

# Contents

---

## CHAPTER 1. ELECTROMAGNETISM

- 1-1 Electrical forces 1-1
- 1-2 Electric and magnetic fields 1-3
- 1-3 Characteristics of vector fields 1-4
- 1-4 The laws of electromagnetism 1-5
- 1-5 What are the fields? 1-9
- 1-6 Electromagnetism in science and technology 1-10

## CHAPTER 2. DIFFERENTIAL CALCULUS OF VECTOR FIELDS

- 2-1 Understanding physics 2-1
- 2-2 Scalar and vector fields— $T$  and  $h$  2-2
- 2-3 Derivatives of fields—the gradient 2-4
- 2-4 The operator  $\nabla$  2-6
- 2-5 Operations with  $\nabla$  2-7
- 2-6 The differential equation of heat flow 2-8
- 2-7 Second derivatives of vector fields 2-9
- 2-8 Pitfalls 2-11

## CHAPTER 3. VECTOR INTEGRAL CALCULUS

- 3-1 Vector integrals; the line integral of  $\nabla\psi$  3-1
- 3-2 The flux of a vector field 3-2
- 3-3 The flux from a cube; Gauss' theorem 3-4
- 3-4 Heat conduction; the diffusion equation 3-6
- 3-5 The circulation of a vector field 3-8
- 3-6 The circulation around a square; Stokes' theorem 3-9
- 3-7 Curl-free and divergence-free fields 3-10
- 3-8 Summary 3-11

## CHAPTER 4. ELECTROSTATICS

- 4-1 Statics 4-1
- 4-2 Coulomb's law; superposition 4-2
- 4-3 Electric potential 4-4
- 4-4  $E = -\nabla\phi$  4-6
- 4-5 The flux of  $E$  4-7
- 4-6 Gauss' law; divergence of  $E$  4-9
- 4-7 Field of a sphere of charge 4-10
- 4-8 Field lines; equipotential surfaces 4-11

## CHAPTER 5. APPLICATION OF GAUSS' LAW

- 5-1 Electrostatics is Gauss' law plus . . . 5-1
- 5-2 Equilibrium in an electrostatic field 5-1
- 5-3 Equilibrium with conductors 5-2
- 5-4 Stability of atoms 5-3
- 5-5 The field of a line charge 5-3
- 5-6 A sheet of charge; two sheets 5-4
- 5-7 A sphere of charge; a spherical shell 5-4
- 5-8 Is the field of a point charge exactly  $1/r^2$ ? 5-5
- 5-9 The fields of a conductor 5-7
- 5-10 The field in a cavity of a conductor 5-8

## CHAPTER 6. THE ELECTRIC FIELD IN VARIOUS CIRCUMSTANCES

- 6-1 Equations of the electrostatic potential 6-1
- 6-2 The electric dipole 6-2
- 6-3 Remarks on vector equations 6-4
- 6-4 The dipole potential as a gradient 6-4
- 6-5 The dipole approximation for an arbitrary distribution 6-6
- 6-6 The fields of charged conductors 6-8
- 6-7 The method of images 6-8
- 6-8 A point charge near a conducting plane 6-9
- 6-9 A point charge near a conducting sphere 6-10
- 6-10 Condensers; parallel plates 6-11
- 6-11 High-voltage breakdown 6-13
- 6-12 The field-emission microscope 6-14

## CHAPTER 7. THE ELECTRIC FIELD IN VARIOUS CIRCUMSTANCES (Continued)

- 7-1 Methods for finding the electrostatic field 7-1
- 7-2 Two-dimensional fields; functions of the complex variable 7-2
- 7-3 Plasma oscillations 7-5
- 7-4 Colloidal particles in an electrolyte 7-8
- 7-5 The electrostatic field of a grid 7-10

## CHAPTER 8. ELECTROSTATIC ENERGY

- 8-1 The electrostatic energy of charges. A uniform sphere 8-1
- 8-2 The energy of a condenser. Forces on charged conductors 8-2
- 8-3 The electrostatic energy of an ionic crystal 8-4
- 8-4 Electrostatic energy in nuclei 8-6
- 8-5 Energy in the electrostatic field 8-9
- 8-6 The energy of a point charge 8-12

## CHAPTER 9. ELECTRICITY IN THE ATMOSPHERE

- 9-1 The electric potential gradient of the atmosphere 9-1
- 9-2 Electric currents in the atmosphere 9-2
- 9-3 Origin of the atmospheric currents 9-4
- 9-4 Thunderstorms 9-5
- 9-5 The mechanism of charge separation 9-7
- 9-6 Lightning 9-10

## CHAPTER 10. DIELECTRICS

- 10-1 The dielectric constant 10-1
- 10-2 The polarization vector  $P$  10-2
- 10-3 Polarization charges 10-3
- 10-4 The electrostatic equations with dielectrics 10-6
- 10-5 Fields and forces with dielectrics 10-7

## CHAPTER 11.—INSIDE DIELECTRICS

- 11-1 Molecular dipoles 11-1
- 11-2 Electronic polarization 11-1
- 11-3 Polar molecules; orientation polarization 11-3
- 11-4 Electric fields in cavities of a dielectric 11-5
- 11-5 The dielectric constant of liquids; the Clausius-Mossotti equation 11-6
- 11-6 Solid dielectrics 11-8
- 11-7 Ferroelectricity; BaTiO<sub>3</sub> 11-8

## CHAPTER 12. ELECTROSTATIC ANALOGS

- 12-1 The same equations have the same solutions 12-1
- 12-2 The flow of heat; a point source near an infinite plane boundary 12-2
- 12-3 The stretched membrane 12-5
- 12-4 The diffusion of neutrons; a uniform spherical source in a homogeneous medium 12-6
- 12-5 Irrotational fluid flow; the flow past a sphere 12-8
- 12-6 Illumination; the uniform lighting of a plane 12-10
- 12-7 The "underlying unity" of nature 12-12

## CHAPTER 13. MAGNETOSTATICS

- 13-1 The magnetic field 13-1
- 13-2 Electric current; the conservation of charge 13-1
- 13-3 The magnetic force on a current 13-2
- 13-4 The magnetic field of steady currents; Ampere's law 13-3
- 13-5 The magnetic field of a straight wire and of a solenoid; atomic currents 13-5
- 13-6 The relativity of magnetic and electric fields 13-6
- 13-7 The transformation of currents and charges 13-11
- 13-8 Superposition; the right-hand rule 13-11

## CHAPTER 14. THE MAGNETIC FIELD IN VARIOUS SITUATIONS

- 14-1 The vector potential 14-1
- 14-2 The vector potential of known currents 14-3
- 14-3 A straight wire 14-4
- 14-4 A long solenoid 14-5
- 14-5 The field of a small loop; the magnetic dipole 14-7
- 14-6 The vector potential of a circuit 14-8
- 14-7 The law of Biot and Savart 14-9

## CHAPTER 15. THE VECTOR POTENTIAL

- 15-1 The forces on a current loop; energy of a dipole 15-1
- 15-2 Mechanical and electrical energies 15-3
- 15-3 The energy of steady currents 15-6
- 15-4  $B$  versus  $A$  15-7
- 15-5 The vector potential and quantum mechanics 15-8
- 15-6 What is true for statics is false for dynamics 15-14

## CHAPTER 16. INDUCED CURRENTS

- 16-1 Motors and generators 16-1
- 16-2 Transformers and inductances 16-4
- 16-3 Forces on induced currents 16-5
- 16-4 Electrical technology 16-8

## CHAPTER 17. THE LAWS OF INDUCTION

- 17-1 The physics of induction 17-1
- 17-2 Exceptions to the "flux rule" 17-2
- 17-3 Particle acceleration by an induced electric field; the betatron 17-3
- 17-4 A paradox 17-5
- 17-5 Alternating-current generator 17-6
- 17-6 Mutual inductance 17-9
- 17-7 Self-inductance 17-11
- 17-8 Inductance and magnetic energy 17-12

## CHAPTER 18. THE MAXWELL EQUATIONS

- 18-1 Maxwell's equations 18-1
- 18-2 How the new term works 18-3
- 18-3 All of classical physics 18-5
- 18-4 A travelling field 18-5
- 18-5 The speed of light 18-8
- 18-6 Solving Maxwell's equations; the potentials and the wave equation 18-9

## CHAPTER 19. THE PRINCIPLE OF LEAST ACTION

- A special lecture—almost verbatim 19-1
- A note added after the lecture 19-14

## CHAPTER 20. SOLUTIONS OF MAXWELL'S EQUATIONS IN FREE SPACE

- 20-1 Waves in free space; plane waves 20-1
- 20-2 Three-dimensional waves 20-8
- 20-3 Scientific imagination 20-9
- 20-4 Spherical waves 20-12

## CHAPTER 21. SOLUTIONS OF MAXWELL'S EQUATIONS WITH CURRENTS AND CHARGES

- 21-1 Light and electromagnetic waves 21-1
- 21-2 Spherical waves from a point source 21-2
- 21-3 The general solution of Maxwell's equations 21-4
- 21-4 The fields of an oscillating dipole 21-5
- 21-5 The potentials of a moving charge; the general solution of Liénard and Wiechert 21-9
- 21-6 The potentials for a charge moving with constant velocity; the Lorentz formula 21-12

## CHAPTER 22. AC CIRCUITS

- 22-1 Impedances 22-1
- 22-2 Generators 22-5
- 22-3 Networks of ideal elements; Kirchhoff's rules 22-7
- 22-4 Equivalent circuits 22-10
- 22-5 Energy 22-11
- 22-6 A ladder network 22-12
- 22-7 Filters 22-14
- 22-8 Other circuit elements 22-16

## CHAPTER 23. CAVITY RESONATORS

- 23-1 Real circuit elements 23-1
- 23-2 A capacitor at high frequencies 23-2
- 23-3 A resonant cavity 23-6
- 23-4 Cavity modes 23-9
- 23-5 Cavities and resonant circuits 23-10

## CHAPTER 24. WAVEGUIDES

- 24-1 The transmission line 24-1
- 24-2 The rectangular waveguide 24-4
- 24-3 The cutoff frequency 24-6
- 24-4 The speed of the guided waves 24-7
- 24-5 Observing guided waves 24-7
- 24-6 Waveguide plumbing 24-8
- 24-7 Waveguide modes 24-10
- 24-8 Another way of looking at the guided waves 24-10

## CHAPTER 25. ELECTRODYNAMICS IN RELATIVISTIC NOTATION

- 25-1 Four-vectors 25-1
- 25-2 The scalar product 25-3
- 25-3 The four-dimensional gradient 25-6
- 25-4 Electrodynamics in four-dimensional notation 25-8
- 25-5 The four-potential of a moving charge 25-9
- 25-6 The invariance of the equations of electrodynamics 25-10

## CHAPTER 26. LORENTZ TRANSFORMATIONS OF THE FIELDS

- 26-1 The four-potential of a moving charge 26-1
- 26-2 The fields of a point charge with a constant velocity 26-2
- 26-3 Relativistic transformation of the fields 26-5
- 26-4 The equations of motion in relativistic notation 26-11

## CHAPTER 27. FIELD ENERGY AND FIELD MOMENTUM

- 27-1 Local conservation 27-1
- 27-2 Energy conservation and electromagnetism 27-2
- 27-3 Energy density and energy flow in the electromagnetic field 27-3
- 27-4 The ambiguity of the field energy 27-6
- 27-5 Examples of energy flow 27-6
- 27-6 Field momentum 27-9

## CHAPTER 28. ELECTROMAGNETIC MASS

- 28-1 The field energy of a point charge 28-1
- 28-2 The field momentum of a moving charge 28-2
- 28-3 Electromagnetic mass 28-3
- 28-4 The force of an electron on itself 28-4
- 28-5 Attempts to modify the Maxwell theory 28-6
- 28-6 The nuclear force field 28-12

## CHAPTER 29. THE MOTION OF CHARGES IN ELECTRIC AND MAGNETIC FIELDS

- 29-1 Motion in a uniform electric or magnetic field 29-1
- 29-2 Momentum analysis 29-1
- 29-3 An electrostatic lens 29-2
- 29-4 A magnetic lens 29-3
- 29-5 The electron microscope 29-3
- 29-6 Accelerator guide fields 29-4
- 29-7 Alternating-gradient focusing 29-6
- 29-8 Motion in crossed electric and magnetic fields 29-8

## CHAPTER 30. THE INTERNAL GEOMETRY OF CRYSTALS

- 30-1 The internal geometry of crystals 30-1
- 30-2 Chemical bonds in crystals 30-2
- 30-3 The growth of crystals 30-3
- 30-4 Crystal lattices 30-3
- 30-5 Symmetries in two dimensions 30-4
- 30-6 Symmetries in three dimensions 30-7
- 30-7 The strength of metals 30-8
- 30-8 Dislocations and crystal growth 30-9
- 30-9 The Bragg-Nye crystal model 30-10

## CHAPTER 31. TENSORS

- 31-1 The tensor of polarizability 31-1
- 31-2 Transforming the tensor components 31-3
- 31-3 The energy ellipsoid 31-3
- 31-4 Other tensors; the tensor of inertia 31-6
- 31-5 The cross product 31-8
- 31-6 The tensor of stress 31-9
- 31-7 Tensors of higher rank 31-11
- 31-8 The four-tensor of electromagnetic momentum 31-12

## CHAPTER 32. REFRACTIVE INDEX OF DENSE MATERIALS

- 32-1 Polarization of matter 32-1
- 32-2 Maxwell's equations in a dielectric 32-3
- 32-3 Waves in a dielectric 32-5
- 32-4 The complex index of refraction 32-8
- 32-5 The index of a mixture 32-8
- 32-6 Waves in metals 32-10
- 32-7 Low-frequency and high-frequency approximations; the skin depth and the plasma frequency 32-11

## CHAPTER 33. REFLECTION FROM SURFACES

- 33-1 Reflection and refraction of light 33-1
- 33-2 Waves in dense materials 33-2
- 33-3 The boundary conditions 33-4
- 33-4 The reflected and transmitted waves 33-7
- 33-5 Reflection from metals 33-11
- 33-6 Total internal reflection 33-12

## CHAPTER 34. THE MAGNETISM OF MATTER

- 34-1 Diamagnetism and paramagnetism 34-1
- 34-2 Magnetic moments and angular momentum 34-3
- 34-3 The precession of atomic magnets 34-4
- 34-4 Diamagnetism 34-5
- 34-5 Larmor's theorem 34-6
- 34-6 Classical physics gives neither diamagnetism nor paramagnetism 34-8
- 34-7 Angular momentum in quantum mechanics 34-8
- 34-8 The magnetic energy of atoms 34-11

## CHAPTER 35. PARAMAGNETISM AND MAGNETIC RESONANCE

- 35-1 Quantized magnetic states 35-1
- 35-2 The Stern-Gerlach experiment 35-3
- 35-3 The Rabi molecular-beam method 35-4
- 35-4 The paramagnetism of bulk materials 35-6
- 35-5 Cooling by adiabatic demagnetization 35-9
- 35-6 Nuclear magnetic resonance 35-10

## CHAPTER 36. FERROMAGNETISM

- 36-1 Magnetization currents 36-1
- 36-2 The field  $H$  36-5
- 36-3 The magnetization curve 36-6
- 36-4 Iron-core inductances 36-8
- 36-5 Electromagnets 36-9
- 36-6 Spontaneous magnetization 36-11

## CHAPTER 37. MAGNETIC MATERIALS

- 37-1 Understanding ferromagnetism 37-1
- 37-2 Thermodynamic properties 37-4
- 37-3 The hysteresis curve 37-5
- 37-4 Ferromagnetic materials 37-10
- 37-5 Extraordinary magnetic materials 37-11

## CHAPTER 38. ELASTICITY

- 38-1 Hooke's law 38-1
- 38-2 Uniform strains 38-2
- 38-3 The torsion bar; shear waves 38-5
- 38-4 The bent beam 38-9
- 38-5 Buckling 38-11

## CHAPTER 39. ELASTIC MATERIALS

- 39-1 The tensor of strain 39-1
- 39-2 The tensor of elasticity 39-4
- 39-3 The motions in an elastic body 39-6
- 39-4 Nonelastic behavior 39-8
- 39-5 Calculating the elastic constants 39-10

## CHAPTER 40. THE FLOW OF DRY WATER

- 40-1 Hydrostatics 40-1
- 40-2 The equations of motion 40-2
- 40-3 Steady flow—Bernoulli's theorem 40-6
- 40-4 Circulation 40-9
- 40-5 Vortex lines 40-10

## CHAPTER 41. THE FLOW OF WET WATER

- 41-1 Viscosity 41-1
- 41-2 Viscous flow 41-4
- 41-3 The Reynolds number 41-5
- 41-4 Flow past a circular cylinder 41-7
- 41-5 The limit of zero viscosity 41-9
- 41-6 Couette flow 41-10

## CHAPTER 42. CURVED SPACE

- 42-1 Curved spaces with two dimensions 42-1
- 42-2 Curvature in three-dimensional space 42-5
- 42-3 Our space is curved 42-6
- 42-4 Geometry in space-time 42-7
- 42-5 Gravity and the principle of equivalence 42-8
- 42-6 The speed of clocks in a gravitational field 42-9
- 42-7 The curvature of space-time 42-11
- 42-8 Motion in curved space-time 42-12
- 42-9 Einstein's theory of gravitation 42-13

## INDEX