

Modern Condensed Matter Physics

Modern Condensed Matter Physics brings together the most important advances in the field from recent decades. It provides instructors teaching graduate-level condensed matter courses with a comprehensive and in-depth textbook that will prepare graduate students for research or further study alongside reading more advanced and specialized books and research literature in the field.

This textbook covers the basics of crystalline solids as well as analogous optical lattices and photonic crystals, while discussing cutting-edge topics such as disordered systems, mesoscopic systems, many-body systems, quantum magnetism, Bose–Einstein condensates, quantum entanglement, and superconducting quantum bits.

Students are provided with the appropriate mathematical background to understand the topological concepts that have been permeating the field, together with numerous physical examples ranging from the fractional quantum Hall effect to topological insulators, the toric code, and Majorana fermions. Exercises, commentary boxes, and appendices afford guidance and feedback for beginners and experts alike.

Steven M. Girvin received his BS in 1971 from Bates College and his PhD in 1977 from Princeton University. He joined the Yale faculty in 2001, where he is Eugene Higgins Professor of Physics and Professor of Applied Physics. From 2007 to 2017 he served as Deputy Provost for Research. His research interests focus on theoretical condensed matter physics, quantum optics, and quantum computation; he is co-developer of the circuit QED paradigm for quantum computation.

Honors: Fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences; Foreign Member of the Royal Swedish Academy of Sciences, Member of the US National Academy of Sciences; Oliver E. Buckley Prize of the American Physical Society (2007); Honorary doctorate, Chalmers University of Technology (2017); Conde Award for Teaching Excellence (2003).

Kun Yang received his BS in 1989 from Fudan University and his PhD in 1994 from Indiana University. In 1999 he joined the faculty of Florida State University, where he is now McKenzie Professor of Physics. His research focuses on many-particle physics in condensed matter and trapped-cold-atom systems.

Honors: Fellow of the American Physical Society and the American Association for the Advancement of Science; Alfred Sloan Research Fellowship (1999); Outstanding Young Researcher Award, Overseas Chinese Physics Association (2003).

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STEVEN M. GIRVIN

Yale University, Connecticut

KUN YANG

Florida State University



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Brief contents


<i>Preface</i>	<i>page</i> xvii
<i>Acknowledgments</i>	xix
1 Overview of Condensed Matter Physics	1
2 Spatial Structure	9
3 Lattices and Symmetries	20
4 Neutron Scattering	44
5 Dynamics of Lattice Vibrations	64
6 Quantum Theory of Harmonic Crystals	78
7 Electronic Structure of Crystals	98
8 Semiclassical Transport Theory	164
9 Semiconductors	198
10 Non-local Transport in Mesoscopic Systems	222
11 Anderson Localization	252
12 Integer Quantum Hall Effect	301
13 Topology and Berry Phase	331
14 Topological Insulators and Semimetals	362
15 Interacting Electrons	376
16 Fractional Quantum Hall Effect	430



vi	BRIEF CONTENTS	
17	Magnetism	480
18	Bose–Einstein Condensation and Superfluidity	531
19	Superconductivity: Basic Phenomena and Phenomenological Theories	549
20	Microscopic Theory of Superconductivity	592
Appendix A.	Linear-Response Theory	632
Appendix B.	The Poisson Summation Formula	640
Appendix C.	Tunneling and Scanning Tunneling Microscopy	642
Appendix D.	Brief Primer on Topology	647
Appendix E.	Scattering Matrices, Unitarity, and Reciprocity	657
Appendix F.	Quantum Entanglement in Condensed Matter Physics	659
Appendix G.	Linear Response and Noise in Electrical Circuits	665
Appendix H.	Functional Differentiation	673
Appendix I.	Low-Energy Effective Hamiltonians	675
Appendix J.	Introduction to Second Quantization	680
	<i>References</i>	685
	<i>Index</i>	692

Contents


<i>Preface</i>	<i>page</i> xvii
<i>Acknowledgments</i>	xix
1 Overview of Condensed Matter Physics	1
1.1 Definition of Condensed Matter and Goals of Condensed Matter Physics	1
1.2 Classification (or Phases) of Condensed Matter Systems	3
1.2.1 Atomic Spatial Structures	4
1.2.2 Electronic Structures or Properties	4
1.2.3 Symmetries	5
1.2.4 Beyond Symmetries 	6
1.3 Theoretical Descriptions of Condensed Matter Phases	6
1.4 Experimental Probes of Condensed Matter Systems	8
2 Spatial Structure	9
2.1 Probing the Structure	9
2.2 Semiclassical Theory of X-Ray Scattering	10
2.3 Quantum Theory of Electron–Photon Interaction and X-Ray Scattering 	13
2.4 X-Ray Scattering from a Condensed Matter System	15
2.5 Relationship of $S(\vec{q})$ and Spatial Correlations	16
2.6 Liquid State versus Crystal State	17
3 Lattices and Symmetries	20
3.1 The Crystal as a Broken-Symmetry State	20
3.2 Bravais Lattices and Lattices with Bases	24
3.2.1 Bravais Lattices	24
3.2.2 Lattices with Bases	26
3.2.3 Lattice Symmetries in Addition to Translation	29
3.3 Reciprocal Lattices	30
3.4 X-Ray Scattering from Crystals	34
3.5 Effects of Lattice Fluctuations on X-Ray Scattering	38
3.6 Notes and Further Reading	41
4 Neutron Scattering	44
4.1 Introduction to Neutron Scattering	44
4.2 Inelastic Neutron Scattering	46

viii	CONTENTS	
4.3	Dynamical Structure Factor and f -Sum Rule	50
4.3.1	Classical Harmonic Oscillator	54
4.3.2	Quantum Harmonic Oscillator	56
4.4	Single-Mode Approximation and Superfluid ^4He	60
5	Dynamics of Lattice Vibrations	64
5.1	Elasticity and Sound Modes in Continuous Media	64
5.2	Adiabatic Approximation and Harmonic Expansion of Atomic Potential	68
5.3	Classical Dynamics of Lattice Vibrations	71
6	Quantum Theory of Harmonic Crystals	78
6.1	Heat Capacity	78
6.2	Canonical Quantization of Lattice Vibrations	83
6.3	Quantum Dynamical Structure Factor	88
6.4	Debye–Waller Factor and Stability of Crystalline Order	91
6.5	Mössbauer Effect	93
7	Electronic Structure of Crystals	98
7.1	Drude Theory of Electron Conduction in Metals	98
7.2	Independent Electron Model	104
7.3	Bloch’s Theorem	105
7.3.1	Band Gaps and Bragg Reflection	114
7.3.2	Van Hove Singularities	115
7.3.3	Velocity of Bloch Electrons	116
7.4	Tight-Binding Method	117
7.4.1	Bonds vs. Bands	122
7.4.2	Wannier Functions	122
7.4.3	Continuum Limit of Tight-Binding Hamiltonians	124
7.4.4	Limitations of the Tight-Binding Model	126
7.4.5	s – d Hybridization in Transition Metals 	129
7.5	Graphene Band Structure	133
7.6	Polyacetylene and the Su–Schrieffer–Heeger Model	138
7.6.1	Dirac electrons in 1D and the Peierls instability	138
7.6.2	Ground-State Degeneracy and Solitons	142
7.6.3	Zero Modes Bound to Solitons	144
7.6.4	Quantum Numbers of Soliton States and Spin–Charge Separation	147
7.7	Thermodynamic Properties of Bloch Electrons	148
7.7.1	Specific Heat	149
7.7.2	Magnetic Susceptibility	150
7.8	Spin–Orbit Coupling and Band Structure	153
7.9	Photonic Crystals	156
7.10	Optical Lattices	159
7.10.1	Oscillator Model of Atomic Polarizability	160
7.10.2	Quantum Effects in Optical Lattices	162
8	Semiclassical Transport Theory	164
8.1	Review of Semiclassical Wave Packets	164

CONTENTS	ix
8.2 Semiclassical Wave-Packet Dynamics in Bloch Bands	165
8.2.1 Derivation of Bloch Electron Equations of Motion 	169
8.2.2 Zener Tunneling (or Interband Transitions)	171
8.3 Holes	171
8.4 Uniform Magnetic Fields	173
8.5 Quantum Oscillations	176
8.6 Semiclassical $\vec{E} \times \vec{B}$ Drift	179
8.7 The Boltzmann Equation	181
8.8 Boltzmann Transport	186
8.8.1 Einstein Relation	191
8.9 Thermal Transport and Thermoelectric Effects	193
9 Semiconductors	198
9.1 Homogeneous Bulk Semiconductors	198
9.2 Impurity Levels	204
9.3 Optical Processes in Semiconductors	207
9.3.1 Angle-Resolved Photoemission Spectroscopy	210
9.4 The p–n Junction	212
9.4.1 Light-Emitting Diodes and Solar Cells	215
9.5 Other Devices	216
9.5.1 Metal–Oxide–Semiconductor Field-Effect Transistors (MOSFETs)	216
9.5.2 Heterostructures	217
9.5.3 Quantum Point Contact, Wire and Dot	220
9.6 Notes and Further Reading	221
10 Non-local Transport in Mesoscopic Systems	222
10.1 Introduction to Transport of Electron Waves	222
10.2 Landauer Formula and Conductance Quantization	225
10.3 Multi-terminal Devices	231
10.4 Universal Conductance Fluctuations	233
10.4.1 Transmission Eigenvalues	238
10.4.2 UCF Fingerprints	240
10.5 Noise in Mesoscopic Systems	242
10.5.1 Quantum Shot Noise	245
10.6 Dephasing	248
11 Anderson Localization	252
11.1 Absence of Diffusion in Certain Random Lattices	253
11.2 Classical Diffusion	256
11.3 Semiclassical Diffusion	258
11.3.1 Review of Scattering from a Single Impurity	258
11.3.2 Scattering from Many Impurities	262
11.3.3 Multiple Scattering and Classical Diffusion	265
11.4 Quantum Corrections to Diffusion	267
11.4.1 Real-Space Picture	268
11.4.2 Enhanced Backscattering	269

x	CONTENTS	
11.5	Weak Localization in 2D	271
11.5.1	Magnetic Fields and Spin–Orbit Coupling	273
11.6	Strong Localization in 1D	275
11.7	Localization and Metal–Insulator Transition in 3D	277
11.8	Scaling Theory of Localization and the Metal–Insulator Transition	279
11.8.1	Thouless Picture of Conductance	279
11.8.2	Persistent Currents in Disordered Mesoscopic Rings	282
11.8.3	Scaling Theory	283
11.8.4	Scaling Hypothesis and Universality	284
11.9	Scaling and Transport at Finite Temperature 	287
11.9.1	Mobility Gap and Activated Transport	291
11.9.2	Variable-Range Hopping	292
11.10	Anderson Model	294
11.11	Many-Body Localization 	297
12	Integer Quantum Hall Effect	301
12.1	Hall-Effect Transport in High Magnetic Fields	301
12.2	Why 2D Is Important	304
12.3	Why Disorder and Localization Are Important	305
12.4	Classical and Semiclassical Dynamics	306
12.4.1	Classical Dynamics	306
12.4.2	Semiclassical Approximation	308
12.5	Quantum Dynamics in Strong B Fields	309
12.6	IQHE Edge States	315
12.7	Semiclassical Percolation Picture of the IQHE	318
12.8	Anomalous Integer Quantum Hall Sequence in Graphene	321
12.9	Magnetic Translation Invariance and Magnetic Bloch Bands	324
12.9.1	Simple Landau Gauge Example	327
12.10	Quantization of the Hall Conductance in Magnetic Bloch Bands	329
13	Topology and Berry Phase	331
13.1	Adiabatic Evolution and the Geometry of Hilbert Space	331
13.2	Berry Phase and the Aharonov–Bohm Effect	336
13.3	Spin-1/2 Berry Phase	339
13.3.1	Spin–Orbit Coupling and Suppression of Weak Localization	343
13.4	Berry Curvature of Bloch Bands and Anomalous Velocity	344
13.4.1	Anomalous Velocity	345
13.5	Topological Quantization of Hall Conductance of Magnetic Bloch Bands	348
13.5.1	Wannier Functions of Topologically Non-trivial Bands	351
13.5.2	Band Crossing and Change of Band Topology	352
13.5.3	Relation Between the Chern Number and Chiral Edge States: Bulk–Edge Correspondence	353
13.6	An Example of Bands Carrying Non-zero Chern Numbers: Haldane Model	356
13.7	Thouless Charge Pump and Electric Polarization	358
13.7.1	Modern Theory of Electric Polarization	360

CONTENTS	xi
14 Topological Insulators and Semimetals	362
14.1 Kane–Mele Model	362
14.2 \mathbb{Z}_2 Characterization of Topological Insulators	364
14.3 Massless Dirac Surface/Interface States	368
14.4 Weyl Semimetals	371
14.4.1 Fermi Arcs on the Surface	372
14.4.2 Chiral Anomaly	373
14.5 Notes and Further Reading	375
15 Interacting Electrons	376
15.1 Hartree Approximation	376
15.2 Hartree–Fock Approximation	378
15.2.1 Koopmans’ Theorem	381
15.3 Hartree–Fock Approximation for the 3D Electron Gas	382
15.3.1 Total Exchange Energy of the 3DEG in the Hartree–Fock Approximation	384
15.4 Density Functional Theory	385
15.5 Kohn–Sham Single-Particle Equations	387
15.6 Local-Density Approximation	389
15.7 Density–Density Response Function and Static Screening	391
15.7.1 Thomas–Fermi Approximation	394
15.7.2 Lindhard Approximation	394
15.8 Dynamical Screening and Random-Phase Approximation	396
15.9 Plasma Oscillation and Plasmon Dispersion	397
15.9.1 Plasma Frequency and Plasmon Dispersion from the RPA	397
15.9.2 Plasma Frequency from Classical Dynamics	398
15.9.3 Plasma Frequency and Plasmon Dispersion from the Single-Mode Approximation	399
15.10 Dielectric Function and Optical Properties	400
15.10.1 Dielectric Function and AC Conductivity	400
15.10.2 Optical Measurements of Dielectric Function	401
15.11 Landau’s Fermi-Liquid Theory	402
15.11.1 Elementary Excitations of a Free Fermi Gas	402
15.11.2 Adiabaticity and Elementary Excitations of an Interacting Fermi Gas	404
15.11.3 Fermi-Liquid Parameters	407
15.12 Predictions of Fermi-Liquid Theory	409
15.12.1 Heat Capacity	409
15.12.2 Compressibility	410
15.12.3 Spin Susceptibility	411
15.12.4 Collective Modes, Dynamical and Transport Properties	411
15.13 Instabilities of Fermi Liquids	412
15.13.1 Ferromagnetic Instability	412
15.13.2 Pomeranchuk Instabilities	413
15.13.3 Pairing Instability	414
15.13.4 Charge and Spin Density-Wave Instabilities	418
15.13.5 One Dimension	419
15.13.6 Two-Dimensional Electron Gas at High Magnetic Field	420

xii	CONTENTS	
15.14	Infrared Singularities in Fermi Liquids	420
15.14.1	Perfect Screening and the Friedel Sum Rule	420
15.14.2	Orthogonality Catastrophe	422
15.14.3	Magnetic Impurities in Metals: The Kondo Problem	423
15.15	Summary and Outlook	429
16	Fractional Quantum Hall Effect	430
16.1	Landau Levels Revisited	431
16.2	One-Body Basis States in Symmetric Gauge	433
16.3	Two-Body Problem and Haldane Pseudopotentials	435
16.4	The $\nu = 1$ Many-Body State and Plasma Analogy	438
16.4.1	Electron and Hole Excitations at $\nu = 1$	441
16.5	Laughlin's Wave Function	442
16.6	Quasiparticle and Quasihole Excitations of Laughlin States	446
16.7	Fractional Statistics of Laughlin Quasiparticles	452
16.7.1	Possibility of Fractional Statistics in 2D	452
16.7.2	Physical Model of Anyons	455
16.7.3	Statistics Angle of Laughlin Quasiholes	457
16.8	Collective Excitations 	460
16.9	Bosonization and Fractional Quantum Hall Edge States	463
16.9.1	Shot-Noise Measurement of Fractional Quasiparticle Charge	467
16.10	Composite Fermions and Hierarchy States	469
16.10.1	Another Take on Laughlin's Wave Function	469
16.10.2	Jain Sequences	470
16.11	General Formalism of Electron Dynamics Confined to a Single Landau Level	470
16.11.1	Finite-Size Geometries	474
16.12	Relation between Fractional Statistics and Topological Degeneracy	476
16.13	Notes and Further Reading	478
17	Magnetism	480
17.1	Basics	480
17.2	Classical Theory of Magnetism	481
17.3	Quantum Theory of Magnetism of Individual Atoms	481
17.3.1	Quantum Diamagnetism	482
17.3.2	Quantum Paramagnetism	485
17.3.3	Quantum Spin	486
17.4	The Hubbard Model and Mott Insulators	486
17.5	Magnetically Ordered States and Spin-Wave Excitations	491
17.5.1	Ferromagnets	491
17.5.2	Antiferromagnets	495
17.6	One Dimension	499
17.6.1	Lieb–Schultz–Mattis Theorem	501
17.6.2	Spin-1/2 Chains	502
17.6.3	Spin-1 Chains, Haldane Gap, and String Order	506
17.6.4	Matrix Product and Tensor Network States	510

CONTENTS	xiii
17.7 Valence-Bond-Solid and Spin-Liquid States in 2D and Higher Dimensions	513
17.7.1 \mathbb{Z}_2 Topological Order in Resonating Valence-Bond Spin Liquid	519
17.8 An Exactly Solvable Model of \mathbb{Z}_2 Spin Liquid: Kitaev's Toric Code	521
17.8.1 Toric Code as Quantum Memory	525
17.9 Landau Diamagnetism	528
18 Bose–Einstein Condensation and Superfluidity	531
18.1 Non-interacting Bosons and Bose–Einstein Condensation	531
18.1.1 Off-Diagonal Long-Range Order	534
18.1.2 Finite Temperature and Effects of Trapping Potential	535
18.1.3 Experimental Observation of Bose–Einstein Condensation	536
18.2 Weakly Interacting Bosons and Bogoliubov Theory	539
18.3 Stability of Condensate and Superfluidity	542
18.4 Bose–Einstein Condensation of Exciton-Polaritons: Quantum Fluids of Light	545
19 Superconductivity: Basic Phenomena and Phenomenological Theories	549
19.1 Thermodynamics	549
19.1.1 Type-I Superconductors	550
19.1.2 Type-II Superconductors	552
19.2 Electrodynamics	553
19.3 Meissner Kernel	556
19.4 The Free-Energy Functional	558
19.5 Ginzburg–Landau Theory	559
19.6 Type-II Superconductors	566
19.6.1 Abrikosov Vortex Lattice	568
19.6.2 Isolated Vortices	569
19.7 Why Do Superconductors Superconduct?	573
19.8 Comparison between Superconductivity and Superfluidity	576
19.9 Josephson Effect	579
19.9.1 Superconducting Quantum Interference Devices (SQUIDS)	585
19.10 Flux-Flow Resistance in Superconductors	587
19.11 Superconducting Quantum Bits	587
20 Microscopic Theory of Superconductivity	592
20.1 Origin of Attractive Interaction	592
20.2 BCS Reduced Hamiltonian and Mean-Field Solution	594
20.2.1 Condensation Energy	598
20.2.2 Elementary Excitations	599
20.2.3 Finite-Temperature Properties	602
20.3 Microscopic Derivation of Josephson Coupling	603
20.4 Electromagnetic Response of Superconductors	606
20.5 BCS–BEC Crossover	609
20.6 Real-Space Formulation and the Bogoliubov–de Gennes Equation	611
20.7 Kitaev's p -Wave Superconducting Chain and Topological Superconductors	614

xiv	CONTENTS	
20.8	Unconventional Superconductors	617
20.8.1	General Solution of Cooper Problem	617
20.8.2	General Structure of Pairing Order Parameter	619
20.8.3	Fulde–Ferrell–Larkin–Ovchinnikov States	620
20.9	High-Temperature Cuprate Superconductors	621
20.9.1	Antiferromagnetism in the Parent Compound	622
20.9.2	Effects of Doping	624
20.9.3	Nature of the Superconducting State	624
20.9.4	Why <i>d</i> -Wave?	627
Appendix A. Linear-Response Theory		632
A.1	Static Response	632
A.2	Dynamical Response	634
A.3	Causality, Spectral Densities, and Kramers–Kronig Relations	636
Appendix B. The Poisson Summation Formula		640
Appendix C. Tunneling and Scanning Tunneling Microscopy		642
C.1	A Simple Example	642
C.2	Tunnel Junction	643
C.3	Scanning Tunneling Microscopy	645
Appendix D. Brief Primer on Topology		647
D.1	Introduction	647
D.2	Homeomorphism	648
D.3	Homotopy	648
D.4	Fundamental Group	650
D.5	Gauss–Bonnet Theorem	651
D.6	Topological Defects	654
Appendix E. Scattering Matrices, Unitarity, and Reciprocity		657
Appendix F. Quantum Entanglement in Condensed Matter Physics		659
F.1	Reduced Density Matrix	659
F.2	Schmidt and Singular-Value Decompositions	661
F.3	Entanglement Entropy Scaling Laws	662
F.4	Other Measures of Entanglement	663
F.5	Closing Remarks	664
Appendix G. Linear Response and Noise in Electrical Circuits		665
G.1	Classical Thermal Noise in a Resistor	665
G.2	Linear Response of Electrical Circuits	668
G.3	Hamiltonian Description of Electrical Circuits	670
G.3.1	Hamiltonian for Josephson Junction Circuits	672
Appendix H. Functional Differentiation		673

CONTENTS	xv
Appendix I. Low-Energy Effective Hamiltonians	675
I.1 Effective Tunneling Hamiltonian	675
I.2 Antiferromagnetism in the Hubbard Model	677
I.3 Summary	679
Appendix J. Introduction to Second Quantization	680
J.1 Second Quantization	680
J.2 Majorana Representation of Fermion Operators	683
<i>References</i>	685
<i>Index</i>	692

Preface

This textbook is intended for both introductory and more advanced graduate-level courses in condensed matter physics and as a pedagogical reference for researchers in the field. This modern textbook provides graduate students with a comprehensive and accessible route from fundamental concepts to modern topics, language, and methods in the rapidly advancing field of quantum condensed matter physics.

The field has progressed and expanded dramatically since the publication four decades ago of the classic text by Ashcroft and Mermin [1], and its name has changed from Solid State Physics to Condensed Matter Physics, reflecting this expansion. The field of inquiry is vast and is typically divided into two halves. The first, often called “soft matter,” covers the classical statistical physics of liquid crystals, glassy materials, polymers, and certain biological systems and materials. This area is nicely addressed in the textbook of Chaikin and Lubensky [2]. The second area, often called “hard matter” or “quantum matter,” primarily covers the quantum physics of electrons in solids but these days also includes correlated quantum states of ultra-cold atomic gases and even photons. While a number of good textbooks [3–5] address various aspects of hard matter, the present text offers broader and more in-depth coverage of the field and provides physical intuition through many deep phenomenological descriptions, in addition to introducing the required mathematical background.

The present text is aimed primarily at graduate students and researchers in quantum condensed matter physics and provides encyclopedic coverage of this very dynamic field. While sharing a similar starting point with Ashcroft and Mermin, we have attempted to cover the aforementioned new developments in considerably greater depth and detail, while providing an overarching perspective on unifying concepts and methodologies. Chapters 1–9 cover traditional introductory concepts, but we have made considerable effort to provide a modern perspective on them. The later chapters introduce modern developments both in theory and in experiment. Among the new topics are coherent transport in mesoscopic systems, Anderson and many-body localization in disordered systems, the integer and fractional quantum Hall effects, Berry phases and the topology of Bloch bands, topological insulators and semimetals, instabilities of Fermi liquids, modern aspects of quantum magnetism (e.g. spinons, the Haldane gap, spin liquids, and the toric code), quantum entanglement, Bose–Einstein condensation, a pedagogical introduction to the phenomenology of superfluidity and superconductivity, superconducting quantum bits (qubits), and finally a modern review of BCS theory that includes unconventional pairing, high-temperature superconductivity, topological superconductors, and majorana fermions. We have also attempted to make contact with other fields, in particular ultra-cold atomic gases, photonic crystals, and quantum information science, emphasizing the unifying principles

among different branches of physics. For this reason the text should also be of interest to students and practitioners outside condensed matter physics.

The text is intended to be accessible and useful to experimentalists and theorists alike, providing an introduction both to the phenomenology and to the underlying theoretical description. In particular, we provide the mathematical background needed to understand the topological aspects of condensed matter systems. We also provide a gentle and accessible introduction to scaling and renormalization group methods with applications to Anderson localization, the Kondo problem, and the modern approach to the BCS problem. The text assumes prior knowledge of quantum mechanics and statistical physics at the level of typical first-year graduate courses. Undergraduate preparation in condensed matter physics at the level of Kittel [6] would be useful but is not essential. We make extensive use of harmonic oscillator ladder operators but almost completely avoid second quantization for fermions until Chapter 17. In addition, we provide a pedagogical appendix for the reader to review second quantization.

Recent decades have seen the application of advanced methods from quantum field theory which provide effective descriptions of “universal” features of strongly correlated many-body quantum systems, usually in the long-wavelength and low-energy limit [7–15]. The present text provides a pedagogical gateway to courses on these advanced methods by introducing and using the language of many-body theory and quantum field theory where appropriate.

This book has evolved over several decades from course notes for graduate condensed matter physics taught by the authors at Indiana University and Florida State University, respectively. The content exceeds the amount of material which can be covered in a one-year course but naturally divides into an introductory portion (Chapters 1–10) which can be covered in the first semester. For the second semester, the instructor can cover Chapters 11–15 and then select from the remaining chapters which cover the fractional quantum Hall effect, magnetism, superfluidity, and superconductivity.

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