

Quantum Computing Cheat Sheet

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bra-ket notation: Quantum states are represented by column vectors, called kets

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

To get a bra from a given ket, we take the conjugate transpose of the ket. (this is known as dagger)

$$\langle\psi| = |\psi\rangle^\dagger = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}^\dagger = (\alpha^* \quad \beta^*)$$

Inner Product: Multiplying a bra and a ket is an inner product that yields the projection, or amplitude, of the states onto each other. The inner product yields a scalar output.

$$\begin{aligned} \langle\psi|\psi\rangle &= \begin{pmatrix} \alpha \\ \beta \end{pmatrix}^\dagger \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = (\alpha^* \quad \beta^*) \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \\ \langle\phi|\psi\rangle &= \begin{pmatrix} \gamma \\ \delta \end{pmatrix}^\dagger \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = (\gamma^* \quad \delta^*) \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \end{aligned}$$

- A state whose inner product with itself equals 1 is normalized.
- States with inner product equaling 0 are orthogonal.

Outer Product: Multiplying a ket and a bra is an outer product, which is a square matrix.

Euler's formula:

$$e^{i\theta} = \cos(\theta) + i \sin(\theta) \qquad e^{-i\theta} = \cos(\theta) - i \sin(\theta)$$

Quantum gates & Matrices:

- Quantum gates are unitary matrices, which satisfy: $UU^\dagger = U^\dagger U = I$
- Unitary matrices are always reversible with: $U^{-1} = U^\dagger$

The dagger operation on a matrix, is the conjugate transpose: $A^\dagger = (\overline{A})^T$
Transpose of a Matrix A:

$$A_{3 \times 3} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \qquad A^T = \begin{bmatrix} a & d & g \\ b & e & h \\ c & f & i \end{bmatrix}$$

An example of dagger operation:

$$A_{2 \times 2} = \begin{bmatrix} 1+i & 3i \\ 0 & 3-i \end{bmatrix} \qquad A^\dagger = \begin{bmatrix} 1-i & 0 \\ -3i & 3+i \end{bmatrix}$$

- **Trace of a matrix** is the sum of all diagonal elements.

Common gates:

Identity and Hadamard gates:

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Pauli gates:

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Phase gate:

$$P_\phi = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{bmatrix} \quad \begin{array}{l} |0\rangle \rightarrow |0\rangle \\ |1\rangle \rightarrow e^{i\phi}|1\rangle \end{array}$$

Gate identities:

Pauli identities:

- | | |
|--------------|---------------|
| 1. $XY = iZ$ | 4. $XZ = -iY$ |
| 2. $YZ = iX$ | 5. $ZY = -iX$ |
| 3. $ZX = iY$ | 6. $YX = -iZ$ |

Hadamard identities:

1. $HZH = X$
2. $HYN = -Y$
3. $HXN = Z$

S identities:

1. $SXS^\dagger = Y$
2. $SY S^\dagger = -X$
3. $SZ S^\dagger = Z$

Qubit basis states:

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\begin{aligned} H|0\rangle &= |+\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle \\ H|1\rangle &= |-\rangle = \frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle \end{aligned}$$

Density Matrix: A general way of expressing a quantum state. When state vectors and wave functions can only describe pure states, a density matrix can describe mixed states as well.

A density matrix is defined as:

$$\rho = \sum_j P_j |\psi_j\rangle \langle \psi_j|$$

where P_j is the probability of obtaining the state $|\psi_j\rangle$.

Every density matrix can also be written as a linear combination of Pauli gates, as follows:

$$\rho = \frac{1}{2}I + c_1X + c_2Y + c_3Z$$

where c_1, c_2, c_3 give us the Bloch vector in cartesian coordinates:

$$\vec{r} = (x, y, z) = (2c_1, 2c_2, 2c_3)$$

State Purity: a scalar quantity to measure how pure a state is:

$$purity = \gamma = tr(\rho^2)$$

such that γ can be between $\frac{1}{d}$ and 1, where d is the dimension of the Hilbert space.

$$\begin{aligned} \gamma = 1 &\rightarrow \text{pure state} \\ \gamma \neq 1 &\rightarrow \text{mixed state} \\ \gamma = \frac{1}{d} &\rightarrow \text{completely mixed state.} \end{aligned}$$

Note: Pure states lie on the surface of a Bloch sphere, whereas mixed states lie within it. so if the length of a Bloch vector ($\sqrt{x^2 + y^2 + z^2}$) equals 1, then the state is pure.

Fidelity: a scalar value to measure the closeness of two quantum states, for example the initial state compared with the final state after going through quantum gates, defined as:

$$F(|\psi_i\rangle, |\psi_f\rangle) = |\langle \psi_i | \psi_f \rangle|^2$$

Fidelity holds the following properties:

- **Symmetry:** $F(|\psi_i\rangle, |\psi_f\rangle) = F(|\psi_f\rangle, |\psi_i\rangle)$
- **Bounded values:** $0 \leq F(|\psi_i\rangle, |\psi_f\rangle) \leq 1$ and $F(|\psi\rangle, |\psi\rangle) = 1$

Bell States: Bell states are set of specific two qubit quantum states that represent the simplest (and maximal) examples of quantum entanglement. Bell states are a form of entangled and normalized basis vectors.

$$\begin{aligned} |\Phi^+\rangle &= \frac{|00\rangle + |11\rangle}{\sqrt{2}} & |\Phi^-\rangle &= \frac{|00\rangle - |11\rangle}{\sqrt{2}} \\ |\Psi^+\rangle &= \frac{|01\rangle + |10\rangle}{\sqrt{2}} & |\Psi^-\rangle &= \frac{|01\rangle - |10\rangle}{\sqrt{2}} \end{aligned}$$
