

# CONTENTS

<b>Preface</b>	<b>vii</b>
<b>1 Supersymmetry algebra and multiplets</b>	<b>1</b>
1.1 Introduction	1
1.2 Dirac, Weyl and Majorana spinors	3
1.3 Simple supersymmetry algebra	13
1.4 Supersymmetry multiplets	16
1.5 Supersymmetric free-field theory	21
1.6 Extended supersymmetry	27
Exercises	31
References	32
<b>2 Lagrangians for chiral superfields</b>	<b>33</b>
2.1 Introduction	33
2.2 Superfield representations of the supersymmetry algebra	34
2.3 Expansion of the chiral superfield in component fields	36
2.4 Products of chiral superfields	38
2.5 Renormalizable supersymmetric Lagrangians for chiral superfields	39
2.6 Feynman rules for chiral supermultiplets	41
2.7 Mass and coupling constant renormalization	42
2.8 Non-renormalization theorems	45
2.9 Spontaneous supersymmetry breaking	47
2.10 $F$ -term supersymmetry breaking	50
Exercises	53
References	54
<b>3 Lagrangians for vector superfields</b>	<b>55</b>
3.1 Introduction	55
3.2 The vector superfield	56
3.3 Supersymmetric gauge invariance	59
3.4 Spontaneously broken gauge invariance	66
3.5 $D$ -term supersymmetry breaking	69
3.6 Supersymmetric non-abelian gauge theories	71

3.7	Supersymmetric electroweak theory	76
3.8	The renormalization group equations	79
	Exercises	82
	References	82
<b>4</b>	<b>Pure supergravity</b>	<b>83</b>
4.1	Introduction	83
4.2	The Noether procedure	84
4.3	The globally supersymmetric Lagrangian for the supergravity multiplet	87
4.4	The locally supersymmetric Lagrangian for the supergravity multiplet	91
	Exercises	93
	References	94
<b>5</b>	<b>Coupling of supergravity to matter</b>	<b>95</b>
5.1	Introduction	95
5.2	The supergravity Lagrangian for the Wess–Zumino model	95
5.3	The general supergravity Lagrangian for chiral supermultiplets	99
5.4	The general supergravity Lagrangian including vector supermultiplets	102
5.5	Spontaneous supersymmetry breaking in supergravity	104
5.6	The super-Higgs mechanism and gravitino mass	107
5.7	Hidden-sector supersymmetry breaking	110
5.8	Supersymmetry breaking by gaugino condensates	112
5.9	Supersymmetry-breaking effects in the observable sector	114
5.10	No-scale supergravity	117
	Exercises	119
	References	119
<b>6</b>	<b>Supergravity grand unified theories</b>	<b>121</b>
6.1	The hierarchy problem	121
6.2	The minimal $SU(5)$ supergravity GUT	125
6.3	Renormalization group equations	130
6.4	Charginos and neutralinos	138
6.5	Experimental signatures	141
6.6	Proton decay	142
	Exercises	148
	References	148

<b>7</b>	<b>The bosonic string</b>	<b>150</b>
7.1	Introduction	150
7.2	The bosonic string action	150
7.3	Equations of motion and covariant gauges	154
7.4	Mode expansion and quantization	155
7.5	Virasoro algebra and masses of states for the closed string	158
7.6	Virasoro algebra and masses of states for the open string	164
7.7	The light cone gauge	165
7.8	Low-lying string states	168
7.9	Path integral quantization	170
	Exercises	172
	References	173
<b>8</b>	<b>The superstring</b>	<b>174</b>
8.1	Introduction	174
8.2	The superstring action	175
8.3	Equations of motion and the covariant gauge	177
8.4	Mode expansions and quantization	179
8.5	Super-Virasoro algebra for the closed string	182
8.6	Closed superstring ground states and superconformal anomalies	188
8.7	The light cone gauge	190
8.8	Superstring states, gso projections and space-time supersymmetry	193
8.9	Other formulations of the superstring	196
	Exercises	197
	References	197
<b>9</b>	<b>The heterotic string</b>	<b>199</b>
9.1	Introduction	199
9.2	Mode expansions and quantization	200
9.3	Compactification of the bosonic string on a circle	202
9.4	Compactification of the heterotic string on a torus	207
9.5	Fermionization and bosonization	211
9.6	Fermionic formulation of the compactified heterotic string	216
	Exercises	220
	References	220

<b>10 Compactification of the ten-dimensional heterotic string to four dimensions</b>	<b>222</b>
10.1 Introduction	222
10.2 Toroidal compactifications	222
10.3 Orbifold compactifications	225
10.4 The untwisted sector of the $Z_3$ orbifold	228
10.5 The twisted sector of the $Z_3$ orbifold	230
10.6 Wilson lines	239
10.7 Calabi–Yau manifolds	243
Exercises	243
References	244
<b>11 Direct construction of four-dimensional heterotic string theories</b>	<b>245</b>
11.1 Introduction	245
11.2 Modular invariance and partition functions	245
11.3 Partition functions and gso projections	250
11.4 Four-dimensional heterotic string theories	256
11.5 Semi-realistic four-dimensional models	261
Exercises	268
References	268
<b>12 Superstring interactions</b>	<b>269</b>
12.1 Introduction	269
12.2 Bosonic string vertex operators and conformal dimensions	272
12.3 Bosonic open-string scattering amplitudes	278
12.4 Bosonic closed-string amplitudes	285
12.5 The superstring vertex operator	290
12.6 Superstring scattering amplitudes	294
12.7 A review of further developments	300
Exercises	306
References	307
<b>Appendix A: Weyl spinor Fierz identities</b>	<b>308</b>
<b>Appendix B: Cyclic symmetry of the open-string scattering amplitude</b>	<b>310</b>
<b>Appendix C: Coherent state methods</b>	<b>314</b>
<b>Appendix D: Closed-string integrals</b>	<b>316</b>
<b>Index</b>	<b>319</b>