Solid State Physics

By identifying unifying concepts across solid state physics, this text covers theory in an accessible way to provide graduate students with the basis for making quantitative calculations and an intuitive understanding of effects. Each chapter focuses on a different set of theoretical tools, using examples from specific systems and demonstrating practical applications to real experimental topics. Advanced theoretical methods including group theory, many-body theory, and phase transitions are introduced in an accessible way, and the quasiparticle concept is developed early, with discussion of the properties and interactions of electrons and holes, excitons, phonons, photons, and polaritons. New to this edition are sections on graphene, surface states, photoemission spectroscopy, two-dimensional spectroscopy, transistor device physics, thermoelectricity, metamaterials, spintronics, exciton-polaritons, and flux quantization in superconductors. Exercises are provided to help put knowledge into practice, with a solutions manual for instructors available online, and appendices review the basic math methods used in the book. A complete set of the symmetry tables used in group theory (presented in Chapter 6) is available at www.cambridge.org/snoke.

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Solid State Physics

Essential Concepts

Second Edition

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There is beauty even in the solids.

I tell you, if these were silent, even the rocks would cry out!
– Luke 19:40

For his invisible attributes, namely, his eternal power and
divine nature, have been clearly perceived, ever since the
creation of the world, in the things that have been made.
– Romans 1:20

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Preface

Imagine teaching a physics course on classical mechanics in which the syllabus is organized around a survey of every type of solid shape and every type of mechanical device. Or imagine teaching thermodynamics by surveying all of the phenomenology of steam engines, rockets, heating systems, and such things. Not only would that be tedious, much of the beauty of the unifying theories would be lost. Or imagine teaching a course on electrodynamics which begins with a lengthy discussion of all the faltering attempts to describe electricity and magnetism before Maxwell. Thankfully, we don't do this in most courses in physics. Instead, we present the main elements of the unifying theories, and use a few of the specific applied and historical cases as examples of working out the theory.

Yet in solid state physics courses, many educators seem to feel a need to survey every type of solid and every significant development in phenomenology. Students are left with the impression that solid state physics has no unifying, elegant theories and is just a grab bag of various effects. Nothing could be further from the truth. There are many unifying concepts in solid state physics. But any book on solid state physics that focuses on unifying concepts must leave out some of the many specialized topics that crowd books on the subject.

This book centers on essential theoretical concepts in all types of solid state physics, using examples from specific systems with real units and numbers. Each chapter focuses on a different set of theoretical tools. "Solid state" physics is particularly intended here, because "condensed matter" physics includes liquids and gases, and this book does not include in-depth discussions of those states. These are covered amply, for example, by Chaikin and Lubensky.[1]

Some books attempt to survey the phenomenology of the entire field, but solid state physics is now too large for any book to do a meaningful survey of all the important effects. The survey approach is also generally unsatisfying for the student. Teaching condensed matter physics by surveying the properties of various materials loses the essential beauty of the topic. On the other hand, some books on condensed matter physics deal only with "toy models," never giving the skills to calculate real-world numbers.

Researchers in the field seem to be split in regard to the importance of the advanced topics of group theory and many-body theory. Some solid state physicists say that all of solid state physics starts with group theory, while others dismiss it entirely – I would guess that well over half of academic researchers in the field have never studied group theory at all. As I discuss in Chapter 1, the existence of electron bands does not depend crucially on

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[1] P.M. Chaikin and T.C. Lubensky, *Principles of Condensed Matter Physics* (Cambridge University Press, 2000).

symmetry properties, although the symmetry theory provides a wide variety of tools to use for systems that approximate certain symmetries.

In the same way, there is a divide on many-body theory. Experimentalists tend to avoid the subject altogether, while theorists start with it. This leads to an "impedance mismatch" when experimentalists and theorists talk to each other. In Chapter 8 of this book, I introduce the elements of many-body theory which will allow experimentalists to cross this divide without taking years of theoretical courses, and which will serve as an introduction to students planning to go deeper into these methods. It may be a surprise to some people that there are actually several different diagrammatic approaches, including the Rayleigh–Schrödinger theory common in optics circles, the Feynmann diagrammatic method, and the Matsubara imaginary-time method. All three are surveyed in Chapter 8, with a discussion of their connections.

While group theory and many-body theory may come across as high-level topics to some, others may be surprised to see "engineering" topics such as semiconductor devices, stress and strain matrices, and optics included. While some experimentalists skip group theory and many-body theory in their education, too many theorists skip these basic topics in their training. Understanding the details of these methods is crucial for understanding many of the experiments on fundamental phenomena, as well as applications in the modern world.

In this book, I have tried to focus on unifying and fundamental theories. This raises the question: Does solid state physics really involve fundamental physics? Are there really any important questions at stake? Many physics students think that astrophysics and particle physics address fundamental questions, but solid state physics doesn't. Perhaps this is because of the way we teach it. Astrophysics and particle physics courses tend to focus much more on unifying, grand questions, especially at the introductory level, while solid state physics courses often focus on a grab bag of various phenomena. If we can get past the listing of material properties, solid state physics does deal with fascinating questions.

One deep philosophical issue is the question of "reductionism" versus "emergent behavior." Since the time of Aristotle and Democritus, philosophers have debated whether matter can be reduced to "basic building blocks" or if it is infinitely divisible. For the past two centuries, many scientists have tended to assume that Democritus was right – that all matter is built from a few indivisible building blocks, and once we understand these, we can deduce all other behavior of matter from the laws of these underlying building blocks. In the past few decades, many solid state physicists, such as Robert Laughlin, have vociferously rejected this view.[2] They would argue that possibly every quantum particle is divisible, but it doesn't matter for our understanding of the essential properties of things.

At one time, people thought atoms were indivisible, but it was found they are made of subatomic particles. Then people thought subatomic particles were indivisible, but it was found that at least some of them are made of smaller particles such as quarks. Are quarks indivisible? Many physicists believe there is at least one level lower. As the distance scale gets smaller, the energy cost gets higher. This debate came to a head in the 1980s when the high-energy physics community proposed to spend billions of dollars on the

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[2] R. Laughlin, *A Different Universe* (Basic Books, 2005).

Superconducting Supercollider in Texas, far more than the total budget of all other physics in the USA, and some solid state physicists such as Rustum Roy opposed it. In the anti-reductionist view, it is pointless to keep searching for one final list of all particles and forces.

Those who hold to the anti-reductionist view often point to the concept of "renormalization" in condensed matter physics. This is a very general concept. Essentially, it means that we can redefine a system at a higher level, ignoring the component parts from which it is made. Then we can work entirely at the higher level, ignoring the underlying complexities. The properties at this higher level depend only on a few basic properties of the system, which could arise from any number of different microscopic properties.

There are two versions of this. The first is many-body renormalization, introduced in Chapter 2 of this book and developed further in Chapter 8. In this theory, the ground state of a system is defined as the "vacuum," and excitations out of this state are "quasiparticles" with properties very different from the particles making up the underlying ground state. These quasiparticles then become the new particles of interest, and can themselves make up a new vacuum ground state with additional excitations. As discussed in Chapter 11, this process can be continued to any number of higher levels.

A second type of renormalization is that of renormalization groups, introduced in Chapter 10. In this approach, the essential properties of a system can be described using subsets of the whole, in which properties are averaged. From this a whole field of theory on **universality** has been developed, in which certain properties of systems can be predicted based on just a few attributes of the underlying system, without reference to the microscopic details.

Another deep topic that comes up in solid state physics is the foundations of statistical mechanics. There was enormous controversy at the founding of the field, and much of this controversy was simply swept under the rug in later years, and there is still philosophical debate.[3] The fundamental questions of statistical mechanics arise especially when we deal with nonequilibrium systems, a major topic of solid state physics. In Chapter 4, I present the quantum mechanical basis of irreversible behavior, which involves the concept of "dephasing" which arises in later chapters, especially Chapter 9.

This connects to another important philosophical question, the "measurement" problem of quantum mechanics, that is, what leads to "collapse" of the wave function and what constitutes a measurement. In both quantum statistical mechanics and quantum collapse, we have irreversible behavior arising from an underlying system which is essentially reversible. Is there a connection? The essential paradoxes of quantum mechanics all arise in the context of condensed matter, and going to subatomic particles does not help at all in the resolution of the paradoxes, nor raise new paradoxes.

One of the deepest issues of our day is the question of emergent phenomena. Is life as we know it essentially a generalization of condensed matter physics, in which structure arises entirely from simple interactions at the microscopic level, or do we need entirely new ways of thinking when approaching biophysics, with concepts such as feedback, systems

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[3] See, e.g., Harvey Brown, "One and for all: the curious role of probability in the Past Hypothesis," in *The Quantum Foundations of Statistical Mechanics*, D. Bedingham, O. Maroney, and C. Timpson (eds.) (Oxford University Press, 2017).

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engineering, and transmission and processing of information?[4] Phase transitions are often viewed as examples of order coming out of disorder, through the process known as spontaneous symmetry breaking (introduced in Chapters 10 and 11 of this book). The effects that come about in solid state physics due to phase transitions can be dramatic, but we are a long way from extrapolating these to an explanation of the origin of life.

This book does not survey the rapidly evolving field of topological effects in condensed matter physics, except briefly at the end of Chapters 2 and 9. We have yet to create a canon of the truly essential phenomena, though it is already possible to list the various topology classes.[5] A discussion of surface states, which arise in many examples of topological effects, is presented at the end of Chapter 1.

Many people contributed to improving this book. I would like to thank in particular Dan Boyanovsky, David Citrin, Hrvoye Petek, Chris Smallwood, and Zoltan Vörös for critical reading of parts of this manuscript. I would also like to thank my wife Sandra for many years of warm support and encouragement.

David Snoke
Pittsburgh, 2019

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[4] See, e.g., A.D. Lander, "A calculus of purpose," *PLoS Biology* 2, e164 (2004).

[5] See A.P. Schnyder, S. Ryu, A. Furusaki, and A.W.W. Ludwig, "Classification of topological insulators and superconductors in three spatial dimensions," *Physical Reviews B* **78**, 195125 (2008), and references therein.