

# Contents

<i>Preface to the First Edition</i>	page xv
<i>Preface to the Second Edition</i>	xviii
<i>A note on the choice of metric</i>	xx
<i>Text website</i>	xxi
<b>Part 1 Effective field theory: the Standard Model, supersymmetry, unification</b>	1
<b>1 Before the Standard Model</b>	3
Suggested reading	7
<b>2 The Standard Model</b>	8
2.1 Yang–Mills theory	8
2.2 Realizations of symmetry in quantum field theory	10
2.3 The quantization of Yang–Mills theories	16
2.4 The particles and fields of the Standard Model: gauge bosons and fermions	20
2.5 The particles and fields of the Standard Model: Higgs scalars and the complete Standard Model	22
2.6 The gauge boson masses	23
2.7 Quark and lepton masses	24
2.8 The Higgs field and its couplings	25
Suggested reading	26
Exercises	26
<b>3 Phenomenology of the Standard Model</b>	27
3.1 The weak interactions	27
3.2 Discovery of the Higgs	29
3.3 The quark and lepton mass matrices	32
3.4 The strong interactions	34
3.5 The renormalization group	36
3.6 Calculating the beta function	39
3.7 The strong interactions and dimensional transmutation	43
3.8 Confinement and lattice gauge theory	44
3.9 Strong interaction processes at high momentum transfer	51
Suggested reading	61
Exercises	62

<b>4</b>	<b>The Standard Model as an effective field theory</b>	<b>63</b>
4.1	Integrating out massive fields	63
4.2	Lepton and baryon number violation; neutrino mass	67
4.3	Challenges for the Standard Model	71
4.4	The naturalness principle	74
4.5	Summary: successes and limitations of the Standard Model	75
	Suggested reading	75
<b>5</b>	<b>Anomalies, instantons and the strong CP problem</b>	<b>76</b>
5.1	The chiral anomaly	77
5.2	A two-dimensional detour	81
5.3	Real QCD	88
5.4	The strong CP problem	98
5.5	Possible solutions of the strong CP problem	100
	Suggested reading	104
	Exercises	104
<b>6</b>	<b>Grand unification</b>	<b>106</b>
6.1	Cancellation of anomalies	108
6.2	Renormalization of couplings	108
6.3	Breaking to $SU(3) \times SU(2) \times U(1)$	109
6.4	$SU(2) \times U(1)$ breaking	110
6.5	Charge quantization and magnetic monopoles	111
6.6	Proton decay	112
6.7	Other groups	112
	Suggested reading	114
	Exercises	115
<b>7</b>	<b>Magnetic monopoles and solitons</b>	<b>116</b>
7.1	Solitons in $1 + 1$ dimensions	117
7.2	Solitons in $2 + 1$ dimensions: strings or vortices	118
7.3	Magnetic monopoles	119
7.4	The BPS limit	120
7.5	Collective coordinates for the monopole solution	122
7.6	The Witten effect: the electric charge in the presence of $\theta$	123
7.7	Electric–magnetic duality	124
	Suggested reading	125
	Exercises	125
<b>8</b>	<b>Technicolor: a first attempt to explain hierarchies</b>	<b>126</b>
8.1	QCD in a world without Higgs fields	127
8.2	Fermion masses: extended technicolor	128
8.3	The Higgs discovery and precision electroweak measurements	130
8.4	The Higgs as a Goldstone particle	131

Suggested reading	131
Exercises	132
<b>Part 2 Supersymmetry</b>	<b>133</b>
<b>9 Supersymmetry</b>	<b>135</b>
9.1 The supersymmetry algebra and its representations	136
9.2 Superspace	136
9.3 $N = 1$ Lagrangians	140
9.4 The supersymmetry currents	142
9.5 The ground state energy in globally supersymmetric theories	143
9.6 Some simple models	144
9.7 Non-renormalization theorems	146
9.8 Local supersymmetry: supergravity	148
Suggested reading	149
Exercises	150
<b>10 A first look at supersymmetry breaking</b>	<b>151</b>
10.1 Spontaneous supersymmetry breaking	151
10.2 The goldstino theorem	153
10.3 Loop corrections and the vacuum degeneracy	154
10.4 Explicit soft supersymmetry breaking	155
10.5 Supersymmetry breaking in supergravity models	157
Suggested reading	159
Exercises	159
<b>11 The Minimal Supersymmetric Standard Model</b>	<b>160</b>
11.1 Soft supersymmetry breaking in the MSSM	162
11.2 $SU(2) \times U(1)$ breaking	166
11.3 Embedding the MSSM in supergravity	167
11.4 Radiative corrections to the Higgs mass limit	168
11.5 Fine tuning of the Higgs mass	170
11.6 Reducing the tuning: the NMSSM	170
11.7 Constraints on low-energy supersymmetry: direct searches and rare processes	171
Suggested reading	176
Exercises	176
<b>12 Supersymmetric grand unification</b>	<b>177</b>
12.1 A supersymmetric grand unified model	177
12.2 Coupling constant unification	178
12.3 Dimension-five operators and proton decay	179
Suggested reading	181
Exercises	181

<b>13 Supersymmetric dynamics</b>	182
13.1 Criteria for supersymmetry breaking: the Witten index	182
13.2 Gaugino condensation in pure gauge theories	184
13.3 Supersymmetric QCD	185
13.4 $N_f < N$ : a non-perturbative superpotential	188
13.5 The superpotential in the case $N_f < N - 1$	190
13.6 $N_f = N - 1$ : the instanton-generated superpotential	191
Suggested reading	196
Exercises	196
<b>14 Dynamical supersymmetry breaking</b>	198
14.1 Models of dynamical supersymmetry breaking	198
14.2 Metastable supersymmetry breaking	200
14.3 Particle physics and dynamical supersymmetry breaking	203
Suggested reading	209
Exercises	210
<b>15 Theories with more than four conserved supercharges</b>	211
15.1 $N = 2$ theories: exact moduli spaces	211
15.2 A still simpler theory: $N = 4$ Yang–Mills	213
15.3 A deeper understanding of the BPS condition	214
15.4 Seiberg–Witten theory	216
Suggested reading	221
Exercises	221
<b>16 More supersymmetric dynamics</b>	222
16.1 Conformally invariant field theories	222
16.2 More supersymmetric QCD	224
16.3 $N_f = N_c$	224
16.4 $N_f > N + 1$	228
16.5 $N_f \geq 3N/2$	229
Suggested reading	229
Exercises	230
<b>17 An introduction to general relativity</b>	231
17.1 Tensors in general relativity	232
17.2 Curvature	236
17.3 The gravitational action	237
17.4 The Schwarzschild solution	239
17.5 Features of the Schwarzschild metric	241
17.6 Coupling spinors to gravity	243
Suggested reading	244
Exercises	244

<b>18 Cosmology</b>	245
18.1 The cosmological principle and the FRW universe	245
18.2 A history of the universe	248
Suggested reading	253
Exercises	253
<b>19 Particle astrophysics and inflation</b>	254
19.1 Inflation	256
19.2 The axion as the dark matter	264
19.3 The LSP as the dark matter	267
19.4 The moduli problem	270
19.5 Baryogenesis	272
19.6 Flat directions and baryogenesis	280
19.7 Supersymmetry breaking in the early universe	281
19.8 The fate of the condensate	282
19.9 Dark energy	284
Suggested reading	285
Exercises	286
<b>Part 3 String theory</b>	287
<b>20 Introduction</b>	289
20.1 The peculiar history of string theory	290
Suggested reading	294
<b>21 The bosonic string</b>	295
21.1 The light cone gauge in string theory	297
21.2 Closed strings	300
21.3 String interactions	301
21.4 Conformal invariance	303
21.5 Vertex operators and the $S$ -matrix	309
21.6 The $S$ -matrix versus the effective action	314
21.7 Loop amplitudes	315
Suggested reading	317
Exercises	318
<b>22 The superstring</b>	319
22.1 Open superstrings	319
22.2 Quantization in the Ramond sector: the appearance of space–time fermions	321
22.3 Type II theory	322
22.4 World-sheet supersymmetry	323
22.5 The spectra of the superstrings	323
22.6 Manifest space–time supersymmetry: the Green–Schwarz formalism	330
22.7 Vertex operators	332

Suggested reading	333
Exercises	333
<b>23 The heterotic string</b>	335
23.1 The $O(32)$ theory	335
23.2 The $E_8 \times E_8$ theory	336
23.3 Heterotic string interactions	337
23.4 A non-supersymmetric heterotic string theory	338
Suggested reading	339
Exercises	339
<b>24 Effective actions in ten dimensions</b>	340
24.1 Eleven-dimensional supergravity	340
24.2 The IIA and IIB supergravity theories	341
24.3 Ten-dimensional supersymmetric Yang–Mills theory	342
24.4 Coupling constants in string theory	343
Suggested reading	346
Exercise	346
<b>25 Compactification of string theory I. Tori and orbifolds</b>	347
25.1 Compactification in field theory: the Kaluza–Klein program	347
25.2 Closed strings on tori	350
25.3 Enhanced symmetries and $T$ -duality	354
25.4 Strings in background fields	355
25.5 Bosonic formulation of the heterotic string	359
25.6 Orbifolds	360
25.7 Effective actions in four dimensions for orbifold models	366
25.8 Non-supersymmetric compactifications	369
Suggested reading	370
Exercises	371
<b>26 Compactification of string theory II. Calabi–Yau compactifications</b>	372
26.1 Mathematical preliminaries	372
26.2 Calabi–Yau spaces: constructions	376
26.3 The spectrum of Calabi–Yau compactifications	379
26.4 World-sheet description of Calabi–Yau compactification	381
26.5 An example: the quintic in $\mathbb{CP}^4$	383
26.6 Calabi–Yau compactification of the heterotic string at weak coupling	385
Suggested reading	395
Exercises	395

<b>Part 4 Appendices</b>	<b>449</b>
<b>Appendix A Two-component spinors</b>	<b>451</b>
<b>Appendix B Goldstone's theorem and the pi mesons</b>	<b>454</b>
Exercises	456
<b>Appendix C Some practice with the path integral in field theory</b>	<b>457</b>
C.1 Path integral review	457
C.2 Finite-temperature field theory	458
C.3 QCD at high temperatures	462
C.4 Weak interactions at high temperatures	463
C.5 Electroweak baryon number violation	464
Suggested reading	466
Exercises	466
<b>Appendix D The beta function in supersymmetric Yang–Mills theory</b>	<b>467</b>
Suggested reading	468
Exercise	469
<b>References</b>	<b>470</b>
<b>Index</b>	<b>477</b>