

Contents

Preface xv

List of symbols xxi

Suggestions for using this book xxxi

1 Introduction 1

1 The field concept 1

2 The equations of electrodynamics 2

3 A lightspeed survey of electromagnetic phenomena 7

4 SI versus Gaussian 10

2 Review of mathematical concepts 18

5 Vector algebra 18

6 Derivatives of vector fields 25

7 Integration of vector fields 30

8 The theorems of Stokes and Gauss 32

9 Fourier transforms, delta functions, and distributions 37

10 Rotational transformations of vectors and tensors 45

11 Orthogonal curvilinear coordinates 51

3 Electrostatics in vacuum 55

12 Coulomb's law 55

13 The electrostatic potential 57

14 Electrostatic energy 58

15 Differential form of Coulomb's law 63

16 Uniqueness theorem of electrostatics 65

17 Solving Poisson's equation: a few examples	68
18 Energy in the electric field	71
19 The multipole expansion	73
20 Charge distributions in external fields	80
4 Magnetostatics in vacuum	82
21 Sources of magnetic field	82
22 The law of Biot and Savart	89
23 Differential equations of magnetostatics; Ampere's law	93
24 The vector potential	101
25 Gauge invariance	105
26 $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$ for a point dipole	108
27 Magnetic multipoles	112
5 Induced electromagnetic fields	114
28 Induction	114
29 Energy in the magnetic field—Feynman's argument	117
30 Energy in the magnetic field—standard argument	120
31 Inductance	121
32 The Ampere-Maxwell law	125
33 Potentials for time-dependent fields	128
6 Symmetries and conservation laws	132
34 Discrete symmetries of the laws of electromagnetism	132
35 Energy flow and the Poynting vector	137
36 Momentum conservation	140
37 Angular momentum conservation*	144
38 Relativity at low speeds	148
39 Electromagnetic mass*	150
7 Electromagnetic waves	152
40 The wave equation for \mathbf{E} and \mathbf{B}	152
41 Plane electromagnetic waves	154
42 Monochromatic plane waves and polarization	156
43 Nonplane monochromatic waves; geometrical optics*	160
44 Electromagnetic fields in a laser beam*	165
45 Partially polarized (quasimonochromatic) light*	168
46 Oscillator representation of electromagnetic waves	171
47 Angular momentum of the free electromagnetic field*	174
8 Interference phenomena	178
48 Interference and diffraction	178

49 Fresnel diffraction	182
50 Fraunhofer diffraction	186
51 Partially coherent light	187
52 The Hanbury-Brown and Twiss effect; intensity interferometry*	191
53 The Pancharatnam phase*	195
9 The electromagnetic field of moving charges	200
54 Green's function for the wave equation	200
55 Fields of a uniformly moving charge	204
56 Potentials of an arbitrarily moving charge—the Lienard-Wiechert solutions	207
57 Electromagnetic fields of an arbitrarily moving charge	210
58 Radiation from accelerated charges: qualitative discussion	214
10 Radiation from localized sources	217
59 General frequency-domain formulas for fields	217
60 Far-zone fields	219
61 Power radiated	223
62 The long-wavelength electric dipole approximation	227
63 Higher multipoles*	229
64 Antennas	233
65 Near-zone fields	237
66 Angular momentum radiated*	239
67 Radiation reaction	241
11 Motion of charges and moments in external fields	245
68 The Lorentz force law	245
69 Motion in a static uniform electric field	246
70 Motion in a static uniform magnetic field	248
71 Motion in crossed \mathbf{E} and \mathbf{B} fields; $E < B$	251
72 Motion in a time-dependent magnetic field; the betatron	255
73 Motion in a quasiuniform static magnetic field—guiding center drift*	257
74 Motion in a slowly varying magnetic field—the first adiabatic invariant*	261
75 The classical gyromagnetic ratio and Larmor's theorem	264
76 Precession of moments in time-dependent magnetic fields*	268
12 Action formulation of electromagnetism	273
77 Charged particle in given field	273
78 The free field	276
79 The interacting system of fields and charges	279
80 Gauge invariance and charge conservation	283

13	Electromagnetic fields in material media	285
	81 Macroscopic fields	286
	82 The macroscopic charge density and the polarization	289
	83 The macroscopic current density and the magnetization	293
	84 Constitutive relations	297
	85 Energy conservation	300
14	Electrostatics around conductors	302
	86 Electric fields inside conductors, and at conductor surfaces	303
	87 Theorems for electrostatic fields	306
	88 Electrostatic energy with conductors; capacitance	308
	89 The method of images	313
	90 Separation of variables and expansions in basis sets	320
	91 The variational method*	329
	92 The relaxation method	334
	93 Microscopic electrostatic field at metal surfaces; work function and contact potential*	339
15	Electrostatics of dielectrics	344
	94 The dielectric constant	344
	95 Boundary value problems for linear isotropic dielectrics	347
	96 Depolarization	350
	97 Thermodynamic potentials for dielectrics	354
	98 Force on small dielectric bodies	360
	99 Models of the dielectric constant	361
16	Magnetostatics in matter	370
	100 Magnetic permeability and susceptibility	370
	101 Thermodynamic relations for magnetic materials	371
	102 Diamagnetism	375
	103 Paramagnetism	378
	104 The exchange interaction; ferromagnetism	378
	105 Free energy of ferromagnets	382
	106 Ferromagnetic domain walls*	391
	107 Hysteresis in ferromagnets	394
	108 Demagnetization	397
	109 Superconductors*	399
17	Ohm's law, emf, and electrical circuits	404
	110 Ohm's law	405
	111 Electric fields around current-carrying conductors—a solvable example*	407

	112 van der Pauw's method*	409
	113 The Van de Graaff generator	412
	114 The thermopile	413
	115 The battery	414
	116 Lumped circuits	417
	117 The telegrapher's equation*	422
	118 The ac generator	424
18	Frequency-dependent response of materials	427
	119 The frequency-dependent conductivity	427
	120 The dielectric function and electric propensity	429
	121 General properties of the ac conductivity*	431
	122 Electromagnetic energy in material media*	435
	123 Drude-Lorentz model of the dielectric response	437
	124 Frequency dependence of the magnetic response*	441
19	Quasistatic phenomena in conductors	443
	125 Quasistatic fields	443
	126 Variable magnetic field: eddy currents and the skin effect in a planar geometry	445
	127 Variable magnetic field: eddy currents and the skin effect in finite bodies*	450
	128 Variable electric field, electrostatic regime	455
	129 Variable electric field, skin-effect regime	457
	130 Eddy currents in thin sheets, Maxwell's receding image construction, and maglev*	459
	131 Motion of extended conductors in magnetic fields*	465
	132 The dynamo*	467
20	Electromagnetic waves in insulators	470
	133 General properties of EM waves in media	470
	134 Wave propagation velocities	472
	135 Reflection and refraction at a flat interface (general case)	475
	136 More reflection and refraction (both media transparent and nonmagnetic)	479
	137 Reflection from a nonmagnetic opaque medium*	483
21	Electromagnetic waves in and near conductors	487
	138 Plasma oscillations	487
	139 Dispersion of plasma waves*	488
	140 Transverse EM waves in conductors	490
	141 Reflection of light from a metal	492

142	Surface plasmons*	493
143	Waveguides	496
144	Resonant cavities	502
22	Scattering of electromagnetic radiation	505
145	Scattering terminology	505
146	Scattering by free electrons	506
147	Scattering by bound electrons	508
148	Scattering by small particles	510
149	Scattering by dilute gases, and why the sky is blue	512
150	Raman scattering	515
151	Scattering by liquids and dense gases*	516
23	Formalism of special relativity	524
152	Review of basic concepts	524
153	Four-vectors	532
154	Velocity, momentum, and acceleration four-vectors	537
155	Four-tensors	540
156	Vector fields and their derivatives in space–time	543
157	Integration of vector fields*	544
158	Accelerated observers*	548
24	Special relativity and electromagnetism	553
159	Four-current and charge conservation	553
160	The four-potential	556
161	The electromagnetic field tensor	556
162	Covariant form of the laws of electromagnetism	559
163	The stress–energy tensor	561
164	Energy–momentum conservation in special relativity	564
165	Angular momentum and spin*	565
166	Observer-dependent properties of light	567
167	Motion of charge in an electromagnetic plane wave*	572
168	Thomas precession*	576
25	Radiation from relativistic sources	581
169	Total power radiated	581
170	Angular distribution of power	584
171	Synchrotron radiation—qualitative discussion	588
172	Full spectral, angular, and polarization distribution of synchrotron radiation*	589
173	Spectral distribution of synchrotron radiation*	592
174	Angular distribution and polarization of synchrotron radiation*	595
175	Undulators and wigglers*	597

<i>Appendix A: Spherical harmonics</i>	605
<i>Appendix B: Bessel functions</i>	617
<i>Appendix C: Time averages of bilinear quantities in electrodynamics</i>	625
<i>Appendix D: Caustics</i>	627
<i>Appendix E: Airy functions</i>	633
<i>Appendix F: Power spectrum of a random function</i>	637
<i>Appendix G: Motion in the earth’s magnetic field—the Stormer problem</i>	643
<i>Appendix H: Alternative proof of Maxwell’s receding image construction</i>	651
<i>Bibliography</i>	655
<i>Index</i>	659