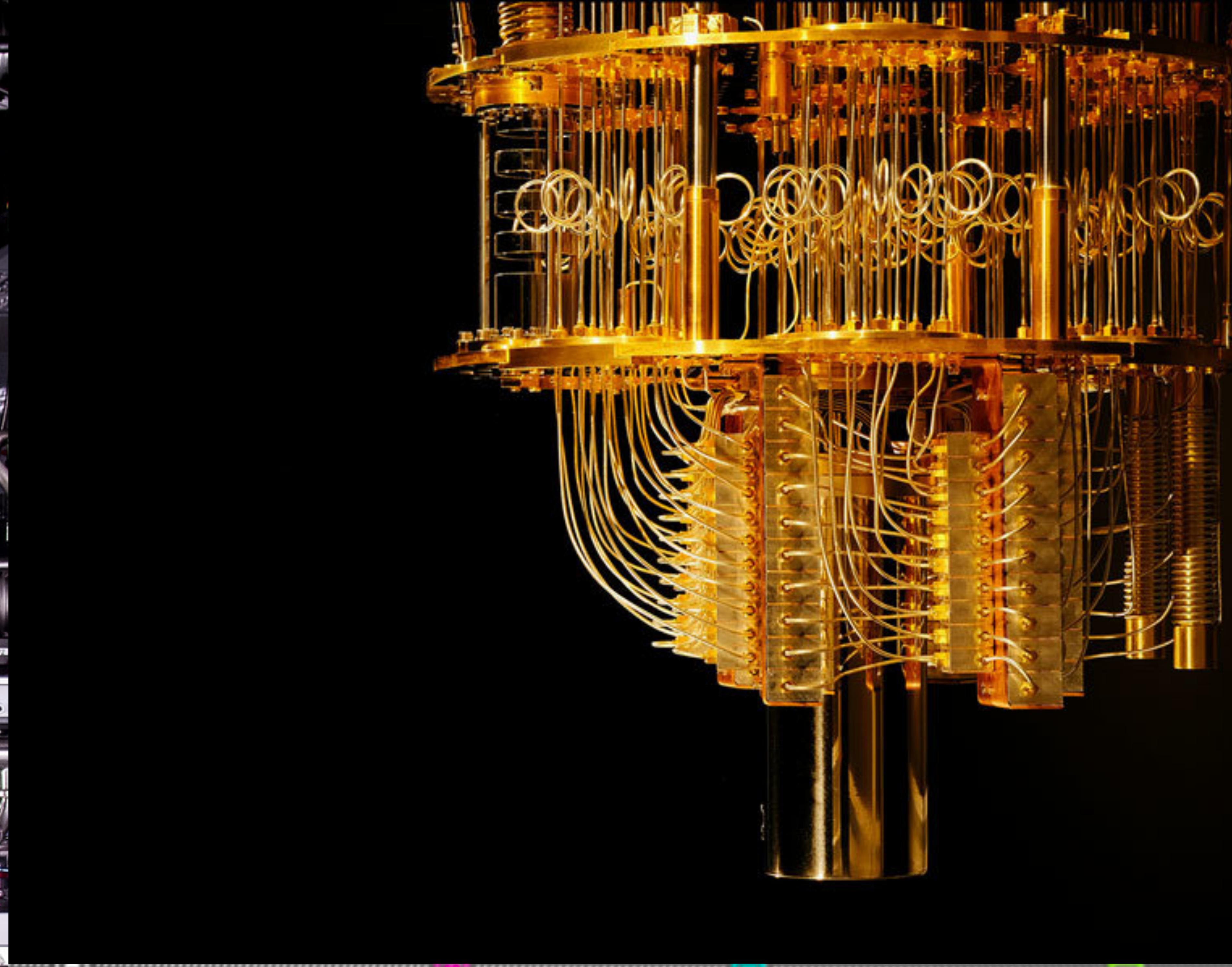


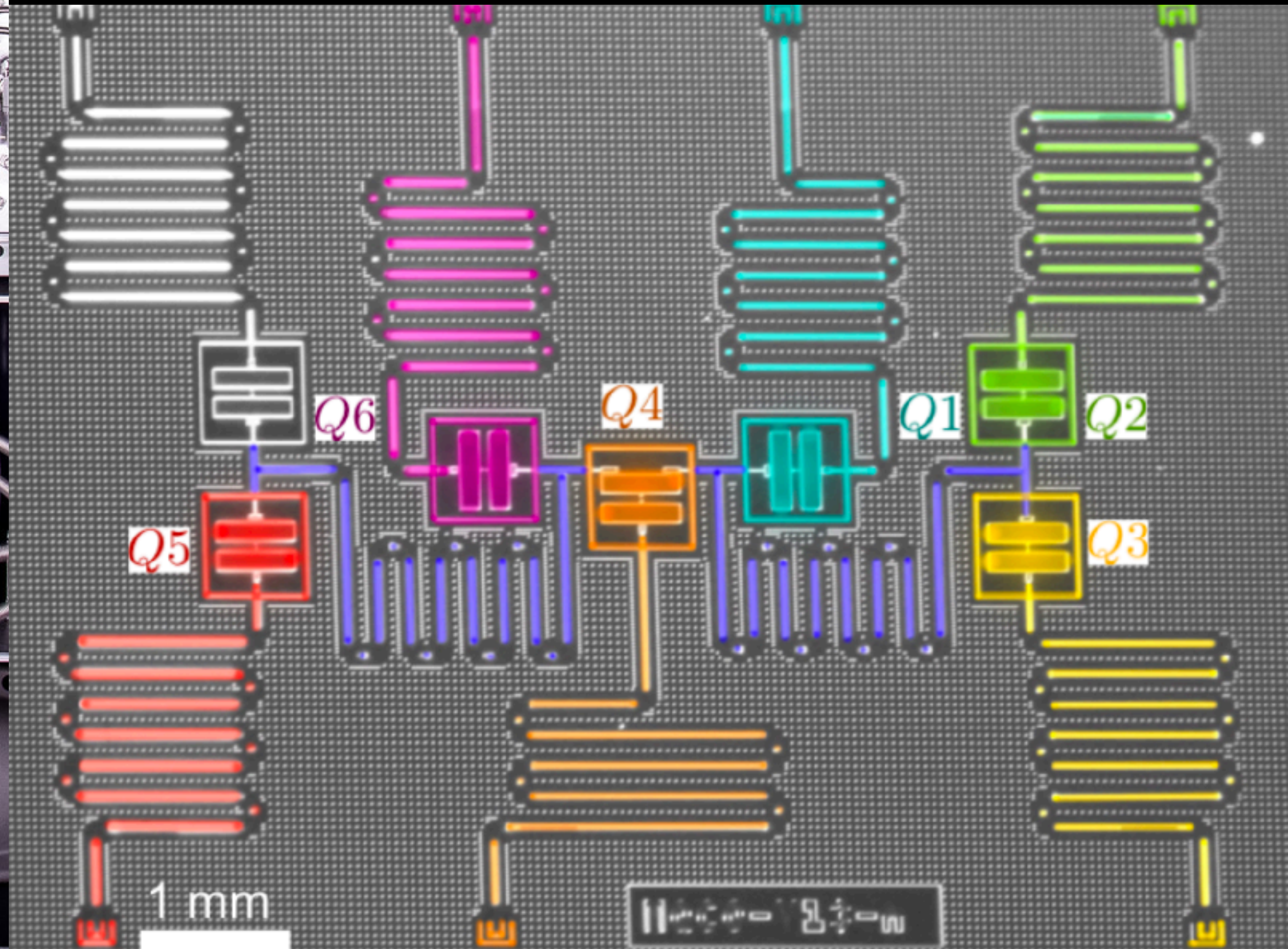
physical layout



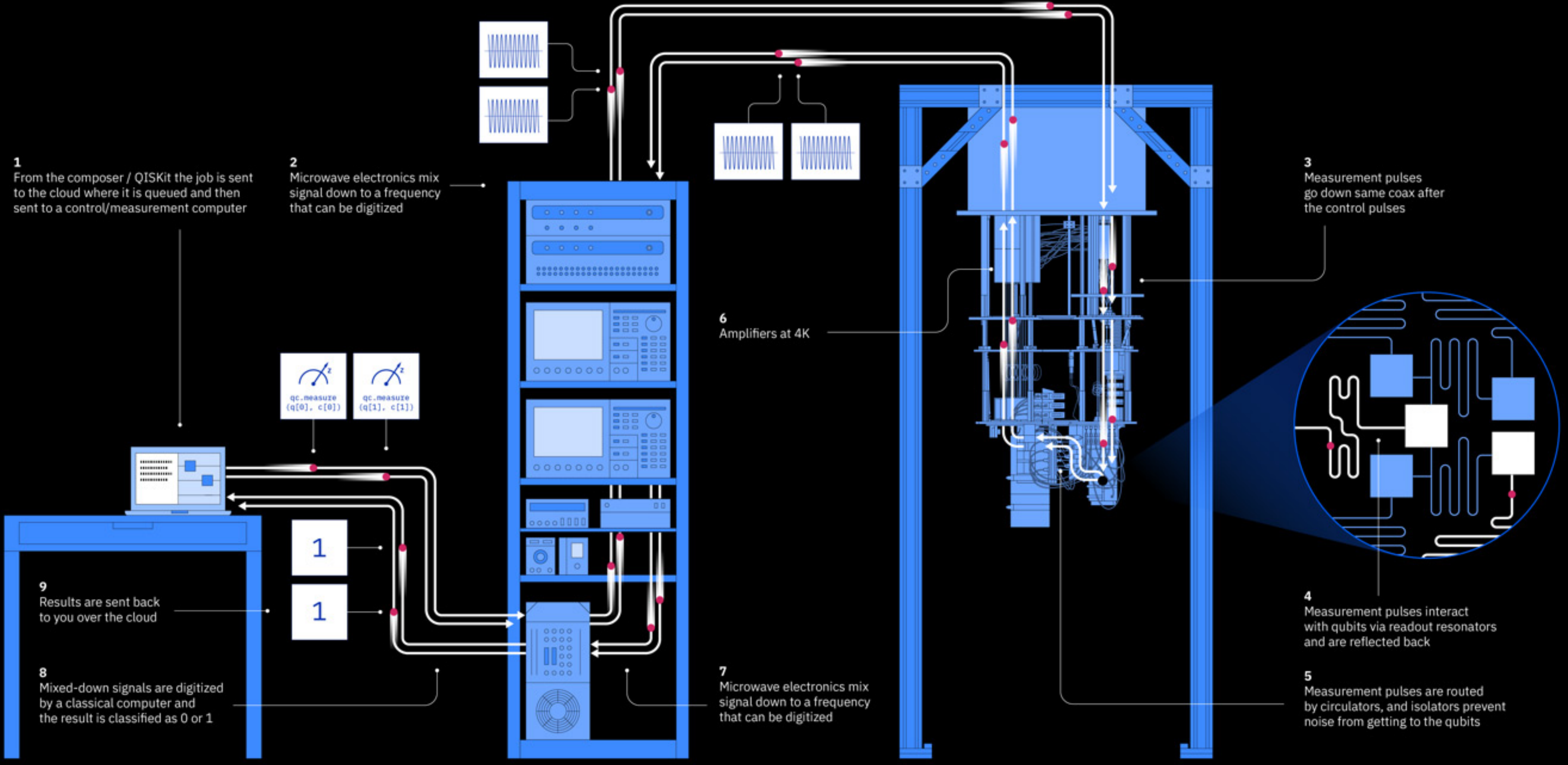
idealization → **physical reality**


IBM Q




Q6
Q4
Q1
Q2
Q5
Q3
1 mm

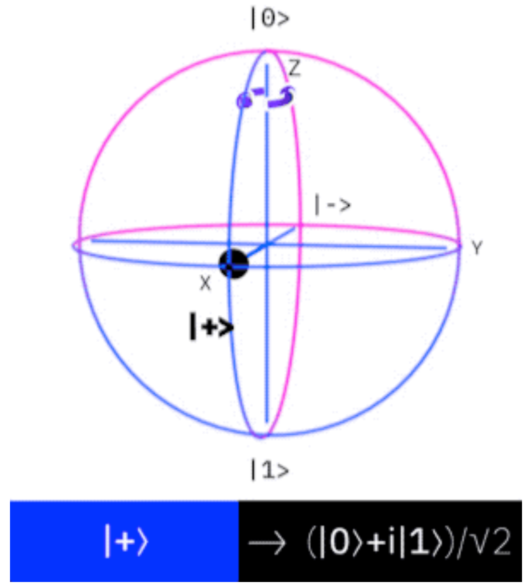

wavelength (m)
Radio
10^3
Microwave
10^{-2}
Infrared
10^{-5}
Visible
0.5×10^{-6}
Ultraviolet
10^{-8}
X-ray
10^{-10}
Gamma ray
10^{-12}
object scale
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
frequency (Hz)
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
$\hbar\omega = k_B T$
temperature
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C
order of magnitude
10^{-2} K
IBM Q
0.5 K, 10 GHz, 3 cm


1
From the composer / QISKit the job is sent to the cloud where it is queued and then sent to a control/measurement computer
2
Microwave electronics mix signal down to a frequency that can be digitized
3
Measurement pulses go down same coax after the control pulses
4
Measurement pulses interact with qubits via readout resonators and are reflected back
5
Measurement pulses are routed by circulators, and isolators prevent noise from getting to the qubits
6
Amplifiers at 4K
7
Microwave electronics mix signal down to a frequency that can be digitized
8
Mixed-down signals are digitized by a classical computer and the result is classified as 0 or 1
9
Results are sent back to you over the cloud
qc.measure (q[0], c[0])
qc.measure (q[1], c[1])
1
1

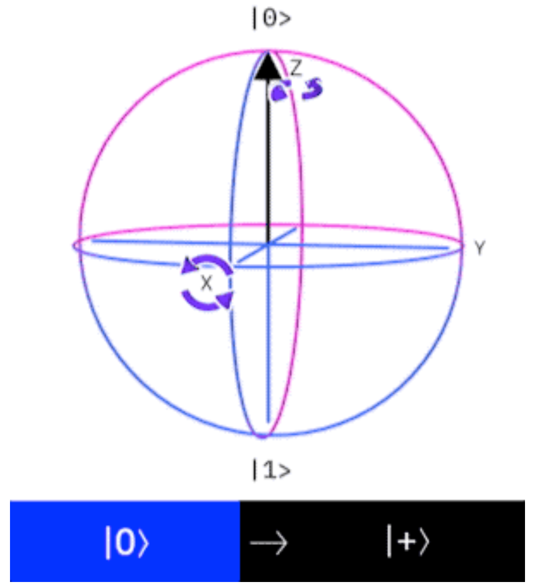
Some qauantum gates

Operations on processors

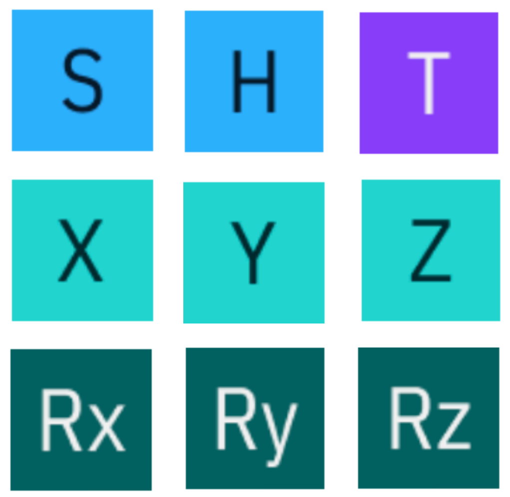
- Single-qubit gates

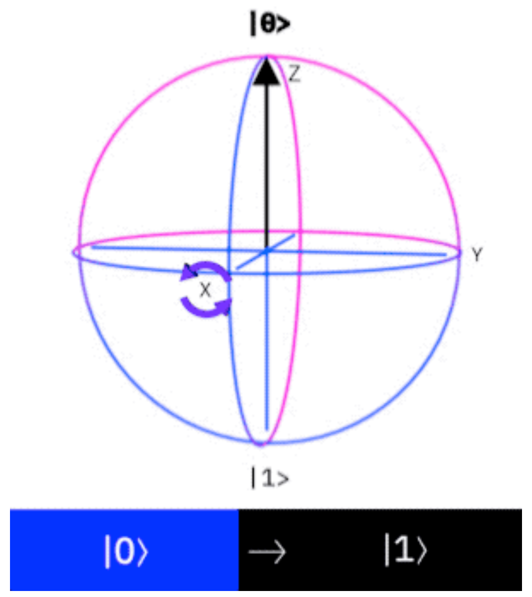


S (Phase gate)

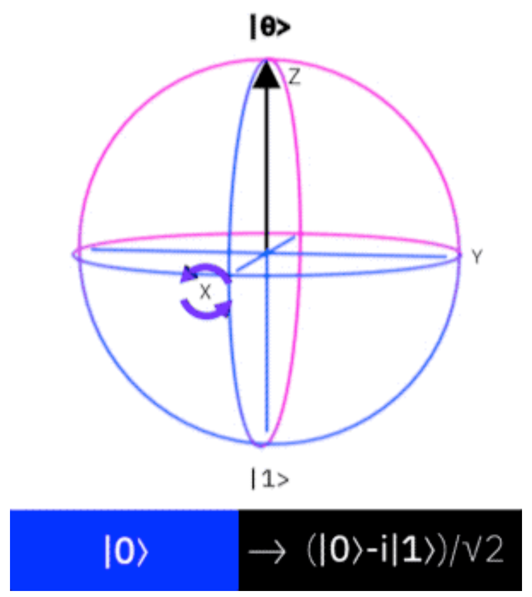


H (Hadamard gate)

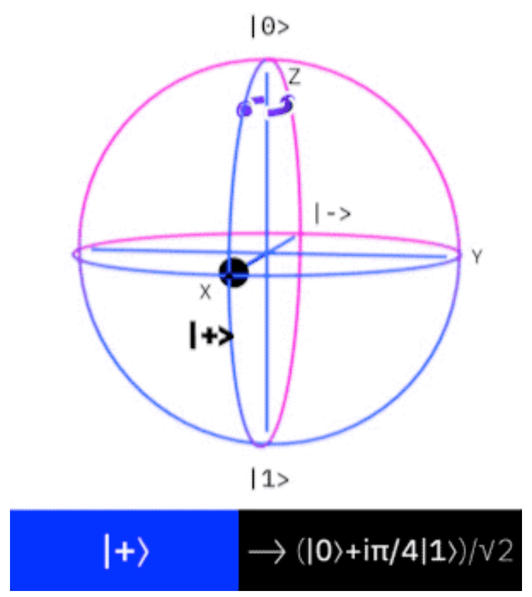




X (NOT gate)



Rx (Rotation-X gate)



T ($\pi/8$ gate)

- Multi-qubit gates
  - CNOT 
  - Controlled-rotation 

  - SWAP 

- Quantum gates are unitary:

$$\mathscr{U}^{-1} = \mathscr{U}^{\dagger} \quad \text{or} \quad \mathscr{U}\mathscr{U}^{\dagger} = \mathbb{I}$$

How to generate those states?

Entangled states

- Bell states

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

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

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

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

- Task: inputs?

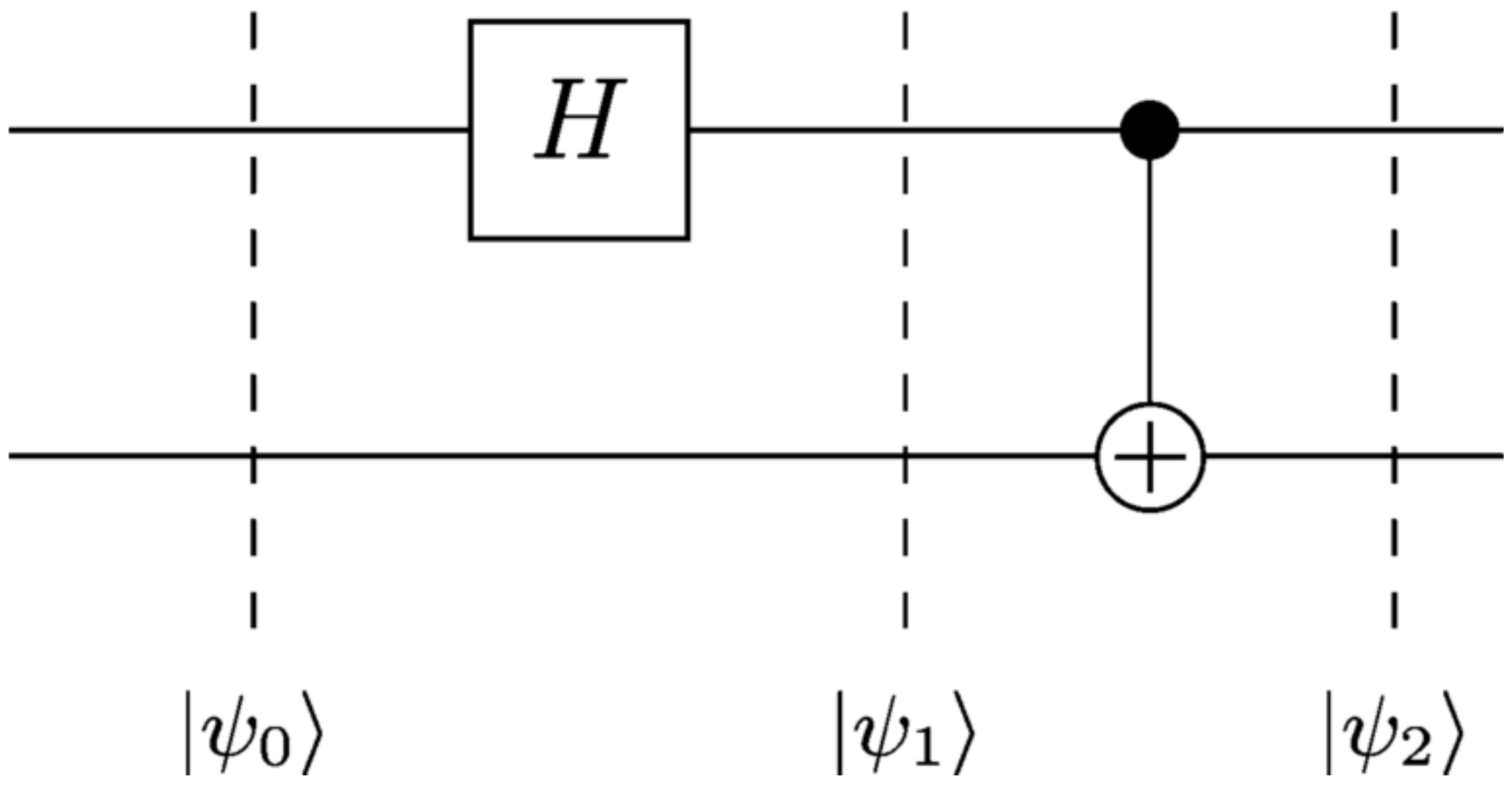
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right)$$

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

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

$$|\alpha\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - i\,|11\rangle\right)$$

$$|\beta\rangle = \frac{1}{\sqrt{2}}\left(|10\rangle + i\,|01\rangle\right)$$



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

How to generate those states?

Answer

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

- `circ.x(q[0])`

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

- `circ.x(q[0])`
- `circ.x(q[1])`

$$|\beta\rangle = \frac{1}{\sqrt{2}}\left(|10\rangle + i\,|01\rangle\right)$$

- `circ.sx(q[0])`
- `circ.x(q[1])`

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

- `circ.x(q[1])`

$$|\alpha\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - i\,|11\rangle\right)$$

- `circ.sxdg(q[0])`