Current Quantum Information Science and Technology

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INTRODUCTION

Quantum information science is based on quantum physics. Information is represented by quantum states defined by energy levels of molecules, atoms, and photons. Quantum information science is the theory of quantum information processing and quantum communication. Quantum information technology includes quantum computers, other quantum information processing devices, quantum programming methodologies, and quantum communication applications such as quantum key distribution systems and quantum signatures. Quantum error correction is an essential property of quantum information technology because of high error vulnerability in implementations of quantum information processing and quantum communication. This error vulnerability is caused by properties of quantum physics. The objective of this article is to present state of the art and future perspectives of quantum information science and technology.

BACKGROUND

In the early 1980s was observed, that the stochastic parallelism of quantum states cannot be simulated efficiently on a classical computer (Feynman, 1982). This observation started research on using quantum mechanical effects for more efficient information processing than is achievable with classical computers. During the 1980s the operating principles and implementation possibilities of quantum computing were outlined in Oxford University (Deutsch, 1985).

In 1984 a quantum protocol called BB84 for information transfer with provable confidentiality was proposed (Bennett & Brassard, 1984). In the 1990s

efficient quantum algorithms, for example Shor's integer factorization quantum algorithm (Shor, 1994), Grover's quantum search algorithms (Grover, 1996), and Simon's algorithm for simulating many-body quantum systems (Simon, 1994) were proposed. The BB84 protocol has been used for secure distribution of symmetric encryption/decryption keys (Quantum Key Distribution, QKD) in research networks (Elliot, 2004; Quellette, 2005; Poppe, 2008; UQCC, 2010). Commercial QKD technology has been available more than 10 years. Quantum digital signatures based on control and measurements of quantum states have been proposed and experimentally verified (Gottesman & Chuang, 2001; Lu & Feng, 2004; Clarke et al., 2012).

Small scale quantum computers based on the quantum circuit computation model have been realized and successfully tested in research laboratories (Vandersypen et al., 2001; Monz et al., 2011). Since 2011 large scale commercial quantum computers based on the adiabatic quantum computation model have been available (Jones, 2011).

Relevant achievements in quantum information science and technology from 1970 till October 2013 are listed in (Timeline, 2013). Not only research laboratories but also several universities are currently engaged in research and education on this topic, see for example (qis.mit.edu, 2013; Quantum, 2011; Quantum, 2012)

INFORMATION REPRESENTATION WITH QUANTUM STATES

Quantum states are energy levels of molecules, atoms, and photons. Two quantum states for which a state transition exists can be used to represent an information bit, if the energy levels of both states can be measured.

A bit defined by quantum states is called a quantum bit or qubit. However, quantum states are probabilistic. When the energy level of a molecule, an atom, or a photon is measured, the outcome is one of all possible energy levels and each possible outcome is associated with a probability. The sum of the probabilities of all possible measurement outcomes is of course 1. A qubit is thus also probabilistic.

Another fundamental qubit property is the *No Cloning Property*, the impossibility to create a copy of an unknown quantum state. However, an unknown quantum state can be transferred between qubit platforms with *teleportation,* in which the original qubit state is lost.

Mathematical Treatment of Quantum Bits (Qubits)

A qubit can be treated by linear algebra as a 2-dimensional vector. The orthogonal base vectors $(1,0)^T$ and $(0,1)^T$ represent binary values 0 and 1 respectively. Usually the *Dirac Notation* is used for qubits. Thus $(1,0)^T = |0>$ and $(0,1)^T = |1>$.

A qubit is a concurrent superposition of $|0>$ and $|1>$. A measured qubit gets the value $|0>$ or $|1>$. A qubit representation is

$$|\psi> = a \cdot |0> + b \cdot |1>, \tag{1}$$

where a and b are complex numbers for which

$$<\psi||\psi> = (a^*,b^*) \cdot (a,b)^T = a^* \cdot a + b^* \cdot b = |a|^2 + |b|^2 = 1. \tag{2}$$

$\{a^*,b^*\}$ are complex conjugates of $\{a,b\}$, and $\{|a|^2,|b|^2\}$ are the probabilities to measure $|0>,|1>$. A qubit has thus 3 dimensions, since complex numbers have two dimensions. A point on a 3-dimensional unit sphere therefore visualizes a qubit.

Multiple Qubits

A *2 qubit* quantum state is a column vector with $2^2 = 4$ components. For the qubits

$$|\psi_1> = a \cdot |0> + b \cdot |1> \text{ and } |\psi_2> = c \cdot |0> + d \cdot |1> \tag{3}$$

the quantum state is

$$|\psi_1\psi_2> = |\psi_1> \otimes |\psi_1> = a \cdot c \cdot |00> + a \cdot d \cdot |01> + b \cdot c \cdot |10> + b \cdot d \cdot |11>. \tag{4}$$

$\otimes$ is the *tensor product* of two column vectors. $|00> = |0> \otimes |0> = (1, 0, 0, 0)^T$, $|01> = |0> \otimes |1> = (0, 1, 0, 0)^T$, $|10> = |1> \otimes |0> = (0, 0, 1, 0)^T$, and $|11> = |1> \otimes |1> = (0, 0, 0, 1)^T$ are the *base vectors* of a 2 qubit state.

A *N qubit* quantum state $|\psi_1\psi_2...\psi_N>$ is a superposition of 2^N base vectors. For a 3 qubit quantum state $|\psi_1\psi_2\psi_3>$ the 2^3 base vectors are $\{|000>, |001>, |010>, |011>, |100>, |101>, |110>, |111>\}$, where $|001> = |0> \otimes |0> \otimes |1> = (0, 1, 0, 0, 0, 0, 0, 0)^T$, etc.

The qubit state $|\psi_1\psi_2...\psi_N>$ is *entangled* if there exists no $|\psi_1>, |\psi_2>,...,|\psi_N>$ for which $|\psi_1\psi_2...\psi_N> = |\psi_1> \otimes |\psi_1> \otimes...\otimes |\psi_N>$. For example, the 2 qubit state $(1/\sqrt{2}) \cdot (|00>+|11>)$ is entangled. *Proof*: $(a \cdot |0>+b \cdot |1>) \otimes (c \cdot |0>+d \cdot |1>) = a \cdot c \cdot |00>+a \cdot d \cdot |01>+b \cdot c \cdot |10>+b \cdot d \cdot |11> \neq (1/\sqrt{2}) \cdot (|00> + |11>)$, since one of $\{a,d\}$ and one of $\{b,c\}$ must be 0.

Physical Implementation of Qubits

Qubits have been implemented by photon states, by ion traps, by cavity quantum electrodynamics (QED), by nuclear magnetic resonance (NMR), by quantum dots, and by superconducting circuits (Nielsen & Chuang, 2002; Devoret & Schoelkopf, 2013).

An essential physical qubit property is decoherence time, during which a qubit state can be controlled before it collapses because of interaction with the physical environment.

A qubit can in quantum communication be implemented by a photon *polarization state* consisting of all planes in which the electromagnetic wave of the photon propagates. A random polarization is a superposition of any pair of orthogonal states. Orthogonal state pair examples are

- Horisontal and vertical polarization
- +45° and -45° diagonal polarization.

A general photon polarization state is thus a qubit

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