

8.77: Using Quantum Gates to Create Superpositions and Entangled States

In the matrix version of quantum mechanics, vectors represent states and matrices represent operators.

Quantum bits or qubit states:

$$\begin{array}{l} \text{Base states:} \\ 0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad 1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{array} \quad \begin{array}{l} \text{A superposition of base states:} \\ \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{array} \quad \text{where } (|\alpha|)^2 + (|\beta|)^2 = 1$$

The identity operator and the two quantum gates that will be used to create quantum superpositions and entangled are provided below.

$$\begin{array}{l} \text{Identity:} \\ \mathbf{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{array} \quad \begin{array}{l} \text{Hadamard gate:} \\ \mathbf{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \end{array} \quad \begin{array}{l} \text{Controlled-NOT gate:} \\ \mathbf{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \end{array}$$

The Hadamard gate operates on the base states to create superpositions:

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \rightarrow \begin{pmatrix} \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} \end{pmatrix} \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \rightarrow \begin{pmatrix} \frac{\sqrt{2}}{2} \\ -\frac{\sqrt{2}}{2} \end{pmatrix}$$

When it operates on the superpositions it returns the base states, demonstrating that the Hadamard gate is reversible.

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{\sqrt{2}}{2} \\ \frac{\sqrt{2}}{2} \end{pmatrix} \rightarrow \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{\sqrt{2}}{2} \\ -\frac{\sqrt{2}}{2} \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Two-qubit states are created by tensor multiplication of single-qubit states. These binary tensor products correspond to the decimal numbers 0, 1, 2 and 3.

$$00 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad 01 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad 10 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad 11 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

The controlled-NOT gate operates on these states yielding the following results.

$$\mathbf{CNOT} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{CNOT} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{CNOT} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 1 \end{pmatrix} \quad \mathbf{CNOT} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

The results are summarized in the following table. The first qubit is the control. If it is 0, nothing happens to the second qubit. If it is 1, the second qubit is flipped using the NOT gate embedded in the lower right quadrant of the CNOT matrix. Thus the name controlled-NOT.

$$\begin{pmatrix} \mathbf{CNOT} \\ 00 > 00 \\ 01 > 01 \\ 10 > 11 \\ 11 > 10 \end{pmatrix} \quad \mathbf{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Something altogether different happens when the CNOT gate operates on the following two-qubit states in which the first qubit is one of the superpositions from above and the second is one of the base states. There are four possible calculations and they yield the well known Bell states.

The Bell states are entangled superpositions and are of great importance in quantum information theory. They cannot be factored and therefore express quantum correlation in a most simple and striking way.

$$\begin{aligned}
 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} & \text{CNOT} & \frac{1}{\sqrt{1}} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} &= \begin{pmatrix} 0.707 \\ 0 \\ 0 \\ 0.707 \end{pmatrix} & \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right] \\
 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} & \text{CNOT} & \frac{1}{\sqrt{1}} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} &= \begin{pmatrix} 0.707 \\ 0 \\ 0 \\ -0.707 \end{pmatrix} & \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right] \\
 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} & \text{CNOT} & \frac{1}{\sqrt{1}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} &= \begin{pmatrix} 0 \\ 0.707 \\ 0.707 \\ 0 \end{pmatrix} & \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right] \\
 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix} & \text{CNOT} & \frac{1}{\sqrt{1}} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix} &= \begin{pmatrix} 0 \\ 0.707 \\ -0.707 \\ 0 \end{pmatrix} & \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} - \begin{pmatrix} 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right]
 \end{aligned}$$

Bell states:

$$\Theta_p = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad \Theta_m = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix} \quad \Psi_p = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix} \quad \Psi_m = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ -1 \\ 0 \end{pmatrix}$$

The same results can be obtained with $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$ by operating on the first qubit with a Hadamard gate (creating a superposition) followed by a CNOT operation.

$$\begin{aligned}
 \text{CNOT kronecker(H, I)} &= \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.707 \\ 0 \\ 0 \\ 0.707 \end{pmatrix} & \text{CNOT kronecker(H, I)} &= \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.707 \\ 0.707 \\ 0 \end{pmatrix} \\
 \text{CNOT kronecker(H, I)} &= \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.707 \\ 0 \\ 0 \\ -0.707 \end{pmatrix} & \text{CNOT kronecker(H, I)} &= \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.707 \\ -0.707 \\ 0 \end{pmatrix}
 \end{aligned}$$

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