Chapter 1
Fundamentals of Quantum Computation

ABSTRACT

This chapter briefly describes the basic concepts and principles of quantum computing. Firstly, the concepts of qubit, quantum coherence, quantum decoherence, quantum entanglement, quantum density operators, linear operators, inner products, outer products, tensor products, Hermite operators, and unitary operators are described. Then, the four basic assumptions of quantum mechanics are introduced, focusing on the measurement assumptions of quantum mechanics. Finally, the definition of commonly used quantum logic gates is given including single qubit gates, double qubit gates, and multiple qubit gates. These contents provide the necessary theoretical basis for subsequent chapters.

INTRODUCTION

On December 14, 1900, Planck proposed the quantization hypothesis of energy at the annual meeting of the physical society, thus establishing the concept of quantum. After that, a group of outstanding physicists, such as Einstein, Heisenberg and Schrodinger, established the theory of quantum mechanics (Long, Pei, & Zeng, 2007; Cong, 2006). Quantum computation based on quantum mechanics has many new characteristics different from classical computation. This chapter briefly introduces the basic concepts and principles of quantum computation. Related mathematics backgrounds

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are shown in Appendix A. The implementation codes of controlled gates are seen in Appendix B.

BASIC CONCEPTS OF QUANTUM COMPUTATION

Basic concepts of quantum computation are described, such as qubit, tensor products, inner products, and outer products.

Qubit

A classical bit has a state: either 0 or 1. In quantum computation, information elements are represented by qubits (Schumacher, 1995), which have two possible states $|0\rangle$ and $|1\rangle$, which are called basis states. Any two-level quantum system can be used to implement qubits. For instance, the ground and excited states of electrons in a hydrogen atom, and the two different polarizations of a photon, can be called as $|0\rangle$ and $|1\rangle$, respectively. Dirac uses the symbol $|\bullet\rangle$ to represent a quantum state, also known as a ket, which is equivalent to a column vector. $\langle\bullet|$ called a bra, is equivalent to a row vector and is a dual vector of $|\bullet\rangle$, which can be simply understood as a conjugate transpose vector of a vector (Dirac, 1947). A qubit can also be a linear combination of two basis states, often called superposition states:

$$\left|\psi\right\rangle = \alpha\left|0\right\rangle + \beta\left|1\right\rangle, \tag{2.1}$$

where the numbers α and β are complex numbers, satisfying $\left|\alpha\right|^2 + \left|\beta\right|^2 = 1$. Therefore, they are called the probability amplitude. When the quantum state $\left|\psi\right\rangle$ is measured, it collapses to $|0\rangle$ with a probability of $|\alpha|^2$, and collapses to $|1\rangle$ with a probability of $|\beta|^2$. Hence a qubit can contain both $|0\rangle$ and $|1\rangle$, which is quite different from classical bits.

The special basis states $|0\rangle$ and $|1\rangle$ are also called computation basis states. Their vector forms are

$$\left|0\right\rangle = \begin{bmatrix}1\\0\end{bmatrix}, \left|1\right\rangle = \begin{bmatrix}0\\1\end{bmatrix}, \tag{2.2}$$

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