

Contents

Part I Mechanics and Basic Relativity

1	Space and Time	3
1.1	Preliminaries to Part I	3
1.2	General Remarks on Space and Time	3
1.3	Space and Time in Classical Mechanics	4
2	Force and Mass	5
2.1	Galileo's Principle (Newton's First Axiom)	5
2.2	Newton's Second Axiom: Inertia; Newton's Equation of Motion	5
2.3	Basic and Derived Quantities; Gravitational Force	6
2.4	Newton's Third Axiom ("Action and Reaction ...")	8
3	Basic Mechanics of Motion in One Dimension	11
3.1	Geometrical Relations for Curves in Space	11
3.2	One-dimensional Standard Problems	13
4	Mechanics of the Damped and Driven Harmonic Oscillator	17
5	The Three Classical Conservation Laws; Two-particle Problems	23
5.1	Theorem for the Total Momentum (or for the Motion of the Center of Mass)	23
5.2	Theorem for the Total Angular Momentum	24
5.3	The Energy Theorem; Conservative Forces	26
5.4	The Two-particle Problem	29
6	Motion in a Central Force Field; Kepler's Problem	31
6.1	Equations of Motion in Planar Polar Coordinates	31
6.2	Kepler's Three Laws of Planetary Motion	32
6.3	Newtonian Synthesis: From Newton's Theory of Gravitation to Kepler	33
6.4	Perihelion Rotation	34

6.5	Newtonian Analysis: From Kepler's Laws to Newtonian Gravitation	36
6.5.1	Newtonian Analysis I: Law of Force from Given Orbits	36
6.5.2	Newtonian Analysis II: From the String Loop Construction of an Ellipse to the Law $F_r = -A/r^2 \dots$	36
6.5.3	Hyperbolas; Comets	37
6.5.4	Newtonian Analysis III: Kepler's Third Law and Newton's Third Axiom	38
6.6	The Runge-Lenz Vector as an Additional Conserved Quantity	39
7	The Rutherford Scattering Cross-section	41
8	Lagrange Formalism I: Lagrangian and Hamiltonian	45
8.1	The Lagrangian Function; Lagrangian Equations of the Second Kind	45
8.2	An Important Example: The Spherical Pendulum with Variable Length	46
8.3	The Lagrangian Equations of the 2nd Kind	47
8.4	Cyclic Coordinates; Conservation of Generalized Momenta ...	49
8.5	The Hamiltonian	50
8.6	The Canonical Equations; Energy Conservation II; Poisson Brackets	51
9	Relativity I: The Principle of Maximal Proper Time (Eigenzeit)	55
9.1	Galilean versus Lorentz Transformations	56
9.2	Minkowski Four-vectors and Their Pseudo-lengths; Proper Time	58
9.3	The Lorentz Force and its Lagrangian	60
9.4	The Hamiltonian for the Lorentz Force; Kinetic versus Canonical Momentum	61
10	Coupled Small Oscillations	63
10.1	Definitions; Normal Frequencies (Eigenfrequencies) and Normal Modes	63
10.2	Diagonalization: Evaluation of the Eigenfrequencies and Normal Modes	65
10.3	A Typical Example: Three Coupled Pendulums with Symmetry	65
10.4	Parametric Resonance: Child on a Swing	68
11	Rigid Bodies	71
11.1	Translational and Rotational Parts of the Kinetic Energy	71

11.2	Moment of Inertia and Inertia Tensor; Rotational Energy and Angular Momentum	72
11.3	Steiner's Theorem; Heavy Roller; Physical Pendulum	74
11.4	Inertia Ellipsoids; Poincot Construction	77
11.5	The Spinning Top I: Torque-free Top	78
11.6	Euler's Equations of Motion and the Stability Problem	79
11.7	The Three Euler Angles φ , ϑ and ψ ; the Cardani Suspension ..	81
11.8	The Spinning Top II: Heavy Symmetric Top	83
12	Remarks on Non-integrable Systems: Chaos	85
13	Lagrange Formalism II: Constraints	89
13.1	D'Alembert's Principle	89
13.2	Exercise: Forces of Constraint for Heavy Rollers on an Inclined Plane	91
14	Accelerated Reference Frames	95
14.1	Newton's Equation in an Accelerated Reference Frame	95
14.2	Coriolis Force and Weather Pattern	97
14.3	Newton's "Bucket Experiment" and the Problem of Inertial Frames	98
14.4	Application: Free Falling Bodies with Earth Rotation	99
15	Relativity II: $E=mc^2$	101

Part II Electrodynamics and Aspects of Optics

16	Introduction and Mathematical Preliminaries to Part II ..	109
16.1	Different Systems of Units in Electromagnetism	109
16.2	Mathematical Preliminaries I: Point Charges and Dirac's δ Function	112
16.3	Mathematical Preliminaries II: Vector Analysis	114
17	Electrostatics and Magnetostatics	119
17.1	Electrostatic Fields in Vacuo	119
17.1.1	Coulomb's Law and the Principle of Superposition ...	119
17.1.2	Integral for Calculating the Electric Field	120
17.1.3	Gauss's Law	121
17.1.4	Applications of Gauss's Law: Calculating the Electric Fields for Cases of Spherical or Cylindrical Symmetry	123
17.1.5	The Curl of an Electrostatic Field; The Electrostatic Potential	124

17.1.6	General Curvilinear, Spherical and Cylindrical Coordinates	126
17.1.7	Numerical Calculation of Electric Fields	131
17.2	Electrostatic and Magnetostatic Fields in Polarizable Matter	132
17.2.1	Dielectric Behavior	132
17.2.2	Dipole Fields; Quadrupoles	132
17.2.3	Electric Polarization	133
17.2.4	Multipole Moments and Multipole Expansion	134
17.2.5	Magnetostatics	139
17.2.6	Forces and Torques on Electric and Magnetic Dipoles	140
17.2.7	The Field Energy	141
17.2.8	The Demagnetization Tensor	142
17.2.9	Discontinuities at Interfaces	143
18	Magnetic Field of Steady Electric Currents	145
18.1	Ampère's Law	145
18.1.1	An Application: 2d Boundary Currents for Superconductors; The Meissner Effect	146
18.2	The Vector Potential; Gauge Transformations	147
18.3	The Biot-Savart Equation	148
18.4	Ampère's Current Loops and their Equivalent Magnetic Dipoles	149
18.5	Gyromagnetic Ratio and Spin Magnetism	151
19	Maxwell's Equations I: Faraday's and Maxwell's Laws	153
19.1	Faraday's Law of Induction and the Lorentz Force	153
19.2	The Continuity Equation	156
19.3	Ampère's Law with Maxwell's Displacement Current	156
19.4	Applications: Complex Resistances etc.	158
20	Maxwell's Equations II: Electromagnetic Waves	163
20.1	The Electromagnetic Energy Theorem; Poynting Vector	163
20.2	Retarded Scalar and Vector Potentials I: D'Alembert's Equation	165
20.3	Planar Electromagnetic Waves; Spherical Waves	166
20.4	Retarded Scalar and Vector Potentials II: The Superposition Principle with Retardation	169
20.5	Hertz's Oscillating Dipole (Electric Dipole Radiation, Mobile Phones)	170
20.6	Magnetic Dipole Radiation; Synchrotron Radiation	171
20.7	General Multipole Radiation	173
20.8	Relativistic Invariance of Electrodynamics	174

21 Applications of Electrodynamics in the Field of Optics	179
21.1 Introduction: Wave Equations; Group and Phase Velocity . . .	179
21.2 From Wave Optics to Geometrical Optics; Fermat's Principle	185
21.3 Crystal Optics and Birefringence	188
21.4 On the Theory of Diffraction	192
21.4.1 Fresnel Diffraction at an Edge; Near-field Microscopy	194
21.4.2 Fraunhofer Diffraction at a Rectangular and Circular Aperture; Optical Resolution	197
21.5 Holography	199
22 Conclusion to Part II	203
<hr/>	
Part III Quantum Mechanics	
<hr/>	
23 On the History of Quantum Mechanics	207
24 Quantum Mechanics: Foundations	211
24.1 Physical States	211
24.1.1 Complex Hilbert Space	212
24.2 Measurable Physical Quantities (Observables)	213
24.3 The Canonical Commutation Relation	216
24.4 The Schrödinger Equation; Gauge Transformations	216
24.5 Measurement Process	218
24.6 Wave-particle Duality	219
24.7 Schrödinger's Cat: Dead <i>and</i> Alive?	220
25 One-dimensional Problems in Quantum Mechanics	223
25.1 Bound Systems in a Box (Quantum Well); Parity	224
25.2 Reflection and Transmission at a Barrier; Unitarity	226
25.3 Probability Current	228
25.4 Tunneling	228
26 The Harmonic Oscillator I	231
27 The Hydrogen Atom according to Schrödinger's Wave Mechanics	235
27.1 Product Ansatz; the Radial Function	235
27.1.1 Bound States ($E < 0$)	237
27.1.2 The Hydrogen Atom for Positive Energies ($E > 0$) . . .	238
27.2 Spherical Harmonics	239
28 Abstract Quantum Mechanics (Algebraic Methods)	241
28.1 The Harmonic Oscillator II: Creation and Destruction Operators	241
28.2 Quantization of the Angular Momenta; Ladder Operators . . .	243

28.3	Unitary Equivalence; Change of Representation	245
29	Spin Momentum and the Pauli Principle (Spin-statistics Theorem)	249
29.1	Spin Momentum; the Hamilton Operator with Spin-orbit Interaction	249
29.2	Rotation of Wave Functions with Spin; Pauli's Exclusion Principle	251
30	Addition of Angular Momenta	255
30.1	Composition Rules for Angular Momenta	255
30.2	Fine Structure of the p-Levels; Hyperfine Structure	256
30.3	Vector Model of the Quantization of the Angular Momentum	257
31	Ritz Minimization	259
32	Perturbation Theory for Static Problems	261
32.1	Formalism and Results	261
32.2	Application I: Atoms in an Electric Field; The Stark Effect	263
32.3	Application II: Atoms in a Magnetic Field; Zeeman Effect	264
33	Time-dependent Perturbations	267
33.1	Formalism and Results; Fermi's "Golden Rules"	267
33.2	Selection Rules	269
34	Magnetism: An Essentially Quantum Mechanical Phenomenon	271
34.1	Heitler and London's Theory of the H ₂ -Molecule	271
34.2	Hund's Rule. Why is the O ₂ -Molecule Paramagnetic?	275
35	Cooper Pairs; Superconductors and Superfluids	277
36	On the Interpretation of Quantum Mechanics (Reality?, Locality?, Retardation?)	279
36.1	Einstein-Podolski-Rosen Experiments	279
36.2	The Aharonov-Bohm Effect; Berry Phases	281
36.3	Quantum Computing	283
36.4	2d Quantum Dots	285
36.5	Interaction-free Quantum Measurement; "Which Path?" Experiments	287
36.6	Quantum Cryptography	289
37	Quantum Mechanics: Retrospect and Prospect	293
38	Appendix: "Mutual Preparation Algorithm" for Quantum Cryptography	297

Part IV Thermodynamics and Statistical Physics

39	Introduction and Overview to Part IV	301
40	Phenomenological Thermodynamics:	
	Temperature and Heat	303
	40.1 Temperature	303
	40.2 Heat	305
	40.3 Thermal Equilibrium and Diffusion of Heat	306
	40.4 Solutions of the Diffusion Equation	307
41	The First and Second Laws of Thermodynamics	313
	41.1 Introduction: Work	313
	41.2 First and Second Laws: Equivalent Formulations	315
	41.3 Some Typical Applications: C_V and $\frac{\partial U}{\partial V}$; The Maxwell Relation	316
	41.4 General Maxwell Relations	318
	41.5 The Heat Capacity Differences $C_p - C_V$ and $C_H - C_m$	318
	41.6 Enthalpy and the Joule-Thomson Experiment; Liquefaction of Air	319
	41.7 Adiabatic Expansion of an Ideal Gas	324
42	Phase Changes, van der Waals Theory and Related Topics	327
	42.1 Van der Waals Theory	327
	42.2 Magnetic Phase Changes; The Arrott Equation	330
	42.3 Critical Behavior; Ising Model; Magnetism and Lattice Gas ..	332
43	The Kinetic Theory of Gases	335
	43.1 Aim	335
	43.2 The General Bernoulli Pressure Formula	335
	43.3 Formula for Pressure in an Interacting System	341
44	Statistical Physics	343
	44.1 Introduction; Boltzmann-Gibbs Probabilities	343
	44.2 The Harmonic Oscillator and Planck's Formula	344
45	The Transition to Classical Statistical Physics	349
	45.1 The Integral over Phase Space; Identical Particles in Classical Statistical Physics	349
	45.2 The Rotational Energy of a Diatomic Molecule	350

46	Advanced Discussion of the Second Law	353
46.1	Free Energy	353
46.2	On the Impossibility of Perpetual Motion of the Second Kind	354
47	Shannon's Information Entropy	359
48	Canonical Ensembles in Phenomenological Thermodynamics	363
48.1	Closed Systems and Microcanonical Ensembles	363
48.2	The Entropy of an Ideal Gas from the Microcanonical Ensemble	363
48.3	Systems in a Heat Bath: Canonical and Grand Canonical Distributions	366
48.4	From Microcanonical to Canonical and Grand Canonical Ensembles	367
49	The Clausius-Clapeyron Equation	369
50	Production of Low and Ultralow Temperatures; Third Law	371
51	General Statistical Physics (Statistical Operator; Trace Formalism)	377
52	Ideal Bose and Fermi Gases	379
53	Applications I: Fermions, Bosons, Condensation Phenomena	383
53.1	Electrons in Metals (Sommerfeld Formalism)	383
53.2	Some Semiquantitative Considerations on the Development of Stars	387
53.3	Bose-Einstein Condensation	391
53.4	Ginzburg-Landau Theory of Superconductivity	395
53.5	Debye Theory of the Heat Capacity of Solids	399
53.6	Landau's Theory of 2nd-order Phase Transitions	403
53.7	Molecular Field Theories; Mean Field Approaches	405
53.8	Fluctuations	408
53.9	Monte Carlo Simulations	411
54	Applications II: Phase Equilibria in Chemical Physics	413
54.1	Additivity of the Entropy; Partial Pressure; Entropy of Mixing	413
54.2	Chemical Reactions; the Law of Mass Action	416
54.3	Electron Equilibrium in Neutron Stars	417
54.4	Gibbs' Phase Rule	419

54.5 Osmotic Pressure 420

54.6 Decrease of the Melting Temperature Due to “De-icing” Salt . 422

54.7 The Vapor Pressure of Spherical Droplets 423

55 Conclusion to Part IV 427

References 431

Index 435

Basic Theoretical Physics

A Concise Overview

Krey, U.; Owen, A.

2007, XVI, 452 p. 31 illus., Hardcover

ISBN: 978-3-540-36804-5