

CONTENTS

<i>Preface</i>	xv
<i>Acknowledgements</i>	xix
Part One Methods and Concepts	1
1 Introduction to Nonequilibrium Systems and Transport Phenomena	3
1.1. Introduction	3
1.2. Classification of Nonequilibrium Phenomena	4
1.3. Hierarchy of Description at Different Levels	6
1.4. Individual-Based Models	7
1.4.1. Newton's Equations, Hamilton's Equations, and Individual Trajectories	7
1.4.2. Langevin Equation	9
1.5. Population-Based Models	10
1.5.1. Master Equation and Irreversibility	10
1.5.2. Fokker–Planck Equation	13
1.6. Fluid Flow: Theoretical Descriptions at Different Levels	14
1.6.1. Liouville Equation and Flow in Phase Space	15
1.6.2. From Liouville Equation to Boltzmann Equation: BBGKY Hierarchy	16
1.6.3. From Kinetic Theory to Navier–Stokes Equation	17
1.7. Back to Discrete Models: Mimicking Hydrodynamics with Fictitious Particles	19
1.7.1. Driven-Diffusive Lattice Gas Models	20
1.8. Phase Transitions, Critical Dynamics, and Kinetics of Phase Ordering	22
1.8.1. Critical Dynamics: Role of Symmetry and Conservation Laws	22
1.8.2. Kinetics of Phase Ordering: Metastable and Unstable Initial States	23
1.8.3. Phase Transitions in Driven Systems	24
2 Methods for the Description of Stochastic Models	27
2.1. Quantum Formalism	28
2.1.1. Master Equation and Stochastic Hamiltonian	28
2.1.2. Spectrum and Expectation Values	31
2.1.3. Discrete Time Dynamics	33
2.2. Mean-Field and Cluster Methods	37
2.2.1. Mean-Field Approximations	37
2.3. Bethe Ansatz	41
2.4. Matrix-Product Ansatz	43
2.4.1. MPA in Quantum Formalism	45
2.4.2. MPA for Discrete Time Updates	48
2.4.3. Dynamical MPA	51
2.4.4. Relation with Bethe Ansatz	52

2.5. Other Methods	52
2.5.1. Hydrodynamic Limit	52
2.5.2. Field-Theoretic Methods and Renormalization Groups	53
2.5.3. Similarity Transformations	54
2.5.4. Ultradiscrete Method	54
2.6. Numerical Methods	57
2.6.1. Computer Simulation (MC Methods)	58
2.6.2. Exact Diagonalization	60
2.6.3. Density-Matrix Renormalization Group	61
2.6.4. Transfer-Matrix DMRG	63
2.7. Appendices	66
2.7.1. Some Mathematics	66
2.7.2. MPA and Optimum Ground States for Quantum Spin Chains	66
2.7.3. Krebs–Sandow Theorem and Extensions	68
3 Particle-Hopping Models of Transport Far from Equilibrium	71
3.1. Elements of Random Walk Theory	72
3.2. Asymmetric Simple Exclusion Process	74
3.3. Zero-Range Process and Exact Results	75
3.3.1. Exact Solution	76
3.3.2. Bethe Ansatz Solution	79
3.4. Extensions and Generalizations	81
3.4.1. Parallel Dynamics	81
3.4.2. Other Lattice Structures	82
3.4.3. ZRP with Disorder	83
3.4.4. ZRP with Fluctuating Particle Number	83
3.4.5. Generalizations	86
3.4.6. Dynamical Urn Models	86
3.4.7. Misanthrope Process	87
3.4.8. Relation of ZRP to Other Models and Some Applications	88
3.5. Physics of the ZRP	90
3.5.1. Condensation Transition	90
3.5.2. Dynamics and Coarsening	94
3.5.3. Criterion for Phase Separation	95
3.6. Particle-Hopping Models with Factorized Stationary States	97
3.6.1. Models with Pair-Factorized Steady States	100
3.7. Generalized Mass Transport Models	102
3.7.1. Models with Continuous States	102
3.7.2. Asymmetric Random Average Process	103
3.7.3. Chipping Model	105
3.8. Appendix	106
3.8.1. Derivation of the Factorization Criterion	106

4	Asymmetric Simple Exclusion Process – Exact Results	109
4.1.	ASEP with Periodic Boundary Conditions	111
4.1.1.	Random-Sequential Dynamics	111
4.1.2.	Bethe Ansatz for Translational Invariant Systems	113
4.1.3.	Mean-Field Theories for Parallel Dynamics	116
4.1.4.	Mapping to ZRP	123
4.1.5.	Paradisical Mean-Field Theory	123
4.1.6.	Combinatorial Solution for Parallel Dynamics	124
4.1.7.	Ordered-Sequential and Sublattice-Parallel Updates	126
4.1.8.	Shuffled Dynamics	128
4.2.	ASEP with Open Boundary Conditions	131
4.2.1.	Mean-Field Theory	132
4.2.2.	Recursion Relations	134
4.2.3.	Matrix-Product Ansatz	135
4.2.4.	Exact Phase Diagram	136
4.2.5.	Phase Transitions	141
4.2.6.	Relation with Combinatorics	142
4.2.7.	Bethe Ansatz	142
4.2.8.	Dynamical MPA	143
4.2.9.	Hydrodynamic Limit	143
4.3.	Partially Asymmetric Version	145
4.3.1.	MPA Solution	146
4.3.2.	Bethe-Ansatz Solution	148
4.3.3.	Phase Diagram of the PASEP	148
4.4.	Extension of the ASEP to Other Update Types	151
4.4.1.	Ordered-Sequential Updates	151
4.4.2.	Sublattice-Parallel Update	154
4.4.3.	Parallel Update	154
4.5.	Boundary-Induced Phase Transitions	158
4.5.1.	Domain Wall Picture	158
4.5.2.	Extremal Principle and Steady-State Selection	161
4.5.3.	More on Shock Dynamics	161
4.5.4.	Fluctuations and Large Deviation Functions	162
4.6.	Extensions of ASEP	163
4.6.1.	Quenched Disorder	164
4.6.2.	Disorder in Open Systems	173
4.6.3.	Langmuir Kinetics	174
4.6.4.	Extended Particles	177
4.6.5.	Other Boundary Conditions	177
4.6.6.	Long-Range Hopping	179
4.6.7.	ASEP Beyond One Dimension	180
4.7.	Multispecies Models	181
4.7.1.	Models with Second-Class Particles	181

4.7.2.	ABC Model	183
4.7.3.	AHR Model	184
4.8.	Other Related Models	185
4.8.1.	Staggered Hopping Rates	185
4.8.2.	Two-Parameter Model	186
4.8.3.	Restricted ASEP	188
4.8.4.	KLS Model	190
4.8.5.	Asymmetric Avalanche Process	191
4.8.6.	Higher Velocities	193
4.8.7.	Reconstituting Dimers	194
4.9.	Appendices	195
4.9.1.	Mapping of ASEP to Surface Growth Model	195
4.9.2.	Mapping of the ASEP to an Ising Model	196
4.9.3.	Solution of the Mean-Field Recursion Relations for the ASEP	197
4.9.4.	Results Obtained from Normal-Ordering of Matrices	199
4.9.5.	Dimension of Matrices in the MPA for the ASEP	200
4.9.6.	Representations of the Matrix Algebra of the ASEP	201
4.9.7.	Mean-Field Approximation of the DTASEP	205
 Part Two Applications		 207
5	Modeling of Traffic and Transport Processes	209
5.1.	Introduction	209
5.1.1.	Fundamental and Practical Questions	210
5.1.2.	Some Fundamental Questions	211
5.2.	Classification of Models	212
5.2.1.	Model Characteristics	212
5.2.2.	Model Classes	214
6	Vehicular Traffic I: Empirical Facts	215
6.1.	Measurement Techniques, Detectors, and So Forth	215
6.2.	Observables and Data Analysis	216
6.3.	Formation and Characterization of Traffic Jams	221
6.3.1.	Jams Induced by Bottlenecks	222
6.3.2.	Spontaneous Traffic Jams	223
6.3.3.	Experiment on Spontaneous Jam Formation	224
6.4.	Fundamental Diagram	226
6.5.	Metastability and Hysteresis	228
6.6.	Phases of Traffic Flow	230
6.6.1.	Level of Service Classification	230
6.6.2.	Traffic Phases and Phase Transitions	231
6.6.3.	Gas-Liquid Analogy	234
6.7.	Ramps, Intersections, and Other Inhomogeneities	235
6.8.	Headway Distributions	236

6.9. Optimal-Velocity Function	238
6.10. Correlation Functions	239
6.11. Psychological Effects	240
7 Vehicular Traffic II: The Nagel–Schreckenberg Model	243
7.1. Definition of the Model	244
7.1.1. Update Rules	244
7.1.2. Relation with Other Models	247
7.2. Fundamental Diagram and Limiting Cases of the NaSch Model	248
7.2.1. Fundamental Diagram	248
7.2.2. NaSch Model in the Deterministic Limit $p = 0$	250
7.2.3. NaSch Model in the Deterministic Limit $p = 1$	251
7.2.4. NaSch Model with $v_{\max} = 1$	251
7.2.5. NaSch Model in the Limit $v_{\max} = \infty$	253
7.3. Analytical Theories for NaSch Model with $v_{\max} > 1$	255
7.3.1. SOMF Theory for the NaSch Model	255
7.3.2. Cluster-Approximations for the NaSch Model	256
7.3.3. pMF Theory of the NaSch Model	257
7.3.4. Car-Oriented Mean-Field Theory of the NaSch Model	259
7.4. Spatio-Temporal Organization of Vehicles	260
7.4.1. Microscopic Structure of the Stationary State	260
7.4.2. Spatial Correlations	261
7.4.3. Headway Distributions	262
7.4.4. Distributions of Jam Sizes and Gaps between Jams	263
7.4.5. Distribution of Lifetimes of Jams	265
7.4.6. Temporal Correlations and Relaxation Time	266
7.4.7. Structure Factor	267
7.4.8. Phase Transition	268
7.4.9. Boundary-Induced Phase Transitions	270
7.5. Appendices	272
7.5.1. Details of SOMF for NaSch	272
7.5.2. Details of PMF for NaSch	276
7.5.3. Details of COMF for NaSch	277
8 Vehicular Traffic III: Other CA Models	281
8.1. Slow-to-Start Rules, Metastability, and Hysteresis	282
8.1.1. General Remarks	282
8.1.2. The Velocity-Dependent-Randomization Model	283
8.1.3. Takayasu–Takayasu Slow-to-Start Rule	288
8.1.4. The BJH Model of Slow-to-Start Rule	289
8.1.5. Other Slow-to-Start Rules	289
8.1.6. Flow Optimization and Metastable States	290
8.2. Cruise-Control Limit	291
8.3. CA Models of Synchronized Traffic	294
8.3.1. Brake-Light or Comfortable Driving Model	295

8.3.2.	Kerner–Klenov–Wolf Model	299
8.3.3.	Mechanical Restrictions Model of Lee et al.	301
8.4.	Other CA Models	304
8.4.1.	Fukui–Ishibashi Model	304
8.4.2.	Velocity-Dependent Braking Model	305
8.4.3.	Time-Oriented CA Model	306
8.4.4.	Models with Anticipation	307
8.4.5.	Galilei-Invariant Model	309
8.4.6.	Car-Following CA	311
8.5.	CA from Ultradiscrete Method	313
8.5.1.	Generalizations of BCA	314
8.5.2.	Euler–Lagrange Transformation	315
8.5.3.	Traffic Models in Lagrange Form	316
8.6.	CA Models of Multilane Traffic	319
8.6.1.	Classification of Lane Changing Rules	319
8.6.2.	CA Models of Bidirectional Traffic	322
8.7.	Effects of Quenched Disorder	324
8.7.1.	Randomness in the Braking Probability	324
8.7.2.	Random v_{\max}	326
8.7.3.	Randomly Placed Bottlenecks	326
8.7.4.	Ramps	328
8.8.	Bus-Route Model	329
8.9.	Accidents	332
9	Vehicular Traffic IV: Non-CA Approaches	335
9.1.	Fluid Dynamical Theories	336
9.1.1.	Lighthill–Whitham–Richards Theory and Kinematic Waves	337
9.1.2.	Diffusion Term in LWR Theory and Its Effects	340
9.1.3.	Greenshields Model and Burgers Equation	341
9.2.	Second-Order Fluid Dynamical Theories	342
9.2.1.	Special Models	344
9.2.2.	Instabilities and Jam Formation	345
9.2.3.	Problems with Second-Order Models	348
9.2.4.	Aw–Rascle Model	348
9.2.5.	Fluid-Dynamical Models and Synchronized Traffic	349
9.2.6.	Fluid-Dynamical Theories of Traffic on Multilane Highways and in Cities	350
9.3.	Gas-Kinetic Models	351
9.3.1.	Prigogine Model	351
9.3.2.	Paveri-Fontana Model	353
9.3.3.	Derivation of Fluid-Dynamical Equations from Gas-Kinetic Equations	356
9.4.	Car-Following Models	357
9.4.1.	Follow-the-Leader Model	358
9.4.2.	Optimal Velocity Model and Its Extensions	360

9.4.3. Generalized Force Models	364
9.4.4. Intelligent Driver Model	366
9.4.5. Kerner–Klenov Model	368
9.4.6. Inertial Car-Following Model	369
9.5. Coupled-Map Models	371
9.5.1. Gipps Model	372
9.5.2. Krauss Model (SK Model)	373
9.5.3. Model of Yukawa and Kikuchi	375
9.5.4. Model of Nagel and Herrmann	376
9.6. Other Approaches	377
9.6.1. Probabilistic Traffic Flow Theory	377
9.6.2. Cell Transmission Model	379
9.6.3. Queueing Models	381
10 Transport on Networks	383
10.1. Networks and Transport	383
10.2. BML Model of City Traffic	384
10.2.1. Phase Transition	385
10.2.2. Generalizations and Extensions of the BML Model	386
10.2.3. More Realistic Description of Streets and Junctions	388
10.3. Chowdhury–Schadschneider Model	390
10.3.1. Crossroads with Signals	390
10.3.2. ChSch Model	390
10.3.3. Traffic Signal Optimization	395
10.4. Highway and City Networks	398
10.4.1. Online Simulation of Traffic Networks	398
10.4.2. Network Analysis	399
10.4.3. Braess Paradox	400
10.5. Computer Networks and Internet Traffic	402
11 Pedestrian Dynamics	407
11.1. Introduction	408
11.2. Empirical Observations and Collective Phenomena	409
11.2.1. Individual Properties	409
11.2.2. Observables	410
11.2.3. Fundamental Diagram	413
11.2.4. Flows at Bottlenecks	415
11.2.5. Collective Phenomena	418
11.3. Cellular Automata Models	423
11.3.1. Fukui–Ishibashi Model	424
11.3.2. Blue–Adler Model	428
11.3.3. Gipps–Marksjös Model	428
11.4. Floor Field CA	430
11.4.1. General Principle	430
11.4.2. Update Rules	432

11.4.3. Construction of the Static Floor Field	435
11.4.4. Conflicts and Friction	436
11.4.5. Other Generalizations and Interactions	437
11.4.6. Moving Beyond Nearest Neighbors: $\nu_{\max} > 1$	440
11.4.7. Collective Effects	441
11.4.8. Evacuation Simulations	444
11.5. Other Models	447
11.5.1. Fluid-Dynamic and Gas-Kinetic Models	447
11.5.2. Social-Force Models	449
11.5.3. Lattice Gas Models	454
11.5.4. Optimal Velocity Model	456
11.5.5. Active Walker Models	458
12 Traffic Phenomena In Biology	461
12.1. Introduction	461
12.1.1. Different Types of Traffic in Biology	462
12.2. TASEP for Hard Rods: Minimal Model of Transcription and Translation	462
12.2.1. TASEP for Hard Rods: Minimal Models of Traffic of Ribosomes and RNAPs	464
12.2.2. TASEP for Hard Rods with Internal States: Effects of Individual Mechano-Chemistry	466
12.3. TASEP for Particles with Langmuir Kinetics: Minimal Model of Kinesin Traffic	466
12.3.1. TASEP-Like Generic Models of Molecular Motor Traffic	467
12.3.2. Traffic of Interacting Particles with "Internal States" and Langmuir Kinetics: Effects of Individual Mechano-Chemistry of KIF1A	468
12.4. Traffic in Social Insect Colonies: Ant-Trails	472
12.4.1. Model of Single-Lane Unidirectional Ant-Traffic	473
12.4.2. Model of Single-Lane Bidirectional Ant-Traffic	478
12.4.3. Model of Two-Lane Bidirectional Ant-Traffic	483
12.4.4. Experimental Investigations of Ant-Traffic	485
12.4.5. Empirical Results for Fundamental Diagrams of Ant-Trails	486
References	489
Index	545