Quantum Information and Computing

A Textbook for Computer Science and Engineering Students

First Edition

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Preface

Quantum information and computing are hot topics, and there are many books around. But there is no book for computer science or engineering students who have not taken any courses on quantum physics. Of course, there are many popular science books and articles that explain quantum physics by drawing analogy to laymen observable things. But can one use the analogies of quantum superposition or entanglement to (IBM) QIS programming? This book is to bridge the gap between quantum physics and engineering so that information and computer sciences students can use their knowledge to implement or even develop quantum algorithms and protocols.

The difficulty of quantum physics lies in the wave behavior of particles. The focus of theoretical is how to solve the wave equations. And experimental physicists focus on how to control the waves. This book leaves out the details of the waves by labelling them with symbols e.g. "0" and "1". The symbols are what computer science and engineering students know how to work with. They are what the computer science data structure and algorithms, and Shannon information theory apply.

How to label waves with symbols is studied by encoding theory whose techniques have been studied by electrical engineering students. They are the bridge between physics in the analog world and information and computer sciences in the digital world.

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Chapter 1

Introduction

The advantage of quantum computing lies in the possibility of parallel comput-
ing using a quantum system. Quantum information theory is mostly used in
distributing encryption keys for telecommunication using quantum systems –
the so called quantum key distribution. The secrecy of quantum key exchange
lies in the uncertainty of quantum measurement. If these statements are too
abstract, read on.

1.1 The Advantage of Parallel Exploration

1.1.1 The Maze Problem

Maze problems are hard. That's because there are too many paths to explore
from the entrance to the exit. Computer scientists have long known parallel
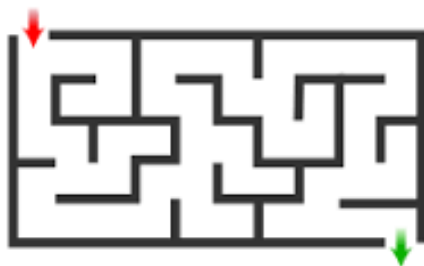computing is the way to speed up finding solutions to such problems.

Figure 1.1: Maze

For a physicist, this experiment is the fast approach to a solution: run water
into the entrance. If we see water out of the exit, we know the maze problem
has at least one solution. But do we know whether there are more than one

good paths or how many good paths there are? We can refine the experiment: run several water drops into the entrance. Of course, these are not the solution to the final maze problem, but we can keep on adding water tricks toward a solution. Of course the solutions to such hard problems are to explore all the paths in parallel. Let's look at how a physicist would use parallel exploration to solve the maze problems.

For the simplest case – we want to know if there is any good path at all. We can put water into the entrance. If there is any water coming out of the exit, we know the answer is positive. Adding complexity to the problem, we want to know how many good paths there are? Again, we can play the water trick. Let's put several water drops into the entrance and see how many drops will come out. Until now, we don't have the solution to the final maze problem, but we can keep on adding water tricks toward a solution.

Playing with water tricks is exactly the idea behind quantum computers. Quantum physics tells us every particle possesses both wave behavior and particle behavior. The wave behavior is like the watery behavior and allows the wave to spread and propagate through out all possible paths. The particle behavior gives use the "drop" behavior and allows the particle to reveal the properties, e.g. the length, of the individual paths.

1.1.2   Waves

We use electromagnetic waves every day. We get Wi-Fi or cellphone signals even when we move around the house or on the streets because the waves can spread and explore unlimited paths to reach us. We can contain electromagnetic waves in boxes. Microwave ovens are examples. We can also optical fibers, co-axile cables and waveguides to channel electromagnetic waves in one dimension along the cable lengths.

All matters, e.g. electrons, are waves in nature. If electrons were not waves, they would collapse to the positively charged nucleus and result in atoms of zero sizes, and we would have not seen the world as we have.

1.1.3   Particles

A particle is the smallest "drop" of matter. But "the smallest" by what measure? That is a critical question we should ask. By the amount of energy, a photon is the smallest drop of an electromagnetic wave. An electron is the smallest drop if measured by both mass and electric charge.

The waves and matters we see or use everyday contain too many particles, and we only see the average effects of the waves and matters. If we have two beams of lights, one is yellow and the other blue, merged into one, what do we see? We see a beam of green light. But if we lower the emissions from each of the lights to one photon at a time, we will see either a yellow or blue photon – we don't see a green photon.

The sound from a guitar string play note E is different in our ears from that played on a violin. That is because the sound from each is composed by many harmonics, an octave apart from each other. The average or combined effects from the strings of different instruments is different. If our ears were sensitive enough to hear individual phonons – the smallest drops of sound – we would hear sound of pure harmonics. Of course making such single particle, photon
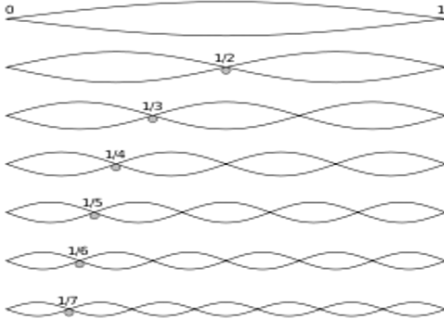

Figure 1.2: Fundamental harmonic and the overtones

or phonon, generators or detectors has been the very challenge to physicists in their effort to make quantum computing and communication.

1.1.4 State and superposition

From a wave's perspective, we see particles in it. From a particle's perspective, we can imagine it rides on a wave like a surfer following the trajectry defined by the wave. State is a quantum physics term referring to the wave that a particle rides on. Physicists use the wavefunction ψ of the wave to note the state $|\psi>$ - the so called "ket" notation. But throughout this book, we use the labels e.g. "0" and "1" of the waves to note the states as $|0>$ and $|1>$.

Can a particle be in two waves? Yes, it can. The two waves may be viewed as two by one measurement but are one by another measurement.

Chapter 2

Qubits for computing

Chapter 3

Qubits for communication

Chapter 4

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Chapter 5

General Tendencies