

Table of Contents

Preface.....	ix
1. Introduction.....	1
Required Background	1
What Is a QPU?	2
A Hands-on Approach	3
A QCEngine Primer	4
Native QPU Instructions	6
Simulator Limitations	8
Hardware Limitations	9
QPU Versus GPU: Some Common Characteristics	9
<hr/>	
Part I. Programming for a QPU.....	13
2. One Qubit.....	13
A Quick Look at a Physical Qubit	15
Introducing Circle Notation	18
Circle Size	18
Circle Rotation	19
The First Few QPU Operations	21
QPU Instruction: NOT	21
QPU Instruction: HAD	22
QPU Instruction: READ	23
QPU Instruction: WRITE	23
Hands-on: A Perfectly Random Bit	24
QPU Instruction: PHASE(θ)	28
QPU Instructions: ROTX(θ) and ROTY(θ)	29

COPY: The Missing Operation	29
Combining QPU Operations	30
QPU Instruction: ROOT-of-NOT	30
Hands-on: Quantum Spy Hunter	32
Conclusion	36
3. Multiple Qubits.....	37
Circle Notation for Multi-Qubit Registers	37
Drawing a Multi-Qubit Register	40
Single-Qubit Operations in Multi-Qubit Registers	41
Reading a Qubit in a Multi-Qubit Register	43
Visualizing Larger Numbers of Qubits	44
QPU Instruction: CNOT	45
Hands-on: Using Bell Pairs for Shared Randomness	49
QPU Instructions: CPHASE and CZ	50
QPU Trick: Phase Kickback	51
QPU Instruction: CCNOT (Toffoli)	53
QPU Instructions: SWAP and CSWAP	54
The Swap Test	55
Constructing Any Conditional Operation	58
Hands-on: Remote-Controlled Randomness	61
Conclusion	65
4. Quantum Teleportation.....	67
Hands-on: Let's Teleport Something	67
Program Walkthrough	73
Step 1: Create an Entangled Pair	74
Step 2: Prepare the Payload	74
Step 3.1: Link the Payload to the Entangled Pair	75
Step 3.2: Put the Payload into a Superposition	76
Step 3.3: READ Both of Alice's Qubits	76
Step 4: Receive and Transform	77
Step 5: Verify the Result	78
Interpreting the Results	79
How Is Teleportation Actually Used?	80
Fun with Famous Teleporter Accidents	81
<hr/>	
Part II. QPU Primitives	
5. Quantum Arithmetic and Logic.....	85
Strangely Different	85

Arithmetic on a QPU	87
Hands-on: Building Increment and Decrement Operators	88
Adding Two Quantum Integers	91
Negative Integers	92
Hands-on: More Complicated Math	94
Getting Really Quantum	95
Quantum-Conditional Execution	95
Phase-Encoded Results	96
Reversibility and Scratch Qubits	98
Uncomputing	100
Mapping Boolean Logic to QPU Operations	103
Basic Quantum Logic	103
Conclusion	106
6. Amplitude Amplification.....	107
Hands-on: Converting Between Phase and Magnitude	107
The Amplitude Amplification Iteration	110
More Iterations?	111
Multiple Flipped Entries	114
Using Amplitude Amplification	120
AA and QFT as Sum Estimation	120
Speeding Up Conventional Algorithms with AA	120
Inside the QPU	121
The Intuition	121
Conclusion	123
7. QFT: Quantum Fourier Transform.....	125
Hidden Patterns	125
The QFT, DFT, and FFT	127
Frequencies in a QPU Register	128
The DFT	132
Real and Complex DFT Inputs	134
DFT Everything	135
Using the QFT	140
The QFT Is Fast	140
Inside the QPU	146
The Intuition	148
Operation by Operation	149
Conclusion	153
8. Quantum Phase Estimation.....	155
Learning About QPU Operations	155

Eigenphases Teach Us Something Useful	156
What Phase Estimation Does	158
How to Use Phase Estimation	158
Inputs	159
Outputs	161
The Fine Print	162
Choosing the Size of the Output Register	162
Complexity	163
Conditional Operations	163
Phase Estimation in Practice	163
Inside the QPU	164
The Intuition	165
Operation by Operation	167
Conclusion	169

Part III. QPU Applications

9. Real Data	173
Noninteger Data	174
QRAM	175
Vector Encodings	179
Limitations of Amplitude Encoding	182
Amplitude Encoding and Circle Notation	184
Matrix Encodings	185
How Can a QPU Operation Represent a Matrix?	185
Quantum Simulation	186
10. Quantum Search	191
Phase Logic	192
Building Elementary Phase-Logic Operations	194
Building Complex Phase-Logic Statements	195
Solving Logic Puzzles	198
Of Kittens and Tigers	198
General Recipe for Solving Boolean Satisfiability Problems	202
Hands-on: A Satisfiable 3-SAT Problem	203
Hands-on: An Unsatisfiable 3-SAT Problem	206
Speeding Up Conventional Algorithms	208
11. Quantum Supersampling	211
What Can a QPU Do for Computer Graphics?	211
Conventional Supersampling	212

Hands-on: Computing Phase-Encoded Images	214
A QPU Pixel Shader	215
Using PHASE to Draw	216
Drawing Curves	218
Sampling Phase-Encoded Images	220
A More Interesting Image	223
Supersampling	223
QSS Versus Conventional Monte Carlo Sampling	227
How QSS Works	227
Adding Color	232
Conclusion	233
12. Shor's Factoring Algorithm.....	235
Hands-on: Using Shor on a QPU	236
What Shor's Algorithm Does	237
Do We Need a QPU at All?	238
The Quantum Approach	240
Step by Step: Factoring the Number 15	242
Step 1: Initialize QPU Registers	243
Step 2: Expand into Quantum Superposition	244
Step 3: Conditional Multiply-by-2	246
Step 4: Conditional Multiply-by-4	248
Step 5: Quantum Fourier Transform	251
Step 6: Read the Quantum Result	254
Step 7: Digital Logic	255
Step 8: Check the Result	257
The Fine Print	257
Computing the Modulus	257
Time Versus Space	259
Coprimes Other Than 2	259
13. Quantum Machine Learning.....	261
Solving Systems of Linear Equations	262
Describing and Solving Systems of Linear Equations	263
Solving Linear Equations with a QPU	264
Quantum Principle Component Analysis	274
Conventional Principal Component Analysis	274
PCA with a QPU	276
Quantum Support Vector Machines	280
Conventional Support Vector Machines	280
SVM with a QPU	284
Other Machine Learning Applications	289

Part IV. Outlook

14. Staying on Top: A Guide to the Literature.....	293
From Circle Notation to Complex Vectors	293
Some Subtleties and Notes on Terminology	295
Measurement Basis	297
Gate Decompositions and Compilation	298
Gate Teleportation	300
QPU Hall of Fame	300
The Race: Quantum Versus Conventional Computers	301
A Note on Oracle-Based Algorithms	302
Deutsch-Jozsa	302
Bernstein-Vazirani	303
Simon	303
Quantum Programming Languages	303
The Promise of Quantum Simulation	305
Error Correction and NISQ Devices	305
Where Next?	306
Books	306
Lecture Notes	306
Online Resources	307
Index.....	309