Principles of condensed matter physics

Now in paperback, this book provides an overview of the physics of condensed matter systems. Assuming a familiarity with the basics of quantum mechanics and statistical mechanics, the book establishes a general framework for describing condensed phases of matter, based on symmetries and conservation laws. It explores the role of spatial dimensionality and microscopic interactions in determining the nature of phase transitions, as well as discussing the structure and properties of materials with different symmetries. Particular attention is given to critical phenomena and renormalization group methods. The properties of liquids, liquid crystals, quasicrystals, crystalline solids, magnetically ordered systems and amorphous solids are investigated in terms of their symmetry, generalized rigidity, hydrodynamics and topological defect structure. Written in a clear and pedagogic style, the book contains problems at the end of each chapter and extensive real-world examples.

In addition to serving as a course text, this book is an essential reference for students and researchers in physics, applied physics, chemistry, materials science and engineering, who are interested in modern condensed matter physics.

Principles of condensed matter physics

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To Amy, David, Ellen, Paula, Diana, and Valerie

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Preface

The use and understanding of matter in its condensed (liquid or solid) state have gone hand in hand with the advances of civilization and technology since the first use of primitive tools. So important has the control of condensed matter been to man that historical ages – the Stone Age, the Bronze Age, the Iron Age – have often been named after the material dominating the technology of the time. Serious scientific study of condensed matter began shortly after the Newtonian revolution. By the end of the nineteenth century, the foundations of our understanding of the macroscopic properties of matter were firmly in place. Thermodynamics, hydrodynamics and elasticity together provided an essentially complete description of the static and dynamic properties of gases, liquids and solids at length scales long compared to molecular lengths. These theories remain valid today. By the early and mid-twentieth century, new ideas, most notably quantum mechanics and new experimental probes, such as scattering and optical spectroscopy, had been introduced. These established the atomic nature of matter and opened the door for investigations and understanding of condensed matter at the microscopic level. The study of quantum properties of solids began in the 1920s and continues today in what we might term "conventional solid state physics". This field includes accomplishments ranging from electronic band theory, which explains metals, insulators and semiconductors, to the theory of superconductivity and the quantum Hall effect. The fundamental problems of how to treat the effects of the strong Coulomb interaction in many electron systems and the effects of lattice disorder remain only partially resolved to this day.

The second half of the twentieth century has seen a new set of paradigms introduced into physics, originating in condensed matter and spreading to other areas. The idea is to span length scales, to see what remains as an observer steps back from the microscopics of a system and then keeps stepping back. X-ray, neutron and light scattering have become powerful probes of structure from microscopic to near macroscopic length scales. The study of critical phenomena has led to the notions of scaling and universality and has spawned the renormalization group, which shows how identical behavior at long length scales can arise from widely different microscopic interactions. At the same time, the concepts of broken symmetry and order parameters have emerged as unifying theoretical concepts applicable not only to condensed matter physics but also to particle physics and

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even to cosmology. These theoretical advances have provided a framework for describing condensed matter phases: liquid crystals, superfluid helium, incommensurate crystals, quasicrystals and systems in one and two dimensions, as well as classical fluids and regular periodic solids.

In spite of these unifying advances, conventional solid state physics and "soft" condensed matter physics (which includes the study of many statistical problems such as critical phenomena as well as the study of soft material such as fluids and liquid crystals) have very much remained distinct fields. The present book grew out of the conviction that graduate programs in physics should offer a course in the broad subject of condensed matter physics, a course that would prepare students to begin research in any area of this vast, yet still expanding, field. Our experience was that students learned either conventional solid state physics or soft condensed matter physics, and that each group remained blissfully ignorant of the other. We therefore developed, and began to teach, a one-year course in condensed matter physics at the University of Pennsylvania.

The first semester of this course was designed to establish a general framework, based on concepts of symmetry, for approaching condensed phases, from high-temperature fluids to low-temperature quantum crystals. It included an overview of the great variety of condensed systems found in nature and a description of their symmetry in terms of order parameters. It then discussed phase transitions, elasticity, hydrodynamics and topological defect structure in terms of these order parameters. It revisited many of the problems of the nineteenth century from a modern viewpoint. The second semester treated subjects normally associated with conventional solid state physics and many-body theory: normal Fermi liquids, electrons, phonons, magnetism and superconductivity. However, these topics were taught within the general framework established during the first semester. None of the concepts in the first semester involved quantum mechanics in an essential way, whereas those in the second semester did. We, therefore, in our own minds, referred to the first semester as "$\hbar = 0$" and the second semester as "$\hbar \neq 0$". The first semester also dealt much more extensively with "soft" systems, such as liquid crystals or microemulsions, and we sometimes referred to the first semester as "soft" condensed matter physics and to the second semester as "hard" condensed matter physics. The concepts to be covered in the first semester were, however, quite general and applied to both "soft" and "hard" systems. We have each taught the full year course described above many times to second-year graduate students at both the University of Pennsylvania and Princeton University.

The present book evolved from notes prepared for the first semester of the course. While there are several excellent texts dealing with $\hbar \neq 0$ solid state physics and with many-body physics, we have been unable to find a text dealing with $\hbar = 0$, or soft condensed matter physics, to recommend to our students or colleagues. Different aspects of this subject are available in the research literature and in several, sometimes material-specific, books. We, and others, have long felt that there is an acute need for a text on modern aspects of condensed matter physics, one that would present a unified picture of structures other than periodic solids, that would treat broken symmetry, critical phenomena and the renormalization group, and that would explore the role of fluctuations and topological defects in determining the existence of order and the nature of phase transitions. This book is an attempt to address this need.

What do you need to make use of this book? Some knowledge of quantum mechanics would be helpful but not essential. Statistical mechanics is an important prerequisite and is used throughout the book. (Although Chapter 3 provides a review of statistical mechanics, it is intended as a refresher to define notation rather than as a substitute for prior exposure.) A course in solid state physics would be helpful, but again not absolutely essential. If you are a field theorist, the book should make nice bedtime reading and introduce you to some really interesting relevant physics. The book is meant as a first course in condensed matter physics for second-year graduate students regardless of their field of specialization. It relies more on a general background of physical understanding and mathematical tools appropriate to that level than it does on any specific previous course.

Though originally intended as a text for graduate courses, the book should also serve as a reference text for researchers in condensed matter physics, materials science, chemistry, engineering and applied physics. We have attempted to cover each subject as completely as possible, beginning with simple ideas and ending with advanced concepts. Thus, for example, we present mean-field theory in a variety of guises, beginning with Bragg-Williams theory, but also including variational and field-theoretic approaches; or we cover descriptive aspects of topological defects and more advanced concepts like lattice duality transformations. Parts of the book could be, and some have been, used in more elementary courses such as undergraduate solid state physics, statistical mechanics or materials science. At the other extreme, in many scientific arguments with colleagues and competitors, we have found the notes for this text an invaluable resource in proving either our point or theirs.

The text as it stands is suitable for a full year graduate course, although we have never taught it as such. Chapters 1–6 establish the fundamentals. They introduce the systems to be studied, present experimental and theoretical tools, set up mean-field theories and show how they break down, investigate critical phenomena, and discuss symmetry breaking and the resulting generalized elasticity. We usually teach all of Chapters 1–6 and parts of the remaining four chapters (usually all of Chapter 9 on topological defects and bits and pieces of the other three chapters). On occasion, we have, instead of including all of Chapter 9, taught Chapters 7 and 8 on dynamical processes and hydrodynamics, followed by parts of Chapter 10 on domain walls, kinks and solitons. When the whole year sequence was taught, we sometimes taught Chapters 1–6 and Chapter 9 in the first semester, followed by parts of Chapters 7 and 8 in the second semester, before moving on to many-body physics. Though we have generally taught this

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text as a part of the full year sequence discussed above, we believe it can serve as an excellent text book for a second semester of statistical mechanics, as a secondary text for a course in many-body physics, and as a stand alone text for condensed matter physics.

Each chapter concludes with a set of problems. We have tried to include problems at all levels of difficulty. Many problems are, however, challenging, even for seasoned professionals. Where possible, we have tried to provide answers or answer clues for the more difficult problems.

Astonishingly, none of our friends or colleagues has tried to dissuade us from completing this book. Some have had a direct or indirect influence on both the content and style of this book. The pedagogical and research approaches of Phil Anderson, P.G. de Gennes, Bert Halperin, Paul Martin and David Nelson can be seen throughout the book. We received constant encouragement and help from Shlomo Alexander, Mark Azbel, Daniel Fisher, Gary Grest, Scott Milner, Burt Ovrut, Phil Pincus, David Pine, Jacques Prost, Cyrus Safinya, David Weitz and Tom Witten. We are extremely grateful to Phil Nelson, who read every word of the manuscript, corrected many misprints and made numerous suggestions for improving the text, to Tetsuji Tokihiro for using preliminary notes as a basis for a course at the University of Tokyo and for providing a lengthy list of corrections, to Ray Goldstein, Mark Robbins, and Holger Stark for pointing out errors right up to the publication date, and to numerous students and postdocs at Penn and Princeton who read and commented on various versions of the notes leading to the final manuscript. We are also grateful to Chris Henley and Josh Socolar for using the unfinished manuscript in courses they taught at Cornell and Duke University, respectively. Finally, we are grateful to Exxon Research and Engineering Co. for providing a friendly environment where many discussions about this book took place. We owe particular thanks to Jodi Forlizzi for most of the artwork.