

Contents

	<i>Preface to the 25th Anniversary Edition</i>	ix
1	Introduction	1
1.1	The early days of dual models	1
1.1.1	The Veneziano amplitude and duality	6
1.1.2	High-energy behavior of the Veneziano model	10
1.1.3	Ramifications of the Veneziano model	12
1.2	Dual models of everything	13
1.2.1	Duality and the graviton	14
1.2.2	Unification in higher dimensions	14
1.2.3	Supersymmetry	16
1.3	String theory	18
1.3.1	The massless point particle	18
1.3.2	Generalization to strings	21
1.3.3	Constraint equations	23
1.4	String interactions	27
1.4.1	Splitting of strings	29
1.4.2	Vertex operators	32
1.4.3	Use of vertex operators	35
1.4.4	Evaluation of the scattering amplitude	38
1.4.5	The mass of the graviton	40
1.5	Other aspects of string theory	42
1.5.1	Gravitational Ward identities	42
1.5.2	Open strings	46
1.5.3	Internal symmetries of open strings	47
1.5.4	Recovery of the Veneziano amplitude	49
1.5.5	Comparison with QCD	51
1.5.6	Unitarity and gravity	52
1.6	Conclusion	55
2	Free bosonic strings	57
2.1	The classical bosonic string	57
2.1.1	String action and its symmetries	59
2.1.2	The free string in Minkowski space	61
2.1.3	Classical covariant gauge fixing and field equations	62
2.2	Quantization – old covariant approach	74

2.2.1	Commutation relations and mode expansions	75
2.2.2	Virasoro algebra and physical states	79
2.2.3	Vertex operators	86
2.3	Light-cone gauge quantization	92
2.3.1	Light-cone gauge and Lorentz algebra	93
2.3.2	Construction of transverse physical states	100
2.3.3	The no-ghost theorem and the spectrum-generating algebra	102
2.3.4	Analysis of the spectrum	113
2.3.5	Asymptotic formulas for level densities	116
2.4	Summary	119
3	Modern covariant quantization	121
3.1	Covariant path-integral quantization	121
3.1.1	Faddeev–Popov ghosts	122
3.1.2	Complex world-sheet tensor calculus	124
3.1.3	Quantization of the ghosts	127
3.2	BRST quantization	131
3.2.1	Construction of BRST charge	131
3.2.2	Covariant calculation of the Virasoro anomaly	139
3.2.3	Virasoro, conformal and gravitational anomalies	144
3.2.4	Bosonization of ghost coordinates	148
3.3	Global aspects of the string world sheet	156
3.4	Strings in background fields	165
3.4.1	Introduction of a background space-time metric	165
3.4.2	Weyl invariance	167
3.4.3	Conformal invariance and the equations of motion	172
3.4.4	String-theoretic corrections to general relativity	177
3.4.5	Inclusion of other modes	178
3.4.6	The dilaton expectation value and the string coupling constant	182
3.5	Summary	184
4	World-sheet supersymmetry in string theory	185
4.1	The classical theory	186
4.1.1	Global world-sheet supersymmetry	188
4.1.2	Superspace	190
4.1.3	Constraint equations	194
4.1.4	Boundary conditions and mode expansions	197
4.2	Quantization – the old covariant approach	199
4.2.1	Commutation relations and mode expansions	200
4.2.2	Super-Virasoro algebra and physical states	203
4.2.3	Boson-emission vertex operators	207

4.3	Light-cone gauge quantization	210
4.3.1	The light-cone gauge	210
4.3.2	No-ghost theorem and the spectrum-generating algebra	214
4.3.3	The GSO conditions	218
4.3.4	Locally supersymmetric form of the action	224
4.3.5	Superstring action and its symmetries	228
4.4	Modern covariant quantization	231
4.4.1	Faddeev–Popov ghosts	231
4.4.2	BRST symmetry	235
4.4.3	Covariant computation of the Virasoro anomaly	236
4.5	Extended world-sheet supersymmetry	237
4.5.1	The $N = 2$ theory	237
4.5.2	The $N = 4$ theory	243
4.6	Summary	244
4.A	Super Yang–Mills theories	244
5	Space-time supersymmetry in string theory	249
5.1	The classical theory	249
5.1.1	The superparticle	249
5.1.2	The supersymmetric string action	253
5.1.3	The local fermionic symmetry	255
5.1.4	Type I and type II superstrings	258
5.2	Quantization	259
5.2.1	Light-cone gauge	260
5.2.2	Super-Poincaré algebra	266
5.3	Analysis of the spectrum	270
5.3.1	Open superstrings	270
5.3.2	Closed superstrings	277
5.4	Remarks concerning covariant quantization	280
5.5	Summary	281
5.A	Properties of $SO(2n)$ groups	282
5.B	The spin(8) Clifford algebra	288
6	Nonabelian gauge symmetry	291
6.1	Open strings	291
6.1.1	The Chan–Paton method	292
6.1.2	Allowed gauge groups and representations	298
6.2	Current algebra on the string world sheet	300
6.3	Heterotic strings	305
6.3.1	The $SO(32)$ theory	307
6.3.2	The $E_8 \times E_8$ theory	312
6.4	Toroidal compactification	317

6.4.1	Compactification on a circle	318
6.4.2	Fermionization	321
6.4.3	Bosonized description of the heterotic string	323
6.4.4	Vertex operator representations	329
6.4.5	Formulas for the cocycles	335
6.4.6	The full current algebra	337
6.4.7	The E_8 and $\text{spin}(32)/Z_2$ lattices	337
6.4.8	The heterotic string spectrum	339
6.5	Summary	343
6.A	Elements of E_8	344
6.B	Modular forms	350
7	Tree amplitudes	353
7.1	Bosonic open strings	354
7.1.1	The structure of tree amplitudes	355
7.1.2	Decoupling of ghosts	362
7.1.3	Cyclic symmetry	364
7.1.4	Examples	371
7.1.5	Tree-level gauge invariance	374
7.1.6	The twist operator	377
7.2	Bosonic closed strings	378
7.2.1	Construction of tree amplitudes	379
7.2.2	Examples	381
7.2.3	Relationship to open-string trees	389
7.3	Superstrings in the RNS formulation	390
7.3.1	Open-string tree amplitudes in the bosonic sector	391
7.3.2	The F_1 picture	393
7.3.3	Examples	395
7.3.4	Tree amplitudes with one fermion line	399
7.3.5	Fermion-emission vertices	401
7.4	Superstrings in the supersymmetric formulation	411
7.4.1	Massless particle vertices	411
7.4.2	Open-string trees	418
7.4.3	Closed-string trees	422
7.4.4	Heterotic-string trees	423
7.5	Summary	428
7.A	Coherent-state methods and correlation functions	429
	<i>Bibliography</i>	435
	<i>Index</i>	465