What is a quantum field theory?

A first introduction for mathematicians

Michel TALAGRAND

If all mathematics were to disappear, physics would be set back exactly one week.

Richard Feynman

Things should be made as simple as possible, but not simpler.

Albert Einstein

The career of a young theoretical physicist consists of treating the harmonic oscillator in ever-increasing levels of abstraction.

Sydney Coleman

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Introduction

When I was a teenager, in the sixties, the scientific magazines I read constantly included articles about "the infinities plaguing the theory of Quantum Mechanics". When I reached 60, after a busy life as a mathematician, I felt that it was now or never that I had to really understand what this meant. (I must admit of course that the realization that I could no longer do research at the level that I wanted to played a major part in this decision.) It turned out that this was much more difficult than I would have expected. I will explain in more detail some of the difficulties I faced. The most important one was the lack of a suitable introductory text, a situation that these notes try to address.

I knew no physics to speak of, but it turned out that there were no specific difficulties in getting an idea (at a very basic level) about what topics such as classical mechanics, electromagnetism, special and even general relativity are all about. The basic reason of course why these topics are friendly for mathematicians is that they can be made very rigorous.

Quantum Mechanics was a different challenge. Quite naturally I looked first for books written by mathematicians for mathematicians. My bad luck was that the first book from which I tried to study is, in my eyes, a catalogue of about every thing one should *not* do when writing a book. Being a mathematician does not mean that I absolutely need to be told about "a one-dimensional central extension of V by a Lie Algebra 2-cocycle" just to be explained what are the Heisenberg commutation relations. Moreover, while there is no question that the mastery of some high level form of Classical Mechanics will help you to get a deeper understanding of Quantum Mechanics, Poisson Manifolds and Symplectic Geometry are not absolute prerequisites to get started. While of course some other books written by mathematicians are less misguided, a common problem with them is that they seem to cover mostly topics which apparently receive little attention in physicist's books with similar titles. Looking into textbooks of physics was not helped either by the worst advice I ever received, to learn the topic from Dirac's book itself. The well-known obstacle of the difference of language between mathematics and physics is all too real. The difference is not only of language, there is an even deeper difference of culture. In a mathematician's eye, some physics textbooks about quantum mechanics are chock-full of somewhat imprecise statements made about rather ill-defined quantities. It is not rare that these statements are simply untrue if taken at face value. Moreover arguments full of implicit assumptions are presented in the most authoritative manner. Looking at elementary textbooks can be an even harder challenge, as these often try to make things easier with a simple-minded approach which need not be fully correct, or try to help the reader by making analogies which turn out under further thinking to be superficial and misleading.[1]

I was lucky however to run in 2012 into the preliminary version of Brian Hall's "Quantum Theory for Mathematicians" [27], which made me feel proud again for mathematicians. I realized that I could learn in this book some of what I needed many times faster than I could have learned at any other place, and that, moreover, the "magic recipe" for this was so obvious that it sounds trivial when you spell it out: *explain the theory in complete detail, starting from the very basics, and in a language the reader can understand.* This seems simple enough but it is very difficult to put in practice, because this requires a lot of *humility* from the author, and humility is not the most common quality among mathematicians. While I certainly don't pretend to be able to emulate Brian's style, his book had a considerable influence on this one and I certainly attempted to go as far as I could in the same direction as his.

After getting some (still very limited) feeling for what Quantum Mechanics is about came the real challenge, understanding something about Quantum Field Theory. I tried to learn from the most eminent [11] but this simply confirmed that I am not eminent. I then tried to look at a few books written by mathematicians for mathematicians. These were certainly not designed as first texts or for ease of reading. Moreover these books focus on attempts to build rigorous theories. As of today these attempts have not been very successful, and the material these books cover seem to be of little concern for most physicists.[2] The most promising road seemed studying Gerald Folland's heroic attempt [22] to make Quantum Field Theory accessible. In particular he does something invaluable: explaining what the physicists do rather than limiting the topic to the (rather small) mathematically sound part of the theory. This book is packed with an unbelievable amount of information, and, if you are exiled with minimum luggage for the rest of your life to a desert island, this is a fantastic value. Unfortunately, as a consequence of this properly neutron-star density, I found it was also much harder to read than I would have liked. At many places, I spent a lot of time. Some of these places deal with rather well established, or even elementary mathematics. This created a difficult situation, because this book has no real competitors and cannot be dispensed with, except by readers able to understand physics textbooks. No doubt

[1] I am certainly not the first mathematician to be appalled by the way physics students get treated, but it seem futile to discuss this matter further.

[2] This being said, [7] is a magnificent piece of work. It is overwhelming at first, but most rewarding once you get started.

that my difficulties are due to my own shortcomings, but still, it is while reading Weinberg's treatise [62] that I finally understood what are induced representations, and this is not the way it should have been. So, as the days I labored through Folland's book turned into weeks, and then into many months, I felt the need to explain this material to myself, or, in other words, to write the text in which I would have liked to learn the first steps in this area. This is how the present work was written. In the rest of the introduction I mostly try to describe what it attempts to do and how.

The overall idea is to provide an easily accessible introduction to some ideas of Quantum Field Theory to a reader well versed in undergraduate mathematics, but not necessarily knowing any physics beyond high-school level or any graduate mathematics.

Let us be clear about a fundamental point. One of the striking features of Quantum Field theory is that it is not mathematically complete, and this is what makes it so challenging for mathematicians. A number of people much brighter than I am have tried for a long time to make this topic rigorous, and have yet to fully succeed. I have nothing new to offer in this direction, and this book contains statements that nobody knows how to mathematically prove. Still, I am trying to explain as far as I can some basic facts *using mathematical language*. I humbly acknowledge right away that familiarity with this language and the suffering I recently underwent to understand the present material are my only credentials for this task.

My main concern has been to spare the reader some of the difficulties from which I have very much suffered while reading others' books (while of course I fear introducing new ones), and I will comment on some of these.

First, while there is no doubt that the research of generality and of the "proper setting" for a theory has been and is a source of immense progress in mathematics, it has become at times a kind of disease among professional mathematicians.[3] They are eager to throw the "second cohomology group of the Lie algebra" of a given Lie group at the reader but ignore the more modest goal of explaining why their important theorem is true when the Lie group is $\mathbb{R}$. My own inclination is that in an introductory work generality should be indulged in only when it is useful beyond doubt. To give another specific example among many others, I cannot feel any need to talk of cotangent bundles to explain basic mechanics in Euclidean space, but the use of tensor products *does* clarify what Fock spaces are. Rather than going after generality, I find that it is far more instructive to explain in complete detail some non-trivial facts and situations, even if they are not so complicated, and especially when they are not immediately found in the literature. This attitude is of course motivated by the fact that whatever small successes I had in my own research were always based on a thorough understanding of very simple structures. In the same

[3] I personally found that the only rather accessible article of the volume [12] is due to E. Witten! But of course this volume is not designed as an introductory course.

line of explaining arguably simple facts, I believe that this is far more useful to the reader than referring her to extensive specialized works, which may have different notation, and may not have been written in priority for ease of reading. Of course, other very different approaches are also possible [42].

Second, I am an extremely ignorant person, and I have suffered from the fact that many textbooks assume too much known by the reader, such as "standard graduate courses in mathematics". For mathematics, I have tried to assume as little as I can and certainly (except on very few occasions) nothing that I did not learn in my first three years of college in Lyon, 1969-1972. As for physics, the difficulty of looking at Quantum Field Theory textbooks is that, even when they try to be as elementary as possible (such as [36]), they assume that the reader has spent lots of time thinking about Quantum Mechanics. Since I am in an excellent position to understand this difficulty from the point of view of the reader, I try not to duplicate this problem by basically assuming nothing that I am aware of.

Third, I am an abysmally slow learner, and I had a hard time at the beginning to recognize at places that different authors treat in fact the same material, each in his own way. Having intensely wished that authors explain more often things several different ways, I have tried to do just that for some of the material which confused me the most.

Fourth, and most importantly, I do not believe that brevity is such a desirable goal that it should be reached at the reader's expense. After all, the goal of a textbook is to communicate ideas, not to try to encrypt them in the shortest possible way (however beautifully this is done). Reading an introductory textbook such as this one *should simply not be a research project.* As G. Folland appropriately points out [22], mathematical readers of notes such as these are likely to be "tourists", in the sense that they do not look to acquire professional expertise in the topic. Where we disagree is that I don't think most tourists enjoy extreme sports, and my overwhelming concern has been to make the book easy to read, in particular by providing everywhere as high a level of detail as I could manage. This book attempts not to contain anything really complicated until the last chapters, so even when rigorous results exist they are not given if they are difficult (such as the spectral theory of self-adjoint operators). Also, while tourists may not enjoy extreme sports, they are more likely to enjoy leisurely sight-seeing and I have tried to provide ample opportunity for this, in a number of appendices which, while not strictly necessary to follow the main story, provide as accessible an introduction as I could to a number of rewarding topics. These either complement the main story, or occur often enough in the related literature that I felt the need to write them in a language I could understand.[4]

[4] The choice of these topics is highly personal, and reflects both my interests and the history of my learning of this topic. There are points which I felt I just *had to* understand, but which I am certain many readers will feel comfortable to accept without proof.

Besides the previous considerations which determine the style of the book, I have also thought that it would be most useful not to duplicate what is done everywhere else. This choice has profound consequences on the organization of these notes. First, while I am as aware as anybody else of the fundamental importance of historical perspective in understanding a topic, I made no attempt whatsoever in this direction. One obvious reason for this is that I am not qualified, and that there is no point repeating in a clumsy way what is said excellently elsewhere. A less obvious reason is that I feel that this is not necessarily the easiest way for a first presentation, and that one gains by presenting early certain central and simple ideas, without respect to how difficult it might have been to discover them. I am in good company here, since this is exactly the approach of Weinberg [62]. Second, I decided to concentrate on the points I had the most difficulty understanding, and to treat these in considerable detail, trying also to explain how these points are presented in physics textbooks. The subtitle of this book, a first introduction for mathematicians, *does not mean* that this book intends to be the fastest possible introduction to the topic, but rather that the reader is not assumed to know anything whatsoever about it. A bare-bones treatment (covering far more material than I do) has already been written [16], and I am aiming here at a more fulfilling level of understanding. I felt that it would be useful to cover some of the fundamental structures in sufficient detail to provide a solid foundation for the reader's future readings. One of my most glaring shortcomings is an inability to make sense of a mathematical statement unless I have taken it apart to the very last bolt and reconstructed it entirely. I have tried to do just that for these fundamental structures, and this often takes several times longer than in standard textbooks. Obviously in these books the reader is expected to produce on her own whatever efforts are required to become a professional and master the field, while I try my best to be much less demanding. On the other hand, some fundamentally important topics, but which I find much easier to learn, get only the barest of coverage when a detailed understanding is not really needed for the main purposes.

Quantum Field Theory is a difficult and voluminous theory. It involves a remarkable number of deep ideas. Many of them are not extremely difficult, but the overall quantity is rather staggering. If one chooses as I did to be at the same time very detailed and very thorough, the number of topics that one is able to cover in a given volume is necessarily rather limited, and difficult choices had to be made. Roger Penrose [43], page 657, qualifies Quantum Field Theory as "this magnificent, profound, difficult, sometimes phenomenonally accurate, and yet often tantalizingly inconsistent scheme of things." As I explained, the only possible contribution of the present work is to describe in a self-contained manner some simple facts in purely mathematical language. It then seems appropriate that it covers mostly topics where the use of mathematical language brings benefits to a mathematical reader well beyond a simple matter of notations. This is no longer the case when one ventures in the "inconsistent scheme of things" part of the theory. Still, a few chapters enter this territory, if only in order to provide at least some form of answer to the question which serves as title, as well as some glimpse on physics methods. It has been a deliberate choice to explain this as clearly as possible on the simplest possible "toy models" without any attempt to study realistic models (where the principles are similar but obscured by many accessory complications). I have purposely avoided to repeat what is already written in so many places, such as describing again the tremendous successes of Quantum Electrodynamics. Do not expect to learn here any real physics or what is the Standard Model. Rather, one of my goals is to prepare the reader to study books which cover these topics, among which I first recommend Folland's book [22]. However demanding, this book is simply brilliant at a number of places, and I see no purpose to repeat the parts which I cannot improve in my own eyes.

On the other hand, the study of renormalization, the method to circumvent the dreadful infinities, receives far more attention than it does in the standard textbooks. Not only curiosity about this procedure started the present quest, but, unexpectedly enough, the procedure itself is completely mathematical. The mathematics involved are arguably elementary, but also magnificently clever. Unfortunately there does not seem to exist any other detailed source than the original papers and the rather specialized monograph [37].[5] We prove in full details the possibility of renormalization at all orders of the so-called ϕ^4_4 and ϕ^3_6 theories, cases of somewhat generic difficulty.

I wrote the present book purely for my own enjoyment, although this project turned out to be the hardest of my scientific life. There is no magic wand to make Quantum Field Theory really easy. Then, necessarily, some effort will be required from the reader. My primary goal has been that this effort be much less for the reader than it was for myself, while striving to keep at least some of the potential for enjoyment and enrichment this fascinating topic offers.

A number of people helped me while I wrote this book. Gerald Folland spent considerable time and displayed infinite patience in trying to explain some of the most delicate points of his book [22]. Shahar Mendelson rescued me many times form the brink of disaster. Comments of Brian Hall, Amey Joshi, Pascal Maillard, Shuta Nakajima, Roy Wilsker and others on the successive versions had a major impact. I express my gratitude to them all.

[5] The major textbooks do not enter details in this topic, but only illustrate some ideas on examples, "referring the serious reader to the study of the original papers" see e.g. [39], p. 157. Most remarkably, this is even the case of books which primarily deal with renormalization, such as [10], [1].