

Contents

<i>Frequently used symbols</i>	<i>page</i> xiv
<i>Preface</i>	xvii
1 Overview	1
Part I Relativity 5	
2 Special relativity	7
2.1 Minkowski coordinates and the relativity principle	7
2.2 Vectors and tensors with Minkowski coordinates	10
2.3 Spacetime lines and geodesics	12
2.4 Fluid dynamics	14
2.5 Energy–momentum tensor	16
2.6 Gas dynamics	19
2.7 Boltzmann equation	21
3 General relativity	26
3.1 Special relativity with generic coordinates: mathematics	26
3.2 Special relativity with generic coordinates: laws of physics	30
3.3 Curved spacetime	31
3.4 Curved space and curved surfaces	34
3.5 The equivalence principle	35
3.6 Einstein gravity	35
3.7 The Robertson–Walker metric	39
3.8 Hubble parameter and horizons	42
3.9 Inflation and the Big Bang	44
3.10 Continuity equation and Friedmann equation	45

Part II	The Universe after the first second	49
4	The unperturbed Universe	51
4.1	Temperature and redshift	51
4.2	Thermal equilibrium in the early Universe	52
4.3	Baryon and lepton number	54
4.4	The evolution up to Big Bang Nucleosynthesis	56
4.5	The Λ CDM model	60
4.6	Evolution of the scale factor	63
4.7	Photon decoupling and reionization	65
4.8	Neutrino mass	67
5	The primordial density perturbation	70
5.1	A first look at the primordial perturbations	70
5.2	Cosmological perturbations	74
5.3	The evolution of cosmological perturbations	76
5.4	Primordial curvature perturbation	78
5.5	Linear density perturbations	81
6	Stochastic properties	85
6.1	Random fields	85
6.2	Fourier expansion	87
6.3	Gaussian perturbations	88
6.4	Non-gaussian perturbations	91
6.5	Ergodic theorem and cosmic variance	94
6.6	Spherical expansion	97
6.7	Correlators of the curvature perturbation	99
7	Newtonian perturbations	103
7.1	Free-streaming, oscillation, and collapse	103
7.2	Newtonian perturbations: total mass density	105
7.3	Effect of the cosmological constant	109
7.4	Baryon density perturbation	110
8	General relativistic perturbations	115
8.1	Scalar, vector, and tensor modes	115
8.2	Perturbing the metric and energy–momentum tensors	118
8.3	Evolution of the scalar mode perturbations	121
8.4	Separate fluids	123
8.5	Matter density transfer function	125
8.6	Acoustic oscillation	127
8.7	Silk damping	129
8.8	Synchronous gauge	132

9	The matter distribution	134
9.1	Smoothing	135
9.2	Bottom-up structure formation	136
9.3	Critical density for collapse	139
9.4	Virialization	142
9.5	Abundance of premature objects	144
9.6	The observed mass density perturbation	146
10	Cosmic microwave background anisotropy	152
10.1	CMB multipoles	153
10.2	Spectrum of the CMB anisotropy	155
10.3	Flat-sky approximation	156
10.4	Scalar mode	158
10.5	Sudden-decoupling approximation	159
10.6	Sachs–Wolfe plateau	162
10.7	Acoustic peaks and Silk damping	165
10.8	Reionization	167
10.9	Non-gaussianity of the CMB anisotropy	168
11	Boltzmann hierarchy and polarization	171
11.1	Perturbed Boltzmann equation	171
11.2	Boltzmann hierarchy	173
11.3	Collision term without polarization	174
11.4	Polarization and Thomson scattering	177
11.5	CMB polarization	180
11.6	Boltzmann hierarchy with polarization	181
11.7	Initial conditions and the transfer functions	184
11.8	Line-of-sight integral	186
12	Isocurvature and tensor modes	190
12.1	Isocurvature modes	190
12.2	Matter isocurvature mode	192
12.3	Neutrino isocurvature mode	196
12.4	The primordial lepton number perturbation	197
12.5	Tensor mode	199
12.6	Seeds and the vector mode	204
12.7	Spatial curvature	205

Part III Field theory	209
13 Scalar fields and gravity	211
13.1 Field theory	211
13.2 Action and Lagrangian	214
13.3 Scalar field in flat spacetime	219
13.4 Energy–momentum tensor	220
13.5 Nearly free scalar field	221
13.6 Several fields	222
13.7 Field theory in curved spacetime	225
13.8 Gravity from the action principle	226
14 Internal symmetry	228
14.1 Symmetry groups	228
14.2 Abelian global symmetries	229
14.3 Non-Abelian continuous global symmetries	231
14.4 Noether’s theorem and conserved quantities	234
14.5 Spontaneously broken global symmetry	236
14.6 $U(1)$ gauge symmetry	239
14.7 $SU(2)$ gauge symmetry	241
14.8 Spontaneously broken gauge symmetry	242
14.9 Discrete gauge symmetry	244
15 Quantum field theory	246
15.1 Schrödinger and Heisenberg pictures	246
15.2 Symmetry and conserved currents	248
15.3 Harmonic oscillator	251
15.4 Quantized free scalar field	253
15.5 Vector field	256
15.6 Spin-1/2 field	258
15.7 Free scalar field with time-dependent mass	261
15.8 Quantized interactions	263
16 The Standard Model	268
16.1 Electroweak Lagrangian	269
16.2 Electroweak theory: particles and interactions	271
16.3 Electroweak theory with three generations	273
16.4 Quantum Chromodynamics (QCD)	275
16.5 The complete Lagrangian and its accidental symmetries	279
16.6 Peccei–Quinn symmetry and the axion	282
16.7 Neutrino mass	284

17	Supersymmetry	288
17.1	The supersymmetry transformation	288
17.2	Renormalizable global supersymmetry	289
17.3	Global supersymmetry breaking	291
17.4	Supergravity	294
17.5	The Minimal Supersymmetric Standard Model	296
17.6	Supersymmetry and the axion	300
Part IV Inflation and the early Universe		303
18	Slow-roll inflation	305
18.1	Inflation defined	305
18.2	Three problems of the pure Big Bang	307
18.3	Initial condition for inflation	311
18.4	The amount of observable inflation	311
18.5	The slow-roll paradigm	314
18.6	Hamilton–Jacobi formulation	316
18.7	Inflationary potentials	318
19	Inflation with modified gravity	325
19.1	Scalar–tensor theories	325
19.2	Induced gravity and variable Planck mass	326
19.3	Extended inflation	327
19.4	R^2 inflation	329
19.5	Modified gravity from the braneworld	329
20	Multi-field dynamics	332
20.1	Multi-field slow-roll inflation	332
20.2	Light and heavy fields	334
21	Reheating and phase transitions	337
21.1	Reheating	337
21.2	Preheating	340
21.3	Phase transitions and solitons	344
21.4	Main types of soliton	347
21.5	Topological defects and the GUT transition	350
21.6	Thermal inflation	351
21.7	Moduli problem	353
22	Thermal equilibrium and the origin of baryon number	358
22.1	Thermal equilibrium before the electroweak phase transition	358
22.2	Thermal equilibrium with non-zero $B - L$	360
22.3	Baryogenesis mechanisms	362

23	Cold dark matter and dark energy	369
23.1	Axion CDM	369
23.2	The LSP as a CDM candidate	372
23.3	Supermassive CDM candidates	376
23.4	Primordial black holes	377
23.5	Dark energy	378
24	Generating field perturbations at horizon exit	382
24.1	Quantum theory of a massless free scalar field during inflation	382
24.2	Quantum to classical transition	386
24.3	Linear corrections to the calculation	387
24.4	Non-gaussianity of the field perturbations	390
24.5	Higher orders of perturbation theory	393
24.6	Stochastic field evolution	394
24.7	Primordial tensor perturbation	397
24.8	Particle production from a perturbation created during inflation	400
25	Generating ζ at horizon exit	404
25.1	Anthropic constraints on the curvature perturbation	405
25.2	Prediction of the standard paradigm for the spectrum	406
25.3	Tensor fraction and constraints on small-field models	407
25.4	Prediction of the standard paradigm for non-gaussianity	410
25.5	Loop contributions to the correlators of ζ	413
25.6	The standard paradigm beyond slow roll	416
25.7	K-inflation	418
25.8	Warm inflation	420
26	Generating ζ after horizon exit	424
26.1	The generic δN formula for ζ	424
26.2	Spectrum of ζ	425
26.3	Non-gaussianity	427
26.4	Curvaton paradigm	429
26.5	Inhomogeneous decay rate	432
26.6	More ways of generating the curvature perturbation	434
27	Generating primordial isocurvature perturbations	437
27.1	The δn_i formula	437
27.2	Axion CDM isocurvature perturbation	439
27.3	Affleck–Dine isocurvature perturbation	443
27.4	Correlated CDM or baryon isocurvature perturbation	443
27.5	Neutrino isocurvature perturbation	445

28	Slow-roll inflation and observation	447
28.1	Historical development	447
28.2	Eternal inflation	449
28.3	Field theory and inflation	451
28.4	The eta problem	451
28.5	Hilltop inflation	454
28.6	Ledge inflation	456
28.7	GUT inflation	458
28.8	<i>D</i> -term inflation	461
28.9	Another potential	463
28.10	Running-mass inflation	463
28.11	Small-field PNGB inflation	466
28.12	Modular inflation	467
28.13	Large-field models	468
29	Perspective	475
<i>Appendix A: Spherical functions</i>		477
<i>Appendix B: Constants and parameters</i>		482
<i>Index</i>		484