Contents

	Foreword	*page* xiii
	Preface	xv
	Acknowledgements	xix
Part I	Basics	1
1	**A brief introduction**	3
1.1	The road to unification	3
1.2	String theory as a unified theory of physics	6
1.3	String theory and its verification	8
2	**Special relativity and extra dimensions**	12
2.1	Units and parameters	12
2.2	Intervals and Lorentz transformations	14
2.3	Light-cone coordinates	20
2.4	Relativistic energy and momentum	24
2.5	Light-cone energy and momentum	26
2.6	Lorentz invariance with extra dimensions	28
2.7	Compact extra dimensions	28
2.8	Quantum mechanics and the square well	32
2.9	Square well with an extra dimension	34
	Problems	36
3	**Electromagnetism and gravitation in various dimensions**	40
3.1	Classical electrodynamics	40
3.2	Electromagnetism in three dimensions	41
3.3	Manifestly relativistic electrodynamics	42
3.4	An aside on spheres in higher dimensions	46
3.5	Electric fields in higher dimensions	49
3.6	Gravitation and Planck's length	52
3.7	Gravitational potentials	55
3.8	The Planck length in various dimensions	57
3.9	Gravitational constants and compactification	57
3.10	Large extra dimensions	60
	Problems	62

4 Nonrelativistic strings 65
4.1 Equations of motion for transverse oscillations 65
4.2 Boundary conditions and initial conditions 67
4.3 Frequencies of transverse oscillation 68
4.4 More general oscillating strings 69
4.5 A brief review of Lagrangian mechanics 70
4.6 The nonrelativistic string Lagrangian 72
Problems 76

5 The relativistic point particle 78
5.1 Action for a relativistic point particle 78
5.2 Reparameterization invariance 82
5.3 Equations of motion 83
5.4 Relativistic particle with electric charge 86
Problems 87

6 Relativistic strings 90
6.1 Area functional for spatial surfaces 90
6.2 Reparameterization invariance of the area 93
6.3 Area functional for spacetime surfaces 96
6.4 The Nambu–Goto string action 100
6.5 Equations of motion, boundary conditions, and D-branes 101
6.6 The static gauge 104
6.7 Tension and energy of a stretched string 106
6.8 Action in terms of transverse velocity 108
6.9 Motion of open string endpoints 111
Problems 113

7 String parameterization and classical motion 116
7.1 Choosing a σ parameterization 116
7.2 Physical interpretation of the string equation of motion 118
7.3 Wave equation and constraints 120
7.4 General motion of an open string 122
Problems 127

8 World-sheet currents 132
8.1 Electric charge conservation 132
8.2 Conserved charges from Lagrangian symmetries 133
8.3 Conserved currents on the world-sheet 137
8.4 The complete momentum current 139
8.5 Lorentz symmetry and associated currents 142
8.6 The slope parameter α' 144
Problems 146

9 Light-cone relativistic strings 149
9.1 A class of choices for τ 149
9.2 The associated σ parameterization 152

9.3 Constraints and wave equations 156
9.4 Wave equation and mode expansions 157
9.5 Light-cone solution of equations of motion 160
Problems 164

10 Light-cone fields and particles 166
10.1 Introduction 166
10.2 An action for scalar fields 167
10.3 Classical plane-wave solutions 169
10.4 Quantum scalar fields and particle states 172
10.5 Maxwell fields and photon states 177
10.6 Gravitational fields and graviton states 180
Problems 183

11 The relativistic quantum point particle 187
11.1 Light-cone point particle 187
11.2 Heisenberg and Schrödinger pictures 189
11.3 Quantization of the point particle 191
11.4 Quantum particle and scalar particles 195
11.5 Light-cone momentum generators 197
11.6 Light-cone Lorentz generators 200
Problems 203

12 Relativistic quantum open strings 206
12.1 Light-cone Hamiltonian and commutators 206
12.2 Commutation relations for oscillators 209
12.3 Strings as harmonic oscillators 215
12.4 Transverse Virasoro operators 219
12.5 Lorentz generators 229
12.6 Constructing the state space 231
12.7 Equations of motion 236
12.8 Tachyons and D-brane decay* 238
Problems 242

13 Relativistic quantum closed strings 247
13.1 Mode expansions and commutation relations 247
13.2 Closed string Virasoro operators 253
13.3 Closed string state space 256
13.4 String coupling and the dilaton 260
13.5 A brief look at superstring theories* 262
Problems 268

Part II Developments 273

14 D-branes and gauge fields 275
14.1 Dp-branes and boundary conditions 275
14.2 Quantizing open strings on Dp-branes 277

14.3 Open strings between parallel Dp-branes 282
14.4 Strings between parallel Dp- and Dq-branes 289
14.5 Intersecting D6-branes 295
Problems 301

15 String charge, electric charge, and particle physics 307
15.1 Fundamental string charge 307
15.2 Visualizing string charge 313
15.3 Strings ending on D-branes 315
15.4 D-brane charges 321
15.5 D-branes and the Standard Model gauge group 323
15.6 Open strings and the Standard Model fermions* 328
15.7 The Standard Model on intersecting D6-branes* 337
15.8 String theory and particle physics* 344
Problems 346

16 String thermodynamics and black holes 352
16.1 A review of statistical mechanics 352
16.2 Partitions and the quantum violin string 354
16.3 Hagedorn temperature 361
16.4 Relativistic particle partition function 363
16.5 Single string partition function 365
16.6 Black holes and entropy 368
16.7 Counting states of a black hole* 373
16.8 A string theory/gauge theory correspondence* 377
Problems 382

17 T-duality of closed strings 386
17.1 Duality symmetries and Hamiltonians 386
17.2 Winding closed strings 388
17.3 Left movers and right movers 391
17.4 Quantization and the double strike 393
17.5 Constraint and mass formula 395
17.6 State space of compactified closed strings 397
17.7 A striking spectrum coincidence 401
17.8 Duality as a full quantum symmetry 403
Problems 406

18 T-duality of open strings 410
18.1 T-duality and D-branes 410
18.2 $U(1)$ gauge transformations 414
18.3 Wilson lines on circles 416
18.4 Open strings and Wilson lines 420
Problems 423

19 Electromagnetic fields on D-branes 425
19.1 Maxwell fields coupling to open strings 425
19.2 D-branes with electric fields 428
19.3 D-branes with magnetic fields 432
Problems 439

20 Nonlinear and Born–Infeld electrodynamics 442
20.1 The framework of nonlinear electrodynamics 442
20.2 Born–Infeld electrodynamics 446
20.3 Born–Infeld theory and T-duality 451
Problems 454

21 Covariant string quantization 459
21.1 Introduction 459
21.2 Open string Virasoro operators 461
21.3 Selecting the quantum constraints 463
21.4 Lorentz covariant state space 468
21.5 Closed string Virasoro operators 471
21.6 The Polyakov string action 472
Problems 477

22 String interactions and Riemann surfaces 481
22.1 Introduction 481
22.2 Interactions and observables 482
22.3 String interactions and global world-sheets 485
22.4 World-sheets as Riemann surfaces 488
22.5 Schwarz–Christoffel map and three-string interaction 492
22.6 Moduli spaces of Riemann surfaces 498
22.7 Four open string interaction 506
22.8 Veneziano amplitude 510
Problems 515

23 Loop amplitudes in string theory 518
23.1 Loop diagrams and ultraviolet divergences 518
23.2 Annuli and one-loop open strings 519
23.3 Annuli and electrostatic capacitance 523
23.4 Nonplanar open string diagrams 529
23.5 Four closed string interactions 531
23.6 The moduli space of tori 534
Problems 543

References 547
Index 552