

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Fifth Edition

Introduction to Electrodynamics

DAVID J. GRIFFITHS

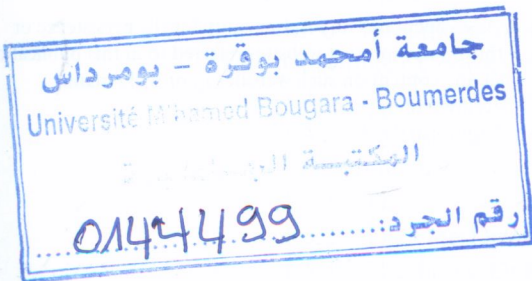
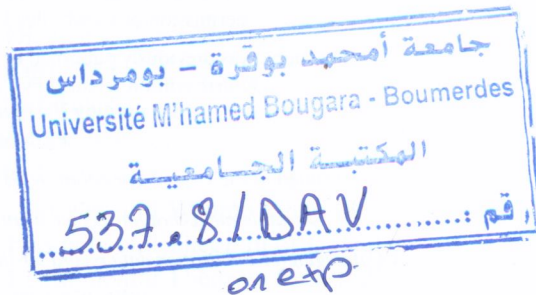


Introduction to Electrodynamics

Fifth Edition

DAVID J. GRIFFITHS

Reed College, Oregon



CAMBRIDGE
UNIVERSITY PRESS

Contents

<i>Preface</i>	page xi
<i>Advertisement</i>	xiv
1 Vector Analysis	1
1.1 Vector Algebra	1
1.1.1 Vector Operations	1
1.1.2 Vector Algebra: Component Form	4
1.1.3 Triple Products	7
1.1.4 Position, Displacement, and Separation Vectors	8
1.1.5 How Vectors Transform	9
1.2 Differential Calculus	12
1.2.1 “Ordinary” Derivatives	12
1.2.2 Gradient	13
1.2.3 The Del Operator	16
1.2.4 The Divergence	17
1.2.5 The Curl	18
1.2.6 Product Rules	20
1.2.7 Second Derivatives	22
1.3 Integral Calculus	24
1.3.1 Line, Surface, and Volume Integrals	24
1.3.2 The Fundamental Theorem of Calculus	28
1.3.3 The Fundamental Theorem for Gradients	29
1.3.4 The Fundamental Theorem for Divergences	31
1.3.5 The Fundamental Theorem for Curls	33
1.3.6 Integration by Parts	35
1.4 Curvilinear Coordinates	37
1.4.1 Spherical Coordinates	37
1.4.2 Cylindrical Coordinates	42
1.5 The Dirac Delta Function	43
1.5.1 The Divergence of $\hat{\mathbf{r}}/r^2$	43
1.5.2 The One-Dimensional Dirac Delta Function	44
1.5.3 The Three-Dimensional Delta Function	48
1.6 The Theory of Vector Fields	50
1.6.1 The Helmholtz Theorem	51
1.6.2 Potentials	51
More Problems on Chapter 1	53

2 Electrostatics	57
2.1 The Electric Field	57
2.1.1 Introduction	57
2.1.2 Coulomb's Law	58
2.1.3 The Electric Field	59
2.1.4 Continuous Charge Distributions	61
2.2 Divergence and Curl of Electrostatic Fields	64
2.2.1 Field Lines, Flux, and Gauss's Law	64
2.2.2 The Divergence of $\mathbf{E}$	68
2.2.3 Applications of Gauss's Law	69
2.2.4 The Curl of $\mathbf{E}$	74
2.3 Electric Potential	76
2.3.1 Introduction to Potential	76
2.3.2 Comments on Potential	78
2.3.3 Poisson's Equation and Laplace's Equation	81
2.3.4 The Potential of a Localized Charge Distribution	82
2.3.5 Boundary Conditions	85
2.4 Work and Energy in Electrostatics	88
2.4.1 The Work It Takes to Move a Charge	88
2.4.2 The Energy of a Point Charge Distribution	89
2.4.3 The Energy of a Continuous Charge Distribution	91
2.4.4 Comments on Electrostatic Energy	93
2.5 Conductors	95
2.5.1 Basic Properties	95
2.5.2 Induced Charges	97
2.5.3 Surface Charge and the Force on a Conductor	100
2.5.4 Capacitors	102
More Problems on Chapter 2	105
3 Potentials	113
3.1 Laplace's Equation	113
3.1.1 Introduction	113
3.1.2 Laplace's Equation in One Dimension	114
3.1.3 Laplace's Equation in Two Dimensions	115
3.1.4 Laplace's Equation in Three Dimensions	116
3.1.5 Boundary Conditions and Uniqueness Theorems	118
3.1.6 Conductors and the Second Uniqueness Theorem	121
3.2 The Method of Images	124
3.2.1 The Classic Image Problem	124
3.2.2 Induced Surface Charge	125
3.2.3 Force and Energy	126
3.2.4 Other Image Problems	127
3.3 Separation of Variables	129
3.3.1 Cartesian Coordinates	130
3.3.2 Spherical Coordinates	139
3.4 Multipole Expansion	147

3.4.1	Approximate Potentials at Large Distances	147
3.4.2	The Monopole and Dipole Terms	151
3.4.3	Origin of Coordinates in Multipole Expansions	153
3.4.4	The Electric Field of a Dipole	154
	More Problems on Chapter 3	157
4	Electric Fields in Matter	166
4.1	Polarization	166
4.1.1	Dielectrics	166
4.1.2	Induced Dipoles	166
4.1.3	Alignment of Polar Molecules	169
4.1.4	Polarization	171
4.2	The Field of a Polarized Object	172
4.2.1	Bound Charges	172
4.2.2	Physical Interpretation of Bound Charges	175
4.2.3	Microscopic and Macroscopic Fields	178
4.3	The Electric Displacement	181
4.3.1	Gauss's Law in the Presence of Dielectrics	181
4.3.2	A Deceptive Parallel	183
4.3.3	Boundary Conditions	184
4.3.4	The Crystal Ambiguity	185
4.4	Linear Dielectrics	186
4.4.1	Susceptibility, Permittivity, Dielectric Constant	186
4.4.2	Boundary Value Problems with Linear Dielectrics	193
4.4.3	Energy in Dielectric Systems	197
4.4.4	Forces on Dielectrics	201
	More Problems on Chapter 4	204
5	Magnetostatics	209
5.1	The Lorentz Force Law	209
5.1.1	Magnetic Fields	209
5.1.2	Magnetic Forces	211
5.1.3	Currents	215
5.2	The Biot–Savart Law	221
5.2.1	Steady Currents	221
5.2.2	The Magnetic Field of a Steady Current	222
5.3	The Divergence and Curl of $\mathbf{B}$	227
5.3.1	Straight-Line Currents	227
5.3.2	The Divergence and Curl of $\mathbf{B}$	229
5.3.3	Ampère's Law	231
5.3.4	Comparison of Magnetostatics and Electrostatics	238
5.4	Magnetic Vector Potential	243
5.4.1	The Vector Potential	243
5.4.2	Boundary Conditions	249
5.4.3	Multipole Expansion of the Vector Potential	251
	More Problems on Chapter 5	255

6	Magnetic Fields in Matter	268
6.1	Magnetization	268
6.1.1	Diamagnets, Paramagnets, Ferromagnets	268
6.1.2	Torques and Forces on Magnetic Dipoles	269
6.1.3	Effect of a Magnetic Field on Atomic Orbits	273
6.1.4	Magnetization	275
6.2	The Field of a Magnetized Object	276
6.2.1	Bound Currents	276
6.2.2	Physical Interpretation of Bound Currents	279
6.2.3	The Magnetic Field inside Matter	281
6.3	The Auxiliary Field $\mathbf{H}$	281
6.3.1	Ampère's Law in Magnetized Materials	281
6.3.2	A Deceptive Parallel	285
6.3.3	Boundary Conditions	286
6.4	Linear and Nonlinear Media	286
6.4.1	Magnetic Susceptibility and Permeability	286
6.4.2	Ferromagnetism	289
	More Problems on Chapter 6	294
7	Electrodynamics	298
7.1	Electromotive Force	298
7.1.1	Ohm's Law	298
7.1.2	Electromotive Force	304
7.1.3	Motional Emf	306
7.2	Electromagnetic Induction	316
7.2.1	Faraday's Law	316
7.2.2	The Induced Electric Field	320
7.2.3	Inductance	325
7.2.4	Energy in Magnetic Fields	331
7.3	Maxwell's Equations	335
7.3.1	Electrodynamics before Maxwell	335
7.3.2	How Maxwell Fixed Ampère's Law	336
7.3.3	Maxwell's Equations	340
7.3.4	Magnetic Charge	341
7.3.5	Maxwell's Equations in Matter	342
7.3.6	Boundary Conditions	345
7.4	The Field of a Rotating Magnet	347
	More Problems on Chapter 7	350
	Intermission	361
8	Conservation Laws	362
8.1	Charge and Energy	362
8.1.1	The Continuity Equation	362
8.1.2	Poynting's Theorem	363
8.2	Momentum	367

8.2.1	Newton's Third Law in Electrodynamics	367
8.2.2	Maxwell's Stress Tensor	368
8.2.3	Conservation of Momentum	372
8.2.4	Angular Momentum	376
8.3	Magnetic Forces Do No Work	379
	More Problems on Chapter 8	384
9	Electromagnetic Waves	390
9.1	Waves in One Dimension	390
9.1.1	The Wave Equation	390
9.1.2	Sinusoidal Waves	393
9.1.3	Boundary Conditions: Reflection and Transmission	396
9.1.4	Polarization	399
9.2	Electromagnetic Waves in Vacuum	401
9.2.1	The Wave Equation for $\mathbf{E}$ and $\mathbf{B}$	401
9.2.2	Monochromatic Plane Waves	402
9.2.3	Energy and Momentum in Electromagnetic Waves	406
9.3	Electromagnetic Waves in Matter	408
9.3.1	Propagation in Linear Media	408
9.3.2	Reflection and Transmission at Normal Incidence	410
9.3.3	Reflection and Transmission at Oblique Incidence	412
9.4	Absorption and Dispersion	418
9.4.1	Electromagnetic Waves in Conductors	418
9.4.2	Reflection at a Conducting Surface	422
9.4.3	The Frequency Dependence of Permittivity	423
9.5	Guided Waves	430
9.5.1	Wave Guides	430
9.5.2	TE Waves in a Rectangular Wave Guide	433
9.5.3	The Coaxial Transmission Line	436
	More Problems on Chapter 9	437
10	Potentials and Fields	442
10.1	The Potential Formulation	442
10.1.1	Scalar and Vector Potentials	442
10.1.2	Gauge Transformations	445
10.1.3	Coulomb Gauge and Lorenz Gauge	446
10.1.4	Lorentz Force Law in Potential Form	448
10.2	Continuous Distributions	450
10.2.1	Retarded Potentials	450
10.2.2	Jefimenko's Equations	454
10.3	Point Charges	456
10.3.1	Liénard-Wiechert Potentials	456
10.3.2	The Fields of a Moving Point Charge	462
	More Problems on Chapter 10	468

11 Radiation	472
11.1 Dipole Radiation	472
11.1.1 What Is Radiation?	472
11.1.2 Electric Dipole Radiation	473
11.1.3 Magnetic Dipole Radiation	479
11.1.4 Radiation from an Arbitrary Source	482
11.2 Power Radiated by a Point Charge	487
11.2.1 The Larmor Formula	487
11.2.2 The Liénard Formula	489
11.3 The Radiation Reaction	493
11.3.1 The Abraham–Lorentz Formula	493
11.3.2 The Self-Force on a Charged Particle	498
More Problems on Chapter 11	502
12 Electrodynamics and Relativity	508
12.1 The Special Theory of Relativity	508
12.1.1 Einstein's Postulates	508
12.1.2 The Geometry of Relativity	514
12.1.3 The Lorentz Transformations	524
12.1.4 The Structure of Space-Time	530
12.2 Relativistic Mechanics	538
12.2.1 Proper Time and Proper Velocity	538
12.2.2 Relativistic Energy and Momentum	540
12.2.3 Relativistic Kinematics	542
12.2.4 Relativistic Dynamics	547
12.3 Relativistic Electrodynamics	554
12.3.1 Magnetism as a Relativistic Phenomenon	554
12.3.2 How the Fields Transform	557
12.3.3 The Field Tensor	566
12.3.4 Electrodynamics in Tensor Notation	569
12.3.5 Relativistic Potentials	572
More Problems on Chapter 12	574
Appendix A Vector Calculus in Curvilinear Coordinates	578
A.1 Introduction	578
A.2 Notation	578
A.3 Gradient	579
A.4 Divergence	580
A.5 Curl	582
A.6 Laplacian	584
Appendix B The Helmholtz Theorem	585
Appendix C Units	588
<i>Index</i>	591