教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

量子计算与量子信息

（影印版）

QUANTUM COMPUTATION AND QUANTUM INFORMATION

■ Michael A. Nielsen
Isaac L. Chuang

高等教育出版社
Higher Education Press

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前　言

20世纪末，以计算机和通信技术为代表的信息科学和技术对世界经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入21世纪，尤其随着我国加入WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在20世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的20多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley公司出版的贝尔实验室信息科学研究中心副总裁Silberschatz教授的经典著作《操作系统概念》，是我们经过反复谈判，做了很多努力才得以引进的。William Stallings先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作者协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者Jiawei Han先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院Thomas Cormen和麻省理工学院、哥伦比亚大学的几

位学者共同编著的经典著作《算法导论》，在经历了 11 年的锤炼之后于 2001 年出版了第二版。目前任教于美国 Massachusetts 大学的 James Kurose 教授，曾在美国三所高校先后 10 次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国 35 所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名 IT 企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

Preface

This book provides an introduction to the main ideas and techniques of the field of quantum computation and quantum information. The rapid rate of progress in this field and its cross-disciplinary nature have made it difficult for newcomers to obtain a broad overview of the most important techniques and results of the field.

Our purpose in this book is therefore twofold. First, we introduce the background material in computer science, mathematics and physics necessary to understand quantum computation and quantum information. This is done at a level comprehensible to readers with a background at least the equal of a beginning graduate student in one or more of these three disciplines; the most important requirements are a certain level of mathematical maturity, and the desire to learn about quantum computation and quantum information. The second purpose of the book is to develop in detail the central results of quantum computation and quantum information. With thorough study the reader should develop a working understanding of the fundamental tools and results of this exciting field, either as part of their general education, or as a prelude to independent research in quantum computation and quantum information.

Structure of the book

The basic structure of the book is depicted in Figure 1. The book is divided into three parts. The general strategy is to proceed from the concrete to the more abstract whenever possible. Thus we study quantum computation before quantum information; specific quantum error-correcting codes before the more general results of quantum information theory; and throughout the book try to introduce examples before developing general theory.

Part I provides a broad overview of the main ideas and results of the field of quantum computation and quantum information, and develops the background material in computer science, mathematics and physics necessary to understand quantum computation and quantum information in depth. Chapter 1 is an introductory chapter which outlines the historical development and fundamental concepts of the field, highlighting some important open problems along the way. The material has been structured so as to be accessible even without a background in computer science or physics. The background material needed for a more detailed understanding is developed in Chapters 2 and 3, which treat in depth the fundamental notions of quantum mechanics and computer science, respectively. You may elect to concentrate more or less heavily on different chapters of Part I, depending upon your background, returning later as necessary to fill any gaps in your knowledge of the fundamentals of quantum mechanics and computer science.

Part II describes quantum computation in detail. Chapter 4 describes the fundamen-

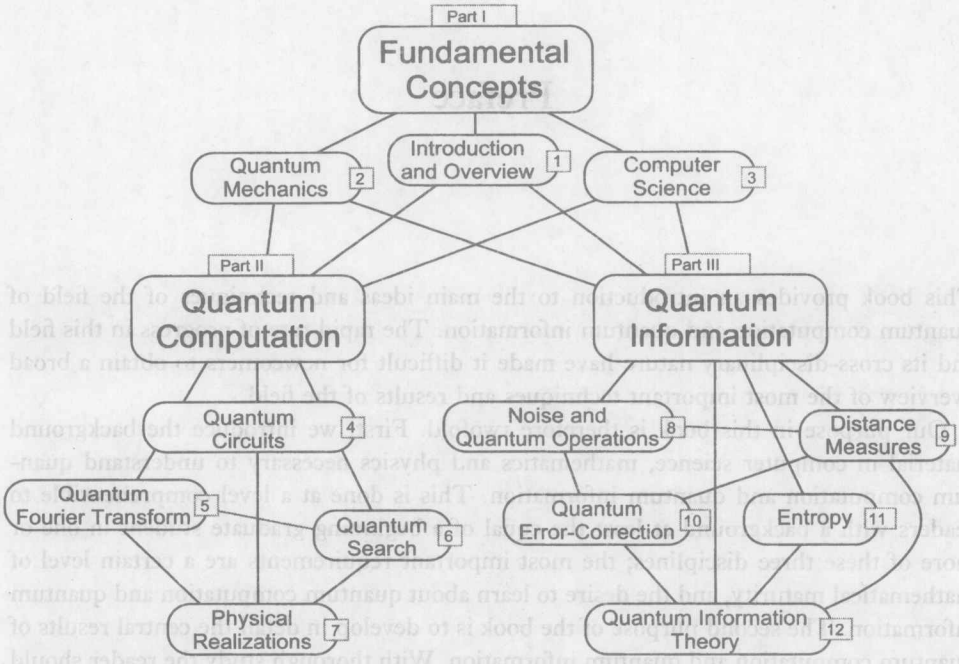

Figure 1. Structure of the book.

tal elements needed to perform quantum computation, and presents many elementary operations which may be used to develop more sophisticated applications of quantum computation. Chapters 5 and 6 describe the quantum Fourier transform and the quantum search algorithm, the two fundamental quantum algorithms presently known. Chapter 5 also explains how the quantum Fourier transform may be used to solve the factoring and discrete logarithm problems, and the importance of these results to cryptography. Chapter 7 describes general design principles and criteria for good physical implementations of quantum computers, using as examples several realizations which have been successfully demonstrated in the laboratory.

Part III is about quantum information: what it is, how information is represented and communicated using quantum states, and how to describe and deal with the corruption of quantum and classical information. Chapter 8 describes the properties of *quantum noise* which are needed to understand real-world quantum information processing, and the *quantum operations formalism*, a powerful mathematical tool for understanding quantum noise. Chapter 9 describes *distance measures* for quantum information which allow us to make quantitatively precise what it means to say that two items of quantum information are similar. Chapter 10 explains quantum error-correcting codes, which may be used to protect quantum computations against the effect of noise. An important result in this chapter is the *threshold theorem*, which shows that for realistic noise models, noise is *in principle* not a serious impediment to quantum computation. Chapter 11 introduces the fundamental information-theoretic concept of *entropy*, explaining many properties of entropy in both classical and quantum information theory. Finally, Chapter 12 discusses the information carrying properties of quantum states and quantum communication chan-

nels, detailing many of the strange and interesting properties such systems can have for the transmission of information both classical and quantum, and for the transmission of secret information.

A large number of exercises and problems appear throughout the book. Exercises are intended to solidify understanding of basic material and appear within the main body of the text. With few exceptions these should be easily solved with a few minutes work. Problems appear at the end of each chapter, and are intended to introduce you to new and interesting material for which there was not enough space in the main text. Often the problems are in multiple parts, intended to develop a particular line of thought in some depth. A few of the problems were unsolved as the book went to press. When this is the case it is noted in the statement of the problem. Each chapter concludes with a summary of the main results of the chapter, and with a 'History and further reading' section that charts the development of the main ideas in the chapter, giving citations and references for the whole chapter, as well as providing recommendations for further reading.

The front matter of the book contains a detailed Table of Contents, which we encourage you to browse. There is also a guide to nomenclature and notation to assist you as you read.

The end matter of the book contains six appendices, a bibliography, and an index.

Appendix 1 reviews some basic definitions, notations, and results in elementary probability theory. This material is assumed to be familiar to readers, and is included for ease of reference. Similarly, Apendix 2 reviews some elementary concepts from group theory, and is included mainly for convenience. Appendix 3 contains a proof of the Solovay–Kitaev theorem, an important result for quantum computation, which shows that a finite set of quantum gates can be used to quickly approximate an arbitrary quantum gate. Appendix 4 reviews the elementary material on number theory needed to understand the quantum algorithms for factoring and discrete logarithm, and the RSA cryptosystem, which is itself reviewed in Appendix 5. Appendix 6 contains a proof of Lieb's theorem, one of the most important results in quantum computation and quantum information, and a precursor to important entropy inequalities such as the celebrated strong subadditivity inequality. The proofs of the Solovay–Kitaev theorem and Lieb's theorem are lengthy enough that we felt they justified a treatment apart from the main text.

The bibliography contains a listing of all reference materials cited in the text of the book. Our apologies to any researcher whose work we have inadvertently omitted from citation.

The field of quantum computation and quantum information has grown so rapidly in recent years that we have not been able to cover all topics in as much depth as we would have liked. Three topics deserve special mention. The first is the subject of *entanglement measures*. As we explain in the book, entanglement is a key element in effects such as quantum teleportation, fast quantum algorithms, and quantum error-correction. It is, in short, a resource of great utility in quantum computation and quantum information. There is a thriving research community currently fleshing out the notion of entanglement as a new type of physical resource, finding principles which govern its manipulation and utilization. We felt that these investigations, while enormously promising, are not yet complete enough to warrant the more extensive coverage we have given to other subjects in this book, and we restrict ourselves to a brief taste in Chapter 12. Similarly, the subject of distributed quantum computation (sometimes known as quantum communication complexity) is an enormously promising subject under such active development that we

have not given it a treatment for fear of being obsolete before publication of the book. The implementation of quantum information processing machines has also developed into a fascinating and rich area, and we limit ourselves to but a single chapter on this subject. Clearly, much more can be said about physical implementations, but this would begin to involve many more areas of physics, chemistry, and engineering, which we do not have room for here.

How to use this book

This book may be used in a wide variety of ways. It can be used as the basis for a variety of courses, from short lecture courses on a specific topic in quantum computation and quantum information, through to full-year classes covering the entire field. It can be used for independent study by people who would like to learn just a little about quantum computation and quantum information, or by people who would like to be brought up to the research frontier. It is also intended to act as a reference work for current researchers in the field. We hope that it will be found especially valuable as an introduction for researchers new to the field.

Note to the independent reader

The book is designed to be accessible to the independent reader. A large number of exercises are peppered throughout the text, which can be used as self-tests for understanding of the material in the main text. The Table of Contents and end of chapter summaries should enable you to quickly determine which chapters you wish to study in most depth. The dependency diagram, Figure 1, will help you determine in what order material in the book may be covered.

Note to the teacher

This book covers a diverse range of topics, and can therefore be used as the basis for a wide variety of courses.

A one-semester course on quantum computation could be based upon a selection of material from Chapters 1 through 3, depending on the background of the class, followed by Chapter 4 on quantum circuits, Chapters 5 and 6 on quantum algorithms, and a selection from Chapter 7 on physical implementations, and Chapters 8 through 10 to understand quantum error-correction, with an especial focus on Chapter 10.

A one-semester course on quantum information could be based upon a selection of material from Chapters 1 through 3, depending on the background of the class. Following that, Chapters 8 through 10 on quantum error-correction, followed by Chapters 11 and 12 on quantum entropy and quantum information theory, respectively.

A full year class could cover all material in the book, with time for additional readings selected from the 'History and further reading' section of several chapters. Quantum computation and quantum information also lend themselves ideally to independent research projects for students.

Aside from classes on quantum computation and quantum information, there is another way we hope the book will be used, which is as the text for an introductory class in quantum mechanics for physics students. Conventional introductions to quantum mechanics rely heavily on the mathematical machinery of partial differential equations. We believe this often obscures the fundamental ideas. Quantum computation and quantum informa-

tion offers an excellent conceptual laboratory for understanding the basic concepts and unique aspects of quantum mechanics, without the use of heavy mathematical machinery. Such a class would focus on the introduction to quantum mechanics in Chapter 2, basic material on quantum circuits in Chapter 4, a selection of material on quantum algorithms from Chapters 5 and 6, Chapter 7 on physical implementations of quantum computation, and then almost any selection of material from Part III of the book, depending upon taste.

Note to the student

We have written the book to be as self-contained as possible. The main exception is that occasionally we have omitted arguments that one really needs to work through oneself to believe; these are usually given as exercises. Let us suggest that you should at least attempt all the exercises as you work through the book. With few exceptions the exercises can be worked out in a few minutes. If you are having a lot of difficulty with many of the exercises it may be a sign that you need to go back and pick up one or more key concepts.

Further reading

As already noted, each chapter concludes with a 'History and further reading' section. There are also a few broad-ranging references that might be of interest to readers. Preskill's[Pre98b] superb lecture notes approach quantum computation and quantum information from a somewhat different point of view than this book. Good overview articles on specific subjects include (in order of their appearance in this book): Aharonov's review of quantum computation[Aha99b], Kitaev's review of algorithms and error-correction[Kit97b], Mosca's thesis on quantum algorithms[Mos99], Fuchs' thesis[Fuc96] on distinguishability and distance measures in quantum information, Gottesman's thesis on quantum error-correction[Got97], Preskill's review of quantum error-correction[Pre97], Nielsen's thesis on quantum information theory[Nie98], and the reviews of quantum information theory by Bennett and Shor[BS98] and by Bennett and DiVincenzo[BD00]. Other useful references include Gruska's book[Gru99], and the collection of review articles edited by Lo, Spiller, and Popescu[LSP98].

Errors

Any lengthy document contains errors and omissions, and this book is surely no exception to the rule. If you find any errors or have other comments to make about the book, please email them to: `qci@squint.org`. As errata are found, we will add them to a list maintained at the book web site: `http://www.squint.org/qci/`.

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Nomenclature and notation

There are several items of nomenclature and notation which have two or more meanings in common use in the field of quantum computation and quantum information. To prevent confusion from arising, this section collects many of the more frequently used of these items, together with the conventions that will be adhered to in this book.

Linear algebra and quantum mechanics

All vector spaces are assumed to be finite dimensional, unless otherwise noted. In many instances this restriction is unnecessary, or can be removed with some additional technical work, but making the restriction globally makes the presentation more easily comprehensible, and doesn't detract much from many of the intended applications of the results.

A *positive* operator A is one for which $\langle\psi|A|\psi\rangle \geq 0$ for all $|\psi\rangle$. A *positive definite* operator A is one for which $\langle\psi|A|\psi\rangle > 0$ for all $|\psi\rangle \neq 0$. The *support* of an operator is defined to be the vector space orthogonal to its kernel. For a Hermitian operator, this means the vector space spanned by eigenvectors of the operator with non-zero eigenvalues.

The notation U (and often but not always V) will generically be used to denote a unitary operator or matrix. H is usually used to denote a quantum logic gate, the *Hadamard gate*, and sometimes to denote the *Hamiltonian* for a quantum system, with the meaning clear from context.

Vectors will sometimes be written in column format, as for example,

$$\begin{bmatrix} 1 \\ 2 \end{bmatrix}, \tag{0.1}$$

and sometimes for readability in the format $(1, 2)$. The latter should be understood as shorthand for a column vector. For two-level quantum systems used as qubits, we shall usually identify the state $|0\rangle$ with the vector $(1, 0)$, and similarly $|1\rangle$ with $(0, 1)$. We also define the Pauli sigma matrices in the conventional way – see 'Frequently used quantum gates and circuit symbols', below. Most significantly, the convention for the Pauli sigma z matrix is that $\sigma_z|0\rangle = |0\rangle$ and $\sigma_z|1\rangle = -|1\rangle$, which is reverse of what some physicists (but usually not computer scientists or mathematicians) intuitively expect. The origin of this dissonance is that the $+1$ eigenstate of σ_z is often identified by physicists with a so-called 'excited state', and it seems natural to many to identify this with $|1\rangle$, rather than with $|0\rangle$ as is done in this book. Our choice is made in order to be consistent with the usual indexing of matrix elements in linear algebra, which makes it natural to identify the first column of σ_z with the action of σ_z on $|0\rangle$, and the second column with the action on $|1\rangle$. This choice is also in use throughout the quantum computation and quantum information community. In addition to the conventional notations σ_x, σ_y and σ_z for the Pauli sigma matrices, it will also be convenient to use the notations $\sigma_1, \sigma_2, \sigma_3$ for these

three matrices, and to define σ_0 as the 2×2 identity matrix. Most often, however, we use the notations I, X, Y and Z for $\sigma_0, \sigma_1, \sigma_2$ and σ_3, respectively.

Information theory and probability

As befits good information theorists, logarithms are *always* taken to base two, unless otherwise noted. We use $\log(x)$ to denote logarithms to base 2, and $\ln(x)$ on those rare occasions when we wish to take a natural logarithm. The term *probability distribution* is used to refer to a finite set of real numbers, p_x, such that $p_x \geq 0$ and $\sum_x p_x = 1$. The *relative entropy* of a positive operator A with respect to a positive operator B is defined by $S(A||B) \equiv \mathrm{tr}(A \log A) - \mathrm{tr}(A \log B)$.

Miscellanea

$\oplus$ denotes modulo two addition. Throughout this book 'z' is pronounced 'zed'.

Frequently used quantum gates and circuit symbols

Certain schematic symbols are often used to denote unitary transforms which are useful in the design of quantum circuits. For the reader's convenience, many of these are gathered together below. The rows and columns of the unitary transforms are labeled from left to right and top to bottom as $00\ldots0, 00\ldots1$ to $11\ldots1$ with the bottom-most wire being the least significant bit. Note that $e^{i\pi/4}$ is the square root of i, so that the $\pi/8$ gate is the square root of the phase gate, which itself is the square root of the Pauli-Z gate.

Hadamard —[H]— $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

Pauli-X —[X]— $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

Pauli-Y —[Y]— $\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$

Pauli-Z —[Z]— $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$

Phase —[S]— $\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$

$\pi/8$ —[T]— $\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$

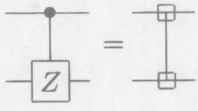
controlled-NOT

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

swap

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

controlled-Z

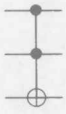


$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

controlled-phase

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & i \end{bmatrix}$$

Toffoli

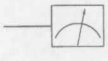


$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Fredkin (controlled-swap)

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

measurement



Projection onto $|0\rangle$ and $|1\rangle$

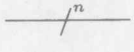
qubit

wire carrying a single qubit (time goes left to right)

classical bit

wire carrying a single classical bit

n qubits



wire carrying n qubits

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