Table of Contents

A Guide for the Reader 1

Qubits, Cbits, Decoherence, Quantum Measurement and Environment
A.J. Leggett 3
1 Lecture 1 – A Single Qubit: Basic Notions 3
2 Lecture 2 – Distinguishing Qubits from Cbits: Multi-qubit Systems and Quantum Computation 10
3 Lecture 3 – The Fundamental Theorem of Decoherence: "Isolated" Systems 16
4 Lecture 4 – Candidate Systems for Qubits: Preliminary Estimate of Decoherence Times 22
5 Lecture 5 – The Environment as a Bath of Oscillators: More Systematic Treatment of Decoherence 30
6 Lecture 6 – The Quantum Measurement Problem 37

Introduction to Quantum Computation
Artur Ekert 47
1 Physical Representation of Information 47
2 Qubits, Gates and Networks 48
3 Quantum Arithmetic and Function Evaluations 53
4 Algorithms and Their Complexity 56
5 From Interferometers to Computers 59
6 The First Quantum Algorithms 63
7 Quantum Search 65
8 Optimal Phase Estimation 67
9 Periodicity and Quantum Factoring 69
10 Cryptography 71

Environment-Induced Decoherence and the Transition from Quantum to Classical
Juan Pablo Paz, Wojciech Hubert Zurek 77
1 Introduction and Overview 77
2 Quantum Measurements 80
2.1 Bit-by-Bit Measurement and Quantum Entanglement 82

2.2 Interactions and the Information Transfer in Quantum Measurements . . . 85
2.3 Monitoring by the Environment and Decoherence . . . 87
2.4 One-Bit Environment for a Bit-by-Bit Measurement . . . 88
2.5 Decoherence of a Single (Qu)Bit . . . 90
2.6 Decoherence, Einselection, and Controlled Shifts . . . 94
3 Dynamics of Quantum Open Systems: Master Equations . . . 96
3.1 Master Equation: Perturbative Evaluation . . . 97
3.2 Example 1: Perturbative Master Equation in Quantum Brownian Motion . . . 100
3.3 Example 2: Perturbative Master Equation for a Two-Level System Coupled to a Bosonic Heat Bath . . . 102
3.4 Example 3: Perturbative Master Equation for a Particle Interacting with a Quantum Field . . . 105
3.5 Exact Master Equation for Quantum Brownian Motion . . . 106
4 Einselection in Quantum Brownian Motion . . . 112
4.1 Decoherence of a Superposition of Two Coherent States . . . 112
4.2 Predictability Sieve and Preferred States for QBM . . . 115
4.3 Energy Eigenstates Can Also Be Selected by the Environment! 117
5 Deconstructing Decoherence: Landscape Beyond the Standard Models . . . 118
5.1 Saturation of the Decoherence Rate at Large Distances . . . 119
5.2 Decoherence at Zero Temperature . . . 120
5.3 Preexisting Correlations Between the System and the Environment . . . 122
6 Decoherence and Chaos . . . 125
6.1 Quantum Predictability Horizon: How the Correspondence Is Lost . . . 125
6.2 Exponential Instability vs. Decoherence . . . 127
6.3 The Arrow of Time: A Price of Classicality? . . . 129
6.4 Decoherence, Einselection, and the Entropy Production . . . 132
7 How to Fight Against Decoherence: Quantum Error Correcting Codes . . . 133
7.1 How to Protect a Classical Bit . . . 134
7.2 How to Protect a Quantum Bit . . . 134
7.3 Stabilizer Quantum Error-Correcting Codes . . . 140
8 Discussion . . . 143

Quantum Information Science Using Photons
Dik Bouwmeester, John C. Howell, Antia Lamas- Linares . . . 149
1 Introduction . . . 149
1.1 A Humble Point of View . . . 149
1.2 Quantum Mystery . . . 150
1.3 Maxwell's Demon . . . 151
1.4 Shannon Entropy . . . 154

1.5 Von Neumann Entropy . . . 156
2 Einstein–Podolsky–Rosen Paradox and Bell's Inequalities . . . 157
3 Producing Entangled Particles . . . 159
3.1 Introduction . . . 159
3.2 Parametric Down-Conversion . . . 159
3.3 Franson's Proposal . . . 160
3.4 Polarization Entanglement . . . 161
4 The Beam Splitter Action on a Two-Photon State . . . 163
4.1 Beamsplitter Transformation . . . 163
4.2 Bell-State Analyzer . . . 164
5 No-Cloning Theorem . . . 165
6 Quantum Cryptography . . . 167
7 Quantum Dense Coding . . . 169
7.1 Theoretical Scheme . . . 169
7.2 Experimental Dense Coding with Qubits . . . 170
8 Quantum Teleportation . . . 171
8.1 Theoretical Scheme . . . 171
8.2 Experimental Quantum Teleportation of Qubits . . . 173
8.3 Teleportation of Entanglement . . . 174
8.4 A Two-Particle Scheme for Quantum Teleportation . . . 174
9 Teleportation of Continuous Quantum Variables . . . 177
9.1 Theoretical Scheme . . . 177
9.2 Quantum Optical Implementation . . . 178
10 Quantum Error Detection and Correction . . . 181
10.1 Introduction . . . 181
10.2 Quantum Error Detection . . . 181
10.3 Avoiding Controlled-NOT Operations . . . 183
10.4 Post-selection . . . 184
11 Stimulated Entanglement . . . 185
11.1 Theory . . . 185
12 Bohm-Type Spin-s Entanglements . . . 193

Quantum Information: Entanglement, Purification, Error Correction, and Quantum Optical Implementations
Juan Ignacio Cirac . . . 199
1 Introduction . . . 199
2 Quantum Computers: Quantum Optical Implementations . . . 200
2.1 Introduction . . . 200
2.2 How to Construct a Quantum Computer . . . 201
2.3 Physical Implementations for Quantum Computation . . . 202
2.4 Quantum Optical Systems for Quantum Computation . . . 202
2.5 Quantum Computation with Trapped Ions . . . 203
3 Decoherence and Error Correction . . . 205
3.1 Introduction . . . 205

3.2 Decoherence . . . 205
3.3 Error Correction . . . 206
3.4 Error Correction and Decoherence . . . 209
4 Entanglement of Pure States . . . 210
4.1 Introduction . . . 210
4.2 2-Partite Entanglement: Definition . . . 211
4.3 2-Partite Entanglement: Qualifying and Quantifying . . . 212
4.4 Multipartite Entanglement . . . 214
5 Entanglement of Mixed States . . . 215
5.1 Introduction . . . 215
5.2 2-Partite Entanglement: Definition . . . 217
5.3 2-Partite Entanglement: Entanglement Witnesses . . . 219
5.4 2-Partite Entanglement: Positive Maps . . . 220
5.5 2-Partite Entanglement: Entangled States with Positive Partial Transposition . . . 224
5.6 Multipartite Entanglement . . . 224
6 Entanglement Distillation . . . 226
6.1 Introduction . . . 226
6.2 Generalized Measurements . . . 227
6.3 Distillation of Pure States . . . 229
6.4 Distillation of Mixed States . . . 231
6.5 Multipartite Distillation . . . 236

Spintronics, Quantum Computing, and Quantum Communication in Quantum Dots
Guido Burkard, Hans-Andreas Engel, Daniel Loss . . . 241
1 Introduction . . . 241
1.1 Quantum Computing . . . 242
1.2 Quantum Communication . . . 242
1.3 General Remarks on Quantum Dots . . . 243
2 Phase Coherence . . . 243
3 Pulsed Switching and Adiabaticity . . . 245
4 Initialization of a Quantum Register . . . 247
5 Two-Qubit Operations in Coupled Quantum Dots . . . 247
5.1 Laterally Coupled Dots . . . 248
5.2 Vertically Coupled Dots . . . 250
5.3 Singlet–Triplet Entangling Gate . . . 253
6 Single-Spin Operations . . . 253
7 Single-Spin Measurement . . . 254
7.1 Spin Measurements Through Spontaneous Magnetization . . . 254
7.2 Spin Measurements via the Charge . . . 254
7.3 Quantum Dot as Spin Filter and Read-Out/Memory Device . 255
7.4 Optical Measurements . . . 257
8 Quantum Communication with Entangled Electrons . . . 257
8.1 Adding Entangled Electrons to the Fermi Sea . . . 257
8.2 Shot Noise of Entangled Electrons . . . 258

8.3 Spin-Dependent Current
Through a Double Dot–Probing Entanglement 260
8.4 Double Dot with Superconducting Leads 262