IBM Quantum – Introduction

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IBM Quantum - setting up

- Register with your email at: **cloud.ibm.com** and academic code **academic.ibm.com**
- Open Qiskit Runtime and create free instance
- Generate, copy and save API Token and CRN
- Have a look

Remarks: IBM Cloud need either credit/debit card or a code. The code can be obtained (a) by academic emails (renewable), (b) at **quantum.cloud.ibm.com** for 1 month per email

IBM Quantum - Installing tools

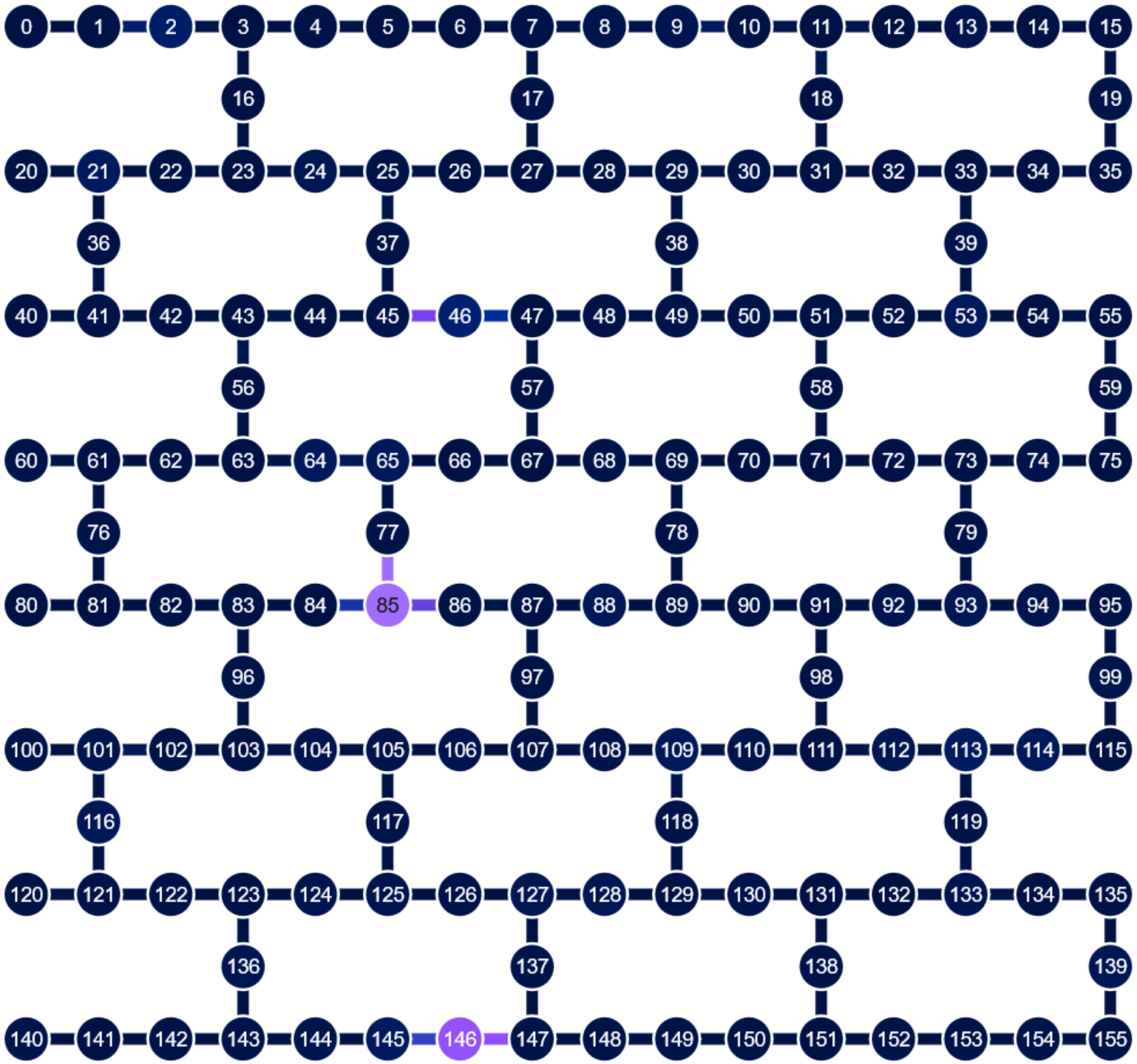
instalation guide: quantum.cloud.ibm.com/docs/en/guides

- Python (works 3.11.9 or later)
- main packages (pip install): qiskit (1.x or 2.x), qiskit-ibm-runtime, qiskit-aer
- packages for data processing and visualization: matplotlib, numpy, pandas

Network of qubits

- Heron – 156, Nighthawk – 120
- qubit coupling to allow interactions
- heavy hexagonal topology
- unique drive frequencies

Connection topology (Heron)



Operations

- Single qubit: Bloch rotation ($\pi/2: SX$, $\pi: X$, RX_θ), (short) pulse (enveloped transmon drive frequency $\sim$ 5GHz) phase shifts RZ_ϕ
- Two-qubit: connection isolated in time and space, 2×2 space interaction map, (medium) cross pulse (CZ, RZZ)
- Measurement: another (long) pulse, different frequency ($\sim$ 7GHz for transmon), IQ kernel/discriminator

Adiabatic approximation: slow pulses prevent external transitions.

Basic single qubit picture

States $|0\rangle$ and $|1\rangle$. General state

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \equiv \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

normalized $|\alpha|^2 + |\beta|^2 = 1$ (α, β complex).
Note: global phase $e^{i\phi}$ is irrelevant (real ϕ).
Initial state $|0\rangle$.
Hamiltonian

$$H = 2\pi\hbar f|1\rangle\langle 1|$$

with the drive frequency $f \sim 5\text{GHz}$

Pauli matrices and operations

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \; X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \; Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \; Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$XY = -YX = iZ$, $YZ = -ZY = iX$, $ZX = -XZ = iY$,
$X^2 = Y^2 = Z^2 = I$

Operation/gates:

$$|\psi\rangle \rightarrow |\psi'\rangle = U|\psi\rangle$$

Basic operations in $|0\rangle$, $|1\rangle$ space

X (aka NOT aka XOR aka $\oplus$)
$X|0\rangle = |1\rangle$, $X|1\rangle = |0\rangle$. SX (aka $\sqrt{X}$)

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

$SX \cdot SX = -iX$. $\sqrt{2}SX|0\rangle = |0\rangle - i|1\rangle$, $\sqrt{2}SX|1\rangle = |1\rangle - i|0\rangle$
Virtual gate

$$RZ_\phi = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix} \equiv \begin{pmatrix} e^{-i\phi/2} & 0 \\ 0 & e^{i\phi/2} \end{pmatrix}$$

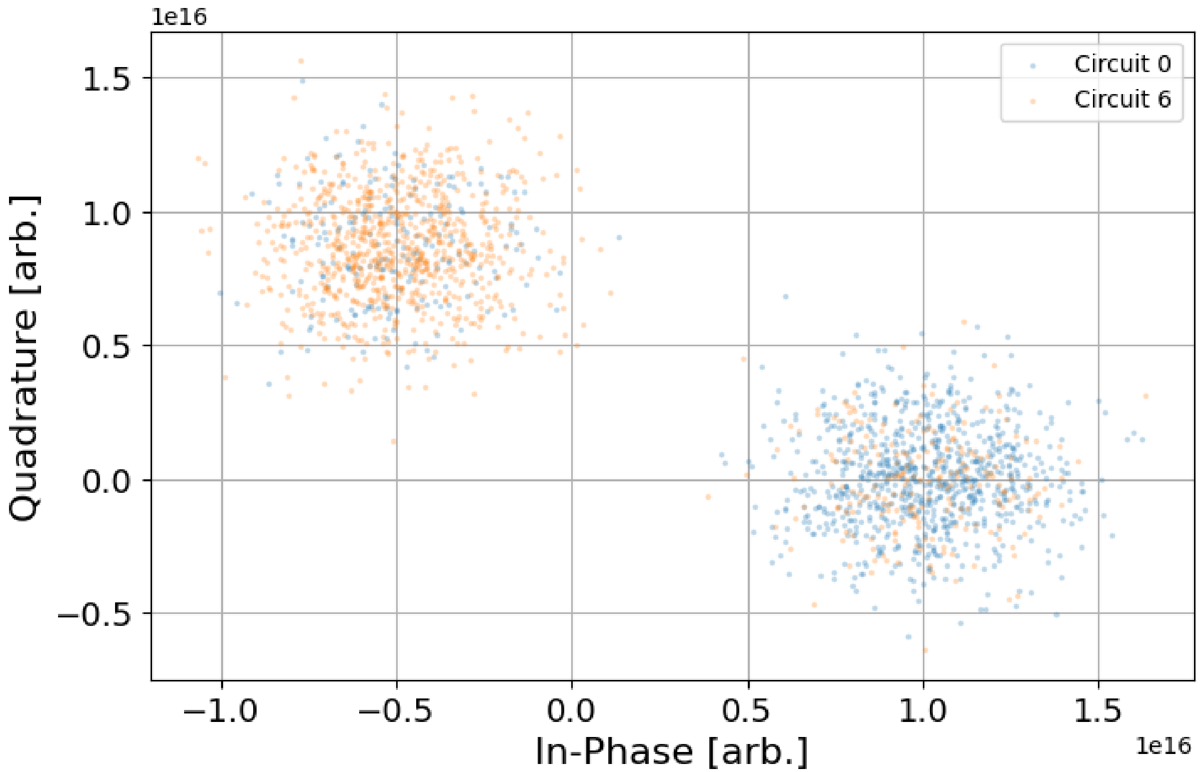
$RZ_\phi|0\rangle = |0\rangle$, $RZ_\phi|1\rangle = e^{i\phi}|1\rangle$, $RZ_\pi \equiv Z$, $RZ_{2\pi} \equiv I$

$$RX_\phi = \begin{pmatrix} \cos\phi/2 & -i\sin\phi/2 \\ -i\sin\phi/2 & \cos\phi/2 \end{pmatrix}$$

Measurement – IQ kernel

Coupling to the cavity resonator (I in-phase, Q - quadrature)

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \rightarrow I + iQ$$



qiskit-community.github.io/qiskit-experiments/tutorials/data_processor.html

Measurement - dichotomic discrimination

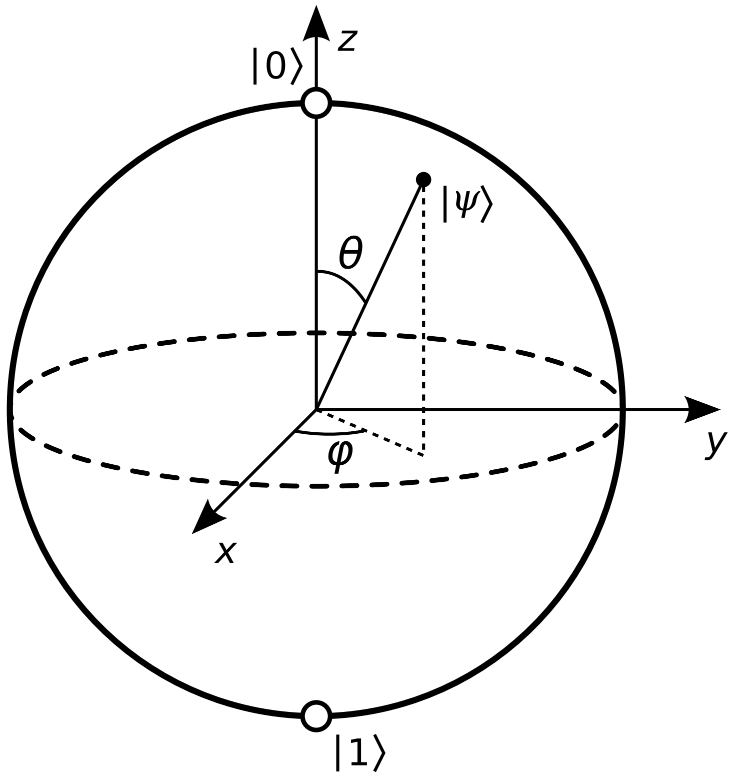
$I + iQ$ is discriminated to 0 and 1 values.
Ideally with probabilities $|\alpha|^2$ and $|\beta|^2$.
Multiqubit states

$$|\psi\rangle = \sum_{abc} \psi_{abc} |abc\rangle$$

gives probability of abc equal $|\psi_{abc}|^2$ for $a, b, c = 0, 1$

Bloch sphere

$$|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle \rightarrow (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$



Bloch sphere – Density matrix

$\langle\psi| = (|\psi\rangle^\dagger)$ († transpose and conjugate)

$$\rho = |\psi\rangle\langle\psi| = \begin{pmatrix} \cos\theta/2 \\ e^{i\phi}\sin\theta/2 \end{pmatrix} \begin{pmatrix} \cos\theta/2 & e^{-i\phi}\sin\theta/2 \end{pmatrix}$$

$$= \frac{1}{2}\begin{pmatrix} 1+\cos\theta & e^{-i\phi}\sin\theta \\ e^{i\phi}\sin\theta & 1-\cos\theta \end{pmatrix}$$

$$= \frac{1}{2}(I + X\sin\theta\cos\phi + Y\sin\theta\sin\phi + Z\cos\theta)$$

Gates and rotations

$$\rho = (I + xX + yY + zZ)/2 \to (I + x'X + y'Y + z'Z)/2$$

$$U(xX + yY + zZ)U^\dagger = x'Y + y'Y + z'Z$$

- $U = X$: π - rotation (180) about x: $x' = x$, $y' = -y$, $z' = -z$
- $U = SX$, $\pi/2$ - rotation (90) about x: $x' = x$, $y' = z$, $z' = -y$
- $U = RZ_\phi$, ϕ - rotation about z: $x' = x\cos\phi - y\sin\phi$, $y' = y\cos\phi + x\sin\phi$, $z' = z$.

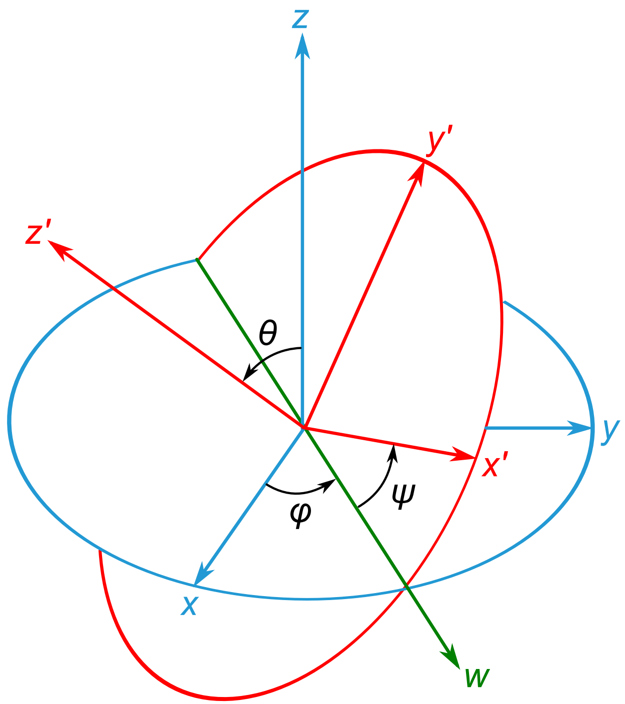
Angle: Counterclockwise looking from positive axis

Universal rotation

$$U(\phi,\theta,\psi) = RZ_{\pi/2+\phi}\cdot SX\cdot RZ_{\pi+\theta}\cdot SX\cdot RZ_{\pi/2+\psi}$$

$$= \begin{pmatrix} -e^{-i(\psi+\phi)/2}\cos\theta/2 & ie^{i(\psi-\phi)/2}\sin\theta/2 \\ ie^{i(\phi-\psi)/2}\sin\theta/2 & -e^{i(\psi+\phi)/2}\cos\theta/2 \end{pmatrix}$$

ϕ, θ, ψ – Euler angles ZXZ rotation.



Other important gates

Hadamard gate – 180 rotation about (1,0,1) axis:

$$H = (X+Z)/\sqrt{2} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \equiv RZ_{\pi/2} \cdot SX \cdot RZ_{\pi/2} \equiv SX \cdot RZ_{\pi/2} \cdot SX$$

(up to global phase!)
$S = RZ_{\pi/2}$, $T = RZ_{\pi/4}$, $Y = RZ_{\pi/2} \cdot X \cdot RZ_{-\pi/2}$

Quantum tomography

Standard measurement $P(0) - P(1) = \langle\psi|Z|\psi\rangle$

Measuring along Bloch axes:

- Z (default),
- Y, applying SX before measurement as $Y = SX^{\dagger} \cdot Z \cdot SX$
- X, applying $SX \cdot RZ_{\pi/2}$ before measurement as $X = RZ^{\dagger}_{\pi/2} \cdot SX^{\dagger} \cdot Z \cdot SX \cdot RZ_{\pi/2}$

Tomography retrieves the FULL information about the state, after many repetitions.

$$\rho = (I + xX + yY + zZ)/2,\ x = \langle X\rangle,\ y = \langle Y\rangle,\ z = \langle Z\rangle$$

Measurement

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \rightarrow \begin{cases} |0\rangle & \text{and outcome 0 with probability } |\alpha|^2 \\ |1\rangle & \text{and outcome 1 with probability } |\beta|^2 \end{cases}$$

- Measurement COLLAPSES the state to the basis states
- Measurement process is NOT unitary

The end? – NO!

The new (collapsed) state can be used again CONDITIONED by the classical outcome

- one can set DIFFERENT gates for 0 and 1
- each readout needs another cbit
- each measurement takes time (do not measure too often)