A. Zee

Quantum Field Theory in a Nutshell

简明量子场论 第2版

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SECOND EDITION

A. Zee

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Praise for the first edition

"Quantum field theory is an extraordinarily beautiful subject, but it can be an intimidating one. The profound and deeply physical concepts it embodies can get lost, to the beginner, amidst its technicalities. In this book, Zee imparts the wisdom of an experienced and remarkably creative practitioner in a user-friendly style. I wish something like it had been available when I was a student."

—Frank Wilczek, Massachusetts Institute of Technology

"Finally! Zee has written a ground-breaking quantum field theory text based on the course I made him teach when I chaired the Princeton physics department. With utmost clarity he gives the eager student a light-hearted and easy-going introduction to the multifaceted wonders of quantum field theory. I wish I had this book when I taught the subject."

—Marvin L. Goldberger, President, Emeritus, California Institute of Technology

"This book is filled with charming explanations that students will find beneficial."

—Ed Witten, Institute for Advanced Study

"This book is perhaps the most user-friendly introductory text to the essentials of quantum field theory and its many modern applications. With his physically intuitive approach, Professor Zee makes a serious topic more reachable for beginners, reducing the conceptual barrier while preserving enough mathematical details necessary for a firm grasp of the subject."

—Bei Lok Hu, University of Maryland

"Like the famous Feynman Lectures on Physics, this book has the flavor of a good blackboard lecture. Zee presents technical details, but only insofar as they serve the larger purpose of giving insight into quantum field theory and bringing out its beauty."

—Stephen M. Barr, University of Delaware

"This is a fantastic book—exciting, amusing, unique, and very valuable."

—Clifford V. Johnson, University of Durham

"Tony Zee explains quantum field theory with a clear and engaging style. For budding or seasoned condensed matter physicists alike, he shows us that field theory is a nourishing nut to be cracked and savored."

—Matthew P. A. Fisher, Kavli Institute for Theoretical Physics

"I was so engrossed that I spent all of Saturday and Sunday one weekend absorbing half the book, to my wife's dismay. Zee has a talent for explaining the most abstruse and arcane concepts in an elegant way, using the minimum number of equations (the jokes and anecdotes help). . . . I wish this were available when I was a graduate student. Buy the book, keep it by your bed, and relish the insights delivered with such flair and grace."

—N. P. Ong, Princeton University

What readers are saying

"Funny, chatty, physical: QFT education transformed!! This text stands apart from others in so many ways that it's difficult to list them all. . . . The exposition is breezy and chatty. The text is never boring to read, and is at times very, very funny. Puns and jokes abound, as do anecdotes. . . . A book which is much easier, and more fun, to read than any of the others. Zee's skills as a popular physics writer have been used to excellent effect in writing this textbook. . . . Wholeheartedly recommended."

—M. Haque

"A readable, and rereadable instant classic on QFT. . . . At an introductory level, this type of book—with its pedagogical (and often very funny) narrative—is priceless. [It] is full of fantastic insights akin to reading the Feynman lectures. I have since used *QFT in a Nutshell* as a review for [my] year-long course covering all of Peskin and Schroder, and have been pleasantly surprised at how Zee is able to preemptively answer many of the open questions that eluded me during my course. . . . I value *QFT in a Nutshell* the same way I do the Feynman lectures. . . . It's a text to teach an understanding of physics."

—Flip Tanedo

"One of those books a person interested in theoretical physics simply must own! A real scientific masterpiece. I bought it at the time I was a physics sophomore and that was the best choice I could have made. It was this book that triggered my interest in quantum field theory and crystallized my dreams of becoming a theoretical physicist. . . . The main goal of the book is to make the reader gain real intuition in the field. Amazing . . . amusing . . . real fun. What also distinguishes this book from others dealing with a similar subject is that it is written like a tale. . . . I feel enormously fortunate to have come across this book at the beginning of my adventure with theoretical physics. . . . Definitely the best quantum field theory book I have ever read."

—Anonymous

"I have used *Quantum Field Theory in a Nutshell* as the primary text. . . . I am immensely pleased with the book, and recommend it highly. . . . Don't let the 'damn the torpedoes, full steam ahead' approach scare you off. Once you get used to seeing the physics quickly, I think you will find the experience very satisfying intellectually."

—Jim Napolitano

"This is undoubtedly the best book I have ever read about the subject. Zee does a fantastic job of explaining quantum field theory, in a way I have never seen before, and I have read most of the other books on this topic. If you are looking for quantum field theory explanations that are clear, precise, concise, intuitive, and fun to read—this is the book for you."

—Anonymous

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"One of the most artistic and deepest books ever written on quantum field theory. Amazing . . . extremely pleasant . . . a lot of very deep and illuminating remarks. . . . I recommend the book by Zee to everybody who wants to get a clear idea what good physics is about."

—Slava Mukhanov

"Perfect for learning field theory on your own—by far the clearest and easiest to follow book I've found on the subject."

—Ian Z. Lovejoy

"A beautifully written introduction to the modern view of fields . . . breezy and enchanting, leading to exceptional clarity without sacrificing depth, breadth, or rigor of content. . . . [It] passes my test of true greatness: I wish it had been the first book on this topic that I had found."

—Jeffrey D. Scargle

"A breeze of fresh air . . . a real literary gem which will be useful for students who make their first steps in this difficult subject and an enjoyable treat for experts, who will find new and deep insights. Indeed, the *Nutshell* is like a bright light source shining among tall and heavy trees—the many more formal books that exist—and helps seeing the forest as a whole! . . . I have been practicing QFT during the past two decades and with all my experience I was thrilled with enjoyment when I read some of the sections."

—Joshua Feinberg

"This text not only teaches up-to-date quantum field theory, but also tells readers how research is actually done and shows them how to think about physics. [It teaches things that] people usually say 'cannot be learned from books.' [It is] in the same style as *Fearful Symmetry* and *Einstein's Universe*. All three books . . . are classics."

—Yu Shi

"I belong to the [group of] enthusiastic laymen having enough curiosity and insistence . . . but lacking the mastery of advanced math and physics. . . . I really could not see the forest for the trees. But at long last I got this book!"

—Makay Attila

"More fun than any other QFT book I have read. The comparisons to Feynman's writings made by several of the reviewers seem quite apt. . . . His enthusiasm is quite infectious. . . . I doubt that any other book will spark your interest like this one does."

—Stephen Wandzura

"I'm having a blast reading this book. It's both deep and entertaining; this is a rare breed, indeed. I usually prefer the more formal style (big Landau fan), but I have to say that when Zee has the talent to present things his way, it's a definite plus."

—Pierre Jouvelot

"Required reading for QFT: [it] heralds the introduction of a book on quantum field theory that you can sit down and read. My professor's lectures made much more sense as I followed along in this book, because concepts were actually EXPLAINED, not just worked out."

—Alexander Scott

"Not your father's quantum field theory text: I particularly appreciate that things are motivated physically before their mathematical articulation. . . . Most especially though, the author's 'heuristic' descriptions are the best I have read anywhere. From them alone the essential ideas become crystal clear."

—Dan Dill

Preface to the First Edition

As a student, I was rearing at the bit, after a course on quantum mechanics, to learn quantum field theory, but the books on the subject all seemed so formidable. Fortunately, I came across a little book by Mandl on field theory, which gave me a taste of the subject enabling me to go on and tackle the more substantive texts. I have since learned that other physicists of my generation had similar good experiences with Mandl.

In the last three decades or so, quantum field theory has veritably exploded and Mandl would be hopelessly out of date to recommend to a student now. Thus I thought of writing a book on the essentials of modern quantum field theory addressed to the bright and eager student who has just completed a course on quantum mechanics and who is impatient to start tackling quantum field theory.

I envisaged a relatively thin book, thin at least in comparison with the many weighty tomes on the subject. I envisaged the style to be breezy and colloquial, and the choice of topics to be idiosyncratic, certainly not encyclopedic. I envisaged having many short chapters, keeping each chapter "bite-sized."

The challenge in writing this book is to keep it thin and accessible while at the same time introducing as many modern topics as possible. A tough balancing act! In the end, I had to be unrepentantly idiosyncratic in what I chose to cover. Note to the prospective book reviewer: You can always criticize the book for leaving out your favorite topics. I do not apologize in any way, shape, or form. My motto in this regard (and in life as well), taken from the Ricky Nelson song "Garden Party," is "You can't please everyone so you gotta please yourself."

This book differs from other quantum field theory books that have come out in recent years in several respects.

I want to get across the important point that the usefulness of quantum field theory is far from limited to high energy physics, a misleading impression my generation of theoretical physicists were inculcated with and which amazingly enough some recent textbooks on

quantum field theory (all written by high energy physicists) continue to foster. For instance, the study of driven surface growth provides a particularly clear, transparent, and physical example of the importance of the renormalization group in quantum field theory. Instead of being entangled in all sorts of conceptual irrelevancies such as divergences, we have the obviously physical notion of changing the ruler used to measure the fluctuating surface. Other examples include random matrix theory and Chern-Simons gauge theory in quantum Hall fluids. I hope that condensed matter theory students will find this book helpful in getting a first taste of quantum field theory. The book is divided into eight parts,[1] with two devoted more or less exclusively to condensed matter physics.

I try to give the reader at least a brief glimpse into contemporary developments, for example, just enough of a taste of string theory to whet the appetite. This book is perhaps also exceptional in incorporating gravity from the beginning. Some topics are treated quite differently than in traditional texts. I introduce the Faddeev-Popov method to quantize electromagnetism and the language of differential forms to develop Yang-Mills theory, for example.

The emphasis is resoundingly on the conceptual rather than the computational. The only calculation I carry out in all its gory details is that of the magnetic moment of the electron. Throughout, specific examples rather than heavy abstract formalism will be favored. Instead of dealing with the most general case, I always opt for the simplest.

I had to struggle constantly between clarity and wordiness. In trying to anticipate and to minimize what would confuse the reader, I often find that I have to belabor certain points more than what I would like.

I tried to avoid the dreaded phrase "It can be shown that . . . " as much as possible. Otherwise, I could have written a much thinner book than this! There are indeed thinner books on quantum field theory: I looked at a couple and discovered that they hardly explain anything. I must confess that I have an almost insatiable desire to explain.

As the manuscript grew, the list of topics that I reluctantly had to drop also kept growing. So many beautiful results, but so little space! It almost makes me ill to think about all the stuff (bosonization, instanton, conformal field theory, etc., etc.) I had to leave out. As one colleague remarked, the nutshell is turning into a coconut shell!

Shelley Glashow once described the genesis of physical theories: "Tapestries are made by many artisans working together. The contributions of separate workers cannot be discerned in the completed work, and the loose and false threads have been covered over." I regret that other than giving a few tidbits here and there I could not go into the fascinating history of quantum field theory, with all its defeats and triumphs. On those occasions when I refer to original papers I suffer from that disconcerting quirk of human psychology of tending to favor my own more than decorum might have allowed. I certainly did not attempt a true bibliography.

[1] Murray Gell-Mann used to talk about the eightfold way to wisdom and salvation in Buddhism (M. Gell-Mann and Y. Ne'eman, *The Eightfold Way*). Readers familiar with contemporary Chinese literature would know that the celestial dragon has eight parts.

The genesis of this book goes back to the quantum field theory course I taught as a beginning assistant professor at Princeton University. I had the enormous good fortune of having Ed Witten as my teaching assistant and grader. Ed produced lucidly written solutions to the homework problems I assigned, to the extent that the next year I went to the chairman to ask "What is wrong with the TA I have this year? He is not half as good as the guy last year!" Some colleagues asked me to write up my notes for a much needed text (those were the exciting times when gauge theories, asymptotic freedom, and scores of topics not to be found in any texts all had to be learned somehow) but a wiser senior colleague convinced me that it might spell disaster for my research career. Decades later, the time has come. I particularly thank Murph Goldberger for urging me to turn what expository talents I have from writing popular books to writing textbooks. It is also a pleasure to say a word in memory of the late Sam Treiman, teacher, colleague, and collaborator, who as a member of the editorial board of Princeton University Press persuaded me to commit to this project. I regret that my slow pace in finishing the book deprived him of seeing the finished product.

Over the years I have refined my knowledge of quantum field theory in discussions with numerous colleagues and collaborators. As a student, I attended courses on quantum field theory offered by Arthur Wightman, Julian Schwinger, and Sidney Coleman. I was fortunate that these three eminent physicists each has his own distinctive style and approach.

The book has been tested "in the field" in courses I taught. I used it in my field theory course at the University of California at Santa Barbara, and I am grateful to some of the students, in particular Ted Erler, Andrew Frey, Sean Roy, and Dean Townsley, for comments. I benefitted from the comments of various distinguished physicists who read all or parts of the manuscript, including Steve Barr, Doug Eardley, Matt Fisher, Murph Goldberger, Victor Gurarie, Steve Hsu, Bei-lok Hu, Clifford Johnson, Mehran Kardar, Ian Low, Joe Polchinski, Arkady Vainshtein, Frank Wilczek, Ed Witten, and especially Joshua Feinberg. Joshua also did many of the exercises.

Talking about exercises: You didn't get this far in physics without realizing the absolute importance of doing exercises in learning a subject. It is especially important that you do most of the exercises in this book, because to compensate for its relative slimness I have to develop in the exercises a number of important points some of which I need for later chapters. Solutions to some selected problems are given.

I will maintain a web page http://theory.kitp.ucsb.edu/~zee/nuts.html listing all the errors, typographical and otherwise, and points of confusion that will undoubtedly come to my attention.

I thank my editors, Trevor Lipscombe, Sarah Green, and the staff of Princeton Editorial Associates (particularly Cyd Westmoreland and Evelyn Grossberg) for their advice and for seeing this project through. Finally, I thank Peter Zee for suggesting the cover painting.

Preface to the Second Edition

What one fool could understand, another can.
—R. P. Feynman[1]

Appreciating the appreciators

It has been nearly six years since this book was published on March 10, 2003. Since authors often think of books as their children, I may liken the flood of appreciation from readers, students, and physicists to the glorious report cards a bright child brings home from school. Knowing that there are people who appreciate the care and clarity crafted into the pedagogy is a most gratifying feeling. In working on this new edition, merely looking at the titles of the customer reviews on Amazon.com would lighten my task and quicken my pace: "Funny, chatty, physical. QFT education transformed!," "A readable, and re-readable instant classic on QFT," "A must read book if you want to understand essentials in QFT," "One of the most artistic and deepest books ever written on quantum field theory," "Perfect for learning field theory on your own," "Both deep and entertaining," "One of those books a person interested in theoretical physics simply must own," and so on.

In a *Physics Today* review, Zvi Bern, a preeminent younger field theorist, wrote:

> Perhaps foremost in his mind was how to make *Quantum Field Theory in a Nutshell* as much fun as possible. . . . I have not had this much fun with a physics book since reading *The Feynman Lectures on Physics*. . . . [This is a book] that no student of quantum field theory should be without. *Quantum Field Theory in a Nutshell* is the ideal book for a graduate student to curl up with after having completed a course on quantum mechanics. But, mainly, it is for anyone who wishes to experience the sheer beauty and elegance of quantum field theory.

A classical Chinese scholar famously lamented "He who knows me are so few!" but here Zvi read my mind.

Einstein proclaimed, "Physics should be made as simple as possible, but not any simpler." My response would be "Physics should be made as fun as possible, but not

[1] R. P. Feynman, *QED: The Strange Theory of Light and Matter*, p. xx.

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any funnier." I overcame the editor's reluctance and included jokes and stories. And yes, I have also written a popular book *Fearful Symmetry* about the "sheer beauty and elegance" of modern physics, which at least in that book largely meant quantum field theory. I want to share that sense of fun and beauty as much as possible. I've heard some people say that "Beauty is truth" but "Beauty is fun" is more like it.

I had written books before, but this was my first textbook. The challenges and rewards in writing different types of book are certainly different, but to me, a university professor devoted to the ideals of teaching, the feeling of passing on what I have learned and understood is simply incomparable. (And the nice part is that I don't have to hand out final grades.) It may sound corny, but I owe it, to those who taught me and to those authors whose field theory texts I studied, to give something back to the theoretical physics community. It is a wonderful feeling for me to meet young hotshot researchers who had studied this text and now know more about field theory than I do.

How I made the book better: The first text that covers the twenty-first century

When my editor Ingrid Gnerlich asked me for a second edition I thought long and hard about how to make this edition better than the first. I have clarified and elaborated here and there, added explanations and exercises, and done more "practical" Feynman diagram calculations to appease those readers of the first edition who felt that I didn't calculate enough. There are now three more chapters in the main text. I have also made the "most accessible" text on quantum field theory even more accessible by explaining stuff that I thought readers who already studied quantum mechanics should know. For example, I added a concise review of the Dirac delta function to chapter I.2. But to the guy on Amazon.com who wanted complex analysis explained, sorry, I won't do it. There is a limit. Already, I gave a basically self-contained coverage of group theory.

More excitingly, and to make my life more difficult, I added, to the existing eight parts (of the celestial dragon), a new part consisting of four chapters, covering field theoretic happenings of the last decade or so. Thus I can say that this is the first text since the birth of quantum field theory in the late 1920s that covers the twenty-first century.

Quantum field theory is a mature but certainly not a finished subject, as some students mistakenly believe. As one of the deepest constructs in theoretical physics and all encompassing in its reach, it is bound to have yet unplumbed depths, secret subterranean connections, and delightful surprises. While many theoretical physicists have moved past quantum field theory to string theory and even string field theory, they often take the limit in which the string description reduces to a field description, thus on occasion revealing previously unsuspected properties of quantum field theories. We will see an example in chapter N.4.

My friends admonished me to maintain, above all else, the "delightful tone" of the first edition. I hope that I have succeeded, even though the material contained in part N is "hot off the stove" stuff, unlike the long-understood material covered in the main text. I also added a few jokes and stories, such as the one about Fermi declining to trace.

As with the first edition, I will maintain a web site http://theory.kitp.ucsb.edu/~zee/nuts2.html listing the errors, typographical or otherwise, that will undoubtedly come to my attention.

Encouraging words

In the quote that started this preface, Feynman was referring to himself, and to you! Of course, Feynman didn't simply understand the quantum field theory of electromagnetism, he also invented a large chunk of it. To paraphrase Feynman, I wrote this book for fools like you and me. If a fool like me could write a book on quantum field theory, then surely you can understand it.

As I said in the preface to the first edition, I wrote this book for those who, having learned quantum mechanics, are eager to tackle quantum field theory. During a sabbatical year (2006–07) I spent at Harvard, I was able to experimentally verify my hypothesis that a person who has mastered quantum mechanics could understand my book on his or her own without much difficulty. I was sent a freshman who had taught himself quantum mechanics in high school. I gave him my book to read and every couple of weeks or so he came by to ask a question or two. Even without these brief sessions, he would have understood much of the book. In fact, at least half of his questions stem from the holes in his knowledge of quantum mechanics. I have incorporated my answers to his field theoretic questions into this edition.

As I also said in the original preface, I had tested some of the material in the book "in the field" in courses I taught at Princeton University and later at the University of California at Santa Barbara. Since 2003, I have been gratified to know that it has been used successfully in courses at many institutions.

I understand that, of the different groups of readers, those who are trying to learn quantum field theory on their own could easily get discouraged. Let me offer you some cheering words. First of all, that is very admirable of you! Of all the established subjects in theoretical physics, quantum field theory is by far the most subtle and profound. By consensus it is much much harder to learn than Einstein's theory of gravity, which in fact should properly be regarded as part of field theory, as will be made clear in this book. So don't expect easy cruising, particularly if you don't have someone to clarify things for you once in a while. Try an online physics forum. Do at least some of the exercises. Remember: "No one expects a guitarist to learn to play by going to concerts in Central Park or by spending hours reading transcriptions of Jimi Hendrix solos. Guitarists practice. Guitarists play the guitar until their fingertips are calloused. Similarly, physicists solve problems."[2] Of course, if you don't have the prerequisites, you won't be able to understand this or any other field theory text. But if you have mastered quantum mechanics, keep on trucking and you will get there.

[2] N. Newbury et al., *Princeton Problems in Physics with Solutions*, Princeton University Press, Princeton, 1991.

The view will be worth it, I promise. My thesis advisor Sidney Coleman used to start his field theory course saying, "Not only God knows, I know, and by the end of the semester, you will know." By the end of this book, you too will know how God weaves the universe out of a web of interlocking fields. I would like to change Dirac's statement "God is a mathematician" to "God is a quantum field theorist."

Some of you steady truckers might want to ask what to do when you get to the end. During my junior year in college, after my encounter with Mandl, I asked Arthur Wightman what to read next. He told me to read the textbook by S. S. Schweber, which at close to a thousand pages was referred to by students as "the monster" and which could be extremely opaque at places. After I slugged my way to the end, Wightman told me, "Read it again." Fortunately for me, volume I of Bjorken and Drell had already come out. But there is wisdom in reading a book again; things that you miss the first time may later leap out at you. So my advice is "Read it again." Of course, every physics student also knows that different explanations offered by different books may click with different folks. So read other field theory books. Quantum field theory is so profound that most people won't get it in one pass.

On the subject of other field theory texts: James Bjorken kindly wrote in my much-used copy of Bjorken and Drell that the book was obsolete. Hey BJ, it isn't. Certainly, volume I will never be passé. On another occasion, Steve Weinberg told me, referring to his field theory book, that "I wrote the book that I would have liked to learn from." I could equally well say that "I wrote the book that *I* would have liked to learn from." Without the least bit of hubris, I can say that I prefer my book to Schweber's. The moral here is that if you don't like this book you should write your own.

I try not to do clunky

I explained my philosophy in the preface to the first edition, but allow me a few more words here. I will teach you how to calculate, but I also have what I regard as a higher aim, to convey to you an enjoyment of quantum field theory in all its splendors (and by "all" I mean not merely quantum field theory as defined by some myopic physicists as applicable only to particle physics). I try to erect an elegant and logically tight framework and put a light touch on a heavy subject.

In spite of the image conjured up by Zvi Bern of some future field theorist curled up in bed reading this book, I expect you to grab pen and paper and work. You could do it in bed if you want, but work you must. I intentionally did not fill in all the steps; it would hardly be a light touch if I do every bit of algebra for you. Nevertheless, I have done algebra when I think that it would help you. Actually, I love doing algebra, particularly when things work out so elegantly as in quantum field theory. But I don't do clunky. I do not like clunky-looking equations. I avoid spelling everything out and so expect you to have a certain amount of "sense." As a small example, near the end of chapter I.10 I suppressed the spacetime dependence of the fields φ_a and $\delta\varphi_a$. If you didn't realize, after

some 70 pages, that fields are functions of where you are in spacetime, you are quite lost, my friend. My plan is to "keep you on your toes" and I purposely want you to feel puzzled occasionally. I have faith that the sort of person who would be reading this book can always figure it out after a bit of thought. I realize that there are at least three distinct groups of readers, but let me say to the students, "How do you expect to do research if you have to be spoon-fed from line to line in a textbook?"

Nuts who do not appreciate the *Nutshell*

In the original preface, I quoted Ricky Nelson on the impossibility of pleasing everyone and so I was not at all surprised to find on Amazon.com a few people whom one of my friends calls "nuts who do not appreciate the *Nutshell*." My friends advise me to leave these people alone but I am sufficiently peeved to want to say a few words in my defense, no matter how nutty the charge. First, I suppose that those who say the book is too mathematical cancel out those who say the book is not mathematical enough. The people in the first group are not informed, while those in the second group are misinformed.

Quantum field theory does not have to be mathematical. I know of at least three Field Medalists who enjoyed the book. A review for the American Mathematical Society offered this deep statement in praise of the book: "It is often deeper to know why something is true rather than to have a proof that it is true." (Indeed, a Fields Medalist once told me that top mathematicians secretly think like physicists and after they work out the broad outline of a proof they then dress it up with epsilons and deltas. I have no idea if this is true only for one, for many, or for all Fields Medalists. I suspect that it is true for many.)

Then there is the person who denounces the book for its lack of rigor. Well, I happen to know, or at least used to know, a thing or two about mathematical rigor, since I wrote my senior thesis with Wightman on what I would call "fairly rigorous" quantum field theory. As we like to say in the theoretical physics community, too much rigor soon leads to rigor mortis. Be warned. Indeed, as Feynman would tell students, if this ain't rigorous enough for you the math department is just one building over. So read a more rigorous book. It is a free country.

More serious is the impression that several posters on Amazon.com have that the book is too elementary. I humbly beg to differ. The book gives the impression of being elementary but in fact covers more material than many other texts. If you master everything in the *Nutshell*, you would know more than most professors of field theory and could start doing research. I am not merely making an idle claim but could give an actual proof. All the ingredients that went into the spinor helicity formalism that led to a deep field theoretic discovery described in part N could be found in the first edition of this book. Of course, reading a textbook is not enough; you have to come up with the good ideas.

As for he who says that the book does not look complicated enough and hence can't be a serious treatment, I would ask him to compare a modern text on electromagnetism with Maxwell's treatises.

Thanks

In the original preface and closing words, I mentioned that I learned a great deal of quantum field theory from Sidney Coleman. His clarity of thought and lucid exposition have always inspired me. Unhappily, he passed away in 2007. After this book was published, I visited Sidney on different occasions, but sadly, he was already in a mental fog.

In preparing this second edition, I am grateful to Nima Arkani-Hamed, Yoni Ben-Tov, Nathan Berkovits, Marty Einhorn, Joshua Feinberg, Howard Georgi, Tim Hsieh, Brendan Keller, Joe Polchinski, Yong-shi Wu, and Jean-Bernard Zuber for their helpful comments. Some of them read parts or all of the added chapters. I thank especially Zvi Bern and Rafael Porto for going over the chapters in part N with great care and for many useful suggestions. I also thank Craig Kunimoto, Richard Neher, Matt Pillsbury, and Rafael Porto for teaching me the black art of composing equations on the computer. My editor at Princeton University Press, Ingrid Gnerlich, has always been a pleasure to talk to and work with. I also thank Kathleen Cioffi and Cyd Westmoreland for their meticulous work in producing this book. Last but not least, I am grateful to my wife Janice for her encouragement and loving support.

Convention, Notation, and Units

For the same reason that we no longer use a certain king's feet to measure distance, we use natural units in which the speed of light c and the Dirac symbol $\hbar$ are both set equal to 1. Planck made the profound observation that in natural units all physical quantities can be expressed in terms of the Planck mass $M_{\text{Planck}} \equiv 1/\sqrt{G_{\text{Newton}}} \simeq 10^{19}$Gev. The quantities c and $\hbar$ are not so much fundamental constants as conversion factors. In this light, I am genuinely puzzled by condensed matter physicists carrying around Boltzmann's constant k, which is no different from the conversion factor between feet and meters.

Spacetime coordinates x^μ are labeled by Greek indices ($\mu = 0, 1, 2, 3$) with the time coordinate x^0 sometimes denoted by t. Space coordinates x^i are labeled by Latin indices ($i = 1, 2, 3$) and $\partial_\mu \equiv \partial/\partial x^\mu$. We use a Minkowski metric $\eta^{\mu\nu}$ with signature $(+, -, -, -)$ so that $\eta^{00} = +1$. We write $\eta^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi = \partial_\mu\varphi\partial^\mu\varphi = (\partial\varphi)^2 = (\partial\varphi/\partial t)^2 - \sum_i(\partial\varphi/\partial x^i)^2$. The metric in curved spacetime is always denoted by $g^{\mu\nu}$, but often I will also use $g^{\mu\nu}$ for the Minkowski metric when the context indicates clearly that we are in flat spacetime.

Since I will be talking mostly about relativistic quantum field theory in this book I will without further clarification use a relativistic language. Thus, when I speak of momentum, unless otherwise specified, I mean energy and momentum. Also since $\hbar = 1$, I will not distinguish between wave vector k and momentum, and between frequency ω and energy.

In local field theory I deal primarily with the Lagrangian density $\mathcal{L}$ and not the Lagrangian $L = \int d^3x\ \mathcal{L}$. As is common practice in the literature and in oral discussion, I will often abuse terminology and simply refer to $\mathcal{L}$ as the Lagrangian. I will commit other minor abuses such as writing 1 instead of I for the unit matrix. I use the same symbol φ for the Fourier transform $\varphi(k)$ of a function $\varphi(x)$ whenever there is no risk of confusion, as is almost always the case. I prefer an abused terminology to cluttered notation and unbearable pedantry.

The symbol $*$ denotes complex conjugation, and $\dagger$ hermitean conjugation: The former applies to a number and the latter to an operator. I also use the notation c.c. and h.c. Often

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