Quantum Machine Learning with Python

Using Cirq from Google Research and IBM Qiskit

—

Santanu Pattanayak

Apress®

สำนักหอสมุด มหาวิทยาลัยเชียงใหม่

q65
2201

b16580205
0125846B7
i2558445

Quantum Machine Learning with Python

Using Cirq from Google Research and IBM Qiskit

สำนักหอสมุดมหาวิทยาลัยเชียงใหม่
CHIANG MAI UNIVERSITY LIBRARY

Santanu Pattanayak

Apress®

Table of Contents

About the Author xi

About the Technical Reviewer xiii

Acknowledgments xv

Introduction xvii

Chapter 1: Introduction to Quantum Computing 1

Quantum Bit 2

Realization of a Quantum Bit 4

Bloch Sphere Representation of a Qubit 5

Stern–Gerlach Experiment 10

Multiple Qubits 14

Bell State 14

Multiple-Qubit State 15

Dirac Notation 16

Ket Vector 17

Bra Vector 17

Inner Product 17

Magnitude of a Vector 18

Outer Product 19

Tensor Product 20

Single-Qubit Gates 21

Quantum NOT Gate 21

Hadamard Gate 24

Quantum *Z* Gate 25

Multiple-Qubit Gates 25
CNOT Gate 25
Controlled-U Gate 28
Copying a Qubit: No Cloning Theorem 29
Measurements in Different Basis 31
Bell States with Quantum Gates 32
Quantum Teleportation 35
Quantum Parallelism Algorithms 38
Quantum Interference 42
Summary 43

Chapter 2: Mathematical Foundations and Postulates of Quantum Computing 45

Topics from Linear Algebra 45
Linear Independence of Vectors 46
Basis Vectors 47
Orthonormal Basis 48
Linear Operators 48
Interpretation of a Linear Operator as a Matrix 49
Linear Operator in Terms of Outer Product 51
Pauli Operators and Their Outer Product Representation 52
Eigenvectors and Eigenvalues of a Linear Operator 53
Diagonal Representation of an Operator 54
Adjoint of an Operator 55
Self-Adjoint or Hermitian Operators 55
Normal Operators 56
Unitary Operators 56
Spectral Decomposition of Linear Operators 57
Trace of Linear Operators 58
Linear Operators on a Tensor Product of Vectors 59
Functions of Normal Operators 61
Commutator and Anti-commutator Operators 62

Postulates of Quantum Mechanics 63
Postulate 1: Quantum State 63
Postulate 2: Quantum Evolution 64
Postulate 3: Quantum Measurement 65
General Measurement Operators 66
Projective Measurement Operators 68
General Heisenberg Uncertainty Principle 70
POVM Operators 74
Density Operator 76
Hamiltonian Simulation and Trotterization 91
Summary 94

Chapter 3: Introduction to Quantum Algorithms 95

Cirq 96
Simulation in Cirq with a Hadamard Gate 96
Qiskit 100
Bell State Creation and Measurement 103
Quantum Teleportation 105
Quantum Random Number Generator 109
Deutsch–Jozsa Algorithm Implementation 113
Bernstein–Vajirani Algorithm 120
Bell's Inequality Test 126
Simon's Algorithm 133
Grover's Algorithm 139
Summary 149

Chapter 4: Quantum Fourier Transform and Related Algorithms 151

Fourier Series 152
Fourier Transform 154
Discrete Fourier Transform 155
Kronecker Delta Function 156

Motivating the Quantum Fourier Transform Using the Kronecker Delta Function 157
Quantum Fourier Transform 159
QFT Implementation in Cirq 165
Hadamard Transform as a Fourier Transform 170
Quantum Phase Estimation 171
Quantum Phase Estimation Illustration in Cirq 176
Error Analysis in the Quantum Phase Estimation 180
Shor's Period Finding Algorithm and Factoring 184
Modular Exponentiation Function 184
Motivating the Order Finding Problem as a Quantum Phase Estimation Problem 185
Continued Fractions Algorithm 190
Period Finding Implementation in Cirq 192
Implementing the Unitary Operator Through Quantum Circuits 200
Factoring Algorithm 204
Factoring Implementation in Cirq 206
Hidden Subgroup Problem 210
Definition of a Group 210
Abelian Group 212
Subgroups 212
Cosets 212
Normal Subgroup 214
Group Homomorphism 215
Kernel of Homomorphism 217
Hidden Subgroup Problem 218
Summary 220

Chapter 5: Quantum Machine Learning 221

HHL Algorithm 222
Initializing the Registers 224
Performing Quantum Phase Estimation 225
Inverting the Eigenvalues 225

Uncomputing the Work Registers 227
Measuring the Ancilla Qubit 227
HHL Algorithm Implementation Using Cirq 228
Quantum Linear Regression 238
Quantum Swap Test Subroutine 241
Initial State 242
Hadamard Gate on the Ancilla Qubit 242
Controlled Swap Operation 242
Hadamard Gate on the Control Qubit 242
Swap Test Implementation 243
Quantum Euclidean Distance Calculation 247
Creating the Initial States Without QRAM 249
Quantum Euclidean Distance Compute Routine Implementation 250
Quantum K-Means Clustering 255
Quantum K-Means Clustering Using Cosine Distance 256
Quantum Principal Component Analysis 261
Preprocessing and Transforming the Classical Data to Quantum States 262
The Mixed Density Matrix or the Covariance Matrix Creation 263
Density Matrix as a Hamiltonian 264
Quantum Phase Estimation for Spectral Decomposition of the Unitary Operator 264
Extracting the Principal Components 266
Quantum Support Vector Machines 267
Quantum Least Square SVM 273
SVM Implementation Using Qiskit 276
Summary 279

Chapter 6: Quantum Deep Learning 281

Hybrid Quantum-Classical Neural Networks 282
Backpropagation in the Quantum Layer 283
MNIST Classification Using Hybrid Quantum-Classical Neural Network 284
Gradient in the Quantum Layer 285

Quantum Neural Network for Classification on Near-Term Processors 294
MNIST Classification Using TensorFlow Quantum 297
Summary 306

Chapter 7: Quantum Variational Optimization and Adiabatic Methods 307

Variational Quantum Eigensolver 308
Defining the Hamiltonian 310
Preparing the Ansatz State Based on the Expectation Optimization 312
Expectation Computation 313
Isling Model and Its Hamiltonian 314
Isling Model for a Quantum System 317
Implementation of the VQE Algorithm 319
Quantum Max-Cut Graph Clustering 324
Max-Cut Clustering Implementation Using VQE 327
Quantum Adiabatic Theorem 332
Proof of the Adiabatic Theorem 333
Quantum Approximate Optimization Algorithm 337
Evolving the Quantum System to the Objective Hamiltonian 337
Starting Hamiltonian for QAOA 341
Starting Hamiltonian and Initial Eigenstate 342
Implementation of QAOA 343
Quantum Random Walk 349
Quantum Random Walk Implementation 351
Summary 355

Index 357