

CONTENTS IN DETAIL

ACKNOWLEDGMENTS	xvii
------------------------	-------------

INTRODUCTION	xix
---------------------	------------

What Is Quantum Computing?	xix
Why Should You Read This Book?	xx
Who This Book Is For	xxi
What You'll Learn	xxi
How We'll Do It	xxi
Using Metaphors	xxii
Using Math	xxiv
Reading Math	xxvi
Proving Things	xxvii
Is Quantum Weird?	xxvii
What You'll Need	xxviii
Who Wrote This Book?	xxix
Overview	xxix
Part I: States, Operators, and Systems	xxix
Part II: Quantum Algorithms	xxx

PART I STATES, OPERATORS, AND SYSTEMS

1	
A CURIOUS DECK OF CARDS	5

Electronic Playing Cards	6
States	7
Superposition	9
Initialization	10
Measurement	11
Operating on Cards	12
Amplitudes and Probabilities	16
Interference	18
Entanglement	19
Entangled Cards	19
Entanglement in Action	21
Summary	24

2	QUANTUM STATES	27
Getting Started		27
Postulate 1		28
Numbers		28
Sets and Lists		29
Types of Numbers		30
Complex Numbers		32
Working with i		33
Visualization		34
Conjugation		37
Working with Complex Numbers		41
List Structure		48
Vectors		49
Linearity		51
Bases		54
The Dot Product		56
Using the Dot Product		61
Projection		62
Change of Basis		65
The Inner Product		66
Defining the Inner Product		67
Finding a Complex Vector's Magnitude		68
Choosing Which Term to Conjugate		69
Projection with the Inner Product		69
Bracket Notation		71
Looking at the Bracket		74
Conjugating the Bracket		78
Qubits		79
Summary		81

3	OPERATORS	83
Postulate 2		84
Linear Operators		84
Operators I , X , and H		88
The Identity Operator I		88
The NOT Operator X		89
The Hadamard Operator H		90
A Few Matrix Operations		91
Unitary Operators		94
Naming a Matrix Element		97
Revisiting I , X , and H		97
Putting It All Together		98
Summary		98

4		
WORKING WITH QUBITS		99
Hello, World!		99
Introducing Hello, XWorld!		100
Superpositions		101
Properties of H		103
Qugates and Basis States		104
Initializing with H		104
Interference		105
Summary		107

5		
SYSTEMS		109
Postulate 3		110
Combining Quantum States		110
The Tensor Product		111
Product States		115
Exploring Product States		117
More Qubits		122
Quantum Algorithm Diagrams		124
Systems of Qugates		127
Horizontal Systems of Qugates		127
Vertical Systems of Qugates		128
Horizontal and Vertical Rules		130
A Circuit Analysis		131
Analysis by Algebra		132
Analysis by Matrix Elements		132
Analysis by Direction		133
The No-Cloning Theorem		138
The CX Qugate		141
CX as a Switch		142
CX as a Copier		146
Entanglement		146
Entangled Pairs		147
Other Controlled Qugates		151
Other Multi-Qubit Qugates		152
Single-Qubit Qugates		154
Summary		156

6		
MEASUREMENT		157
The Main Ideas of Measurement		158
Measuring Qubits		160
Postulate 4		161
Meters		161

Experiments	162
Measuring Hello, World!	162
Measuring $X 0\rangle$	164
Measuring $H 0\rangle$	164
Measuring $HH 0\rangle$	166
Measuring an Unequal Superposition	167
Amplitudes from Projection	171
The Outer Product	172
Back to Measurement	177
Measuring Multiple Qubits	179
Measuring Some Qubits	182
Computing Probabilities	185
Returning to Measurement	187
Partial Measurement	189
Measurement and Entanglement	190
Introducing Bell States	190
Measuring Bell States	193
Phase	197
Global Phase	197
Relative Phase and Interference	199
Summary	201

PART II QUANTUM ALGORITHMS

7	
TELEPORTATION	207
The Teleportation Thought Experiment	209
The Teleportation State $ \tau\rangle$	210
The Teleportation Process	212
Building $ \tau\rangle$	212
Alice Measures Her Qubits	218
Alice Tells Bob the Measurements	219
Bob Recovers $ \sigma\rangle$	219
Drawing the Teleportation Protocol	221
Probabilistic Teleportation	221
Summary	225

8	
DEUTSCH'S ALGORITHM	227
Deutsch's Problem	228
Oracles	229
Quantum Oracles	232
Promise Oracles	234

Quantum Parallelism	234
The Three Steps of Deutsch’s Algorithm	238
Step 1: Initialization	239
Step 2: Querying the Oracle	240
Step 3: Postprocessing and Measurement	242
Phase Kickback	243
Analyzing Deutsch’s Algorithm with Phase Kickback	244
Deutsch’s Algorithm Revisited	245
CX Terminology	247
Return to Quantum Parallelism	247
Revisiting Phase Kickback	248
Summary	250

9

DEUTSCH-JOZSA’S ALGORITHM 251

Introducing Deutsch–Jozsa	252
The Three Steps of Deutsch–Jozsa’s Algorithm	255
Step 1: Initialization	255
Step 2: Querying the Oracle	257
Step 3: Postprocessing and Measurement	258
Results in Constant and Balanced Cases	264
A Constant Function	264
A Balanced Function	265
Actual Results of Deutsch–Jozsa’s Algorithm	266
Why Does the Math Work So Well?	266
Summary	267

10

BERNSTEIN–VAZIRANI’S ALGORITHM 269

The Classical Solution	270
The Bernstein–Vazirani Circuit	270
Circuit Analysis After Deutsch–Jozsa	271
Running the Algorithm	273
Simplifying with a Quantum Identity	274
Summary	275

11

SIMON’S ALGORITHM 277

Exponential Growth	278
Simon’s Oracle	279
The Classical Solution	283
The Quantum Part of the Algorithm	285
Rewriting x and Measuring	287
Combining the Quantum Outputs	289

An Example of Simon’s Algorithm	291
The Balancing Act	293
Summary	294

12
GROVER’S ALGORITHM **295**

An Overview of Grover’s Algorithm	297
Reflections	298
The Stages of Grover’s Oracle	300
G_1 : Marking	301
G_2 : Diffusion	305
Iterating the Grover Oracle	308
An Example of Grover’s Algorithm	310
Observations and Discussion	313
Summary	314

13
SHOR’S ALGORITHM **315**

Primes and Encryption	316
Shor’s Algorithm	318
Period Finding	319
Analyzing the Circuit	322
Applying the <i>QFT</i>	324
Finding the Probability of $ k\rangle$	326
Connecting to Prime Factoring	330
An Example of Shor’s Algorithm	331
Discussion	333
Summary	334

14
NEXT STEPS **337**

Further Ideas	338
Superdense Coding	338
POVM and the Density Matrix	339
Quantum Encryption	340
Quantum Error Correction	341
Other Diagrams	341
Quantum Advantage	342
Further Reading	343
Quantum Mechanics Books	343
Quantum Computing Books	343
Quantum Computing Lecture Notes	343
Quantum Computing Online	343

Quantum Computing Resources	344
Simulators	344
Other Software	344
Real Hardware	344
Drawing Circuits	345
Getting Help	345
The Philosophy of Quantum Mechanics	346
Applications	348
Maze Solving	348
Ray Tracing	349
Games	350
Other Applications	350
Wrapping Up	350

APPENDIX: NOTATION **351**

BIBLIOGRAPHY **359**

INDEX **377**