Physics 202a – Quantum Field Theory

Syllabus for Winter/Spring 2015

1 Official business

- Class times: Monday-Wednesday 2-3:20, Physics room 229.
- Office Hours: TBA in my office (97-344), and by appointment.
- Email: albion@brandeis.edu

2 Course outline

This is primarily a course in the quantum mechanics of fields (such as the electromagnetic field), including the quantum mechanics of many-particle systems (when particles can be created and destroyed). This is a framework covering a wide variety of phenomena: particle physics, quantum condensed matter systems, fluctuations of the CMBR during inflation, string theory and quantum gravity, and so on.

However, a simple mathematical trick (which we will explain) provides a map between quantum field theory problems and classical equilibrium statistical mechanics; the calculations one performs, and many interpretational aspects, are the same. Similarly, noise-driven nonequilibrium systems can also be described by a statistical field theory amenable to the same kind of analysis. Many detailed aspects of relativistic quantum field theory make their appearance in interesting ways in statistical problems.

Thus, while this course is rooted in relativistic quantum field theory as practiced by particle physics, I will discuss the statistical physics interpretations in parallel. The best practitioners of field theory are well-versed in its myriad applications, and the connections between them. My goal is a course which will be of value to both high-energy and (soft) condensed matter physicists, though astrophysicists and some mathematicians should find it valuable as well. The precise balance will depend on the final makeup of the class.

Ask lots of questions if you are confused. Me just pouring information into your ear will not lead to effective learning.
1. Introduction
   (a) Why Field Theory? Quantum and statistical fields.
   (b) Particle creation and decay, relativistic and nonrelativistic QFTs.
   (c) Representations of the Poincare group; particle spins.

   (a) Classical mechanics. Lagrangian and Hamiltonian dynamics. Sym-
   metries and Noether’s theorem. Lorentz invariance and the stress-
   energy tensor.
   (b) Quantum mechanics: Second quantization.
   (c) Feynman Path integrals and QFT. Relations to canonical quanti-
   zation. Relationship to statistical mechanics.
   (d) Interacting field theories/perturbation theory. Wick’s theorem, 
   Feynman diagrams, the loop expansion.
   (e) What do we want to calculate? What is done in the laboratory?
      i. Correlation functions, response functions, linear response the-
         ory, what’s done in the lab.
      ii. Scattering amplitudes from correlation functions – the LSZ
         reduction formulae

3. Higher spin fields
   (a) Relativistic spin-$\frac{1}{2}$ particles.
   (b) Massless spin-1 particles. (Abelian) gauge invariance and gauge 
      fixing.
   (c) Quantum electrodynamics.

4. Radiative corrections, Renormalization, Effective Field Theories. Crit-
   ical exponents and deviations from mean field theory.

3 Assignments

Problem sets will be posted (on Latte) every two weeks on Wednesdays and 
 generally due at the beginning of class two weeks after the assignment is 
 posted. I will not accept late assignments unless I am contacted before the 
 due date with a valid reason (professional travel, family emergency, etc.)
4 Grading

Grading will be based entirely on the problem sets.

5 Availability

Office hours will be negotiated first week of class. If the times we set up do not work for you, or you want to discuss something less publicly, you can ask me by email or schedule an appointment by email (email is best). I’m always happy to chat about physics and will make sure we work something out.

If you want to talk about broader topics — physics in general, life at Brandeis, shopping for a research topic/thesis advisor, career possibilities/preparation, etc — please contact me and we can set up a time.

6 Expectations

The course is designed around the lectures, so while I won’t grade on attendance, you should come to class. I don’t follow any of the books precisely, and furthermore will provide motivations you won’t find in any one textbook.

Working problems is essential to learning quantum field theory. You don’t understand it until you can do it. The problems in this class will sometimes be demanding, which is traditional in any course in quantum field theory. I expect students to complete the problem sets to the best of their abilities, even if the problems seem longer than expected. Sometimes it is just important to work through a hard problem. It’s also true that there is sometimes a time-saving method. The best method is to jump in, get your hands dirty, and then step back for a bit and think about the best way to proceed after you’ve played around for a bit.

In general, these will not be problem sets you can do the night before. You should look them over soon after you get them, take a first pass, and see what you don’t understand. From there some combination of reading, asking me questions, and discussing the problems with your classmates should point the way forward.

You are strongly encouraged to discuss the problem sets and the class material with each other. By this I mean discussing what the question means, and what techniques and strategies you might use to solve them. I feel that
physics is best learned socially, with your peers. I also encourage people to use the library and read about the subject from multiple sources. However, it should go without saying that the solutions you present should be your own; you should have understood the solution and explained it yourself, in your own way. Simply copying other people’s (or other books) problem set solutions constitutes plagiarism. Evidence of such will be dealt with via the procedures outlined in the student’s guide to their rights and responsibilities.

7 Reading List

No book is perfect, and each has its strengths and weaknesses. In particular, I’ve never found a perfect book suited for the typical Brandeis audience, a mix of people interested in particle physics and soft condensed matter physics, although I think such a course is natural to teach.

This is a subject that rewards reading about things which confuse you from mutiple points of view. So I am listing a number of books I know at least a little something about. I will put as much as I can on reserve.

I will also post several readings on Latte, particularly later in the course.

1. **Required.** Peskin and Schroeder, *An Introduction to Quantum Field Theory*. This is one of the better pedagogical books I have found on quantum field theory from the particle physics point of view, and has become a standard. I find the presentation to be clear and straightforward. It is a serious, in-depth book and a useful reference. It goes much farther than I will, and the emphasis is different (e.g., it is weighted more heavily towards particle physics), but it does have some very nice sections on the use of field theory in statistical physics.

2. **Strongly recommended.** Zee, *Quantum Field Theory in a Nutshell*. This book is quite clearly written and unusually insightful, as one would expect from one of the masters of applications of modern QFT to condensed matter physics and particle physics. It is very modern and cuts through a lot of BS from the physics standpoint. The presentation is not as rigorous or thorough as other texts, and it should be a supplement to a more thorough textbook like Srednicki or Peskin and Schroeder. It discusses quite intensively both particle physics and condensed matter applications of quantum field theory, and in this sense its approach is the most modern. It actually covers some quite advanced
subjects with significant insight, so people with a serious interest in either subject are encouraged to own a copy.

3. **Recommended books with a particle physics point of view.**

(a) Srednicki, *Quantum Field Theory*. An excellent, modern treatment of the subject, mostly from a particle physics point of view. I tried teaching out of this and it didn’t quite work for my purposes, though in a different context (audience of primarily particle physicists, and a 2-semester course) it would be superb. Note that an almost-final draft is available online at Mark Srednicki’s website (you can Google it).

(b) Weinberg, *The Quantum Theory of Fields, v. 1-III*. A modern classic by a master of the subject. (This is the Weinberg that got the Nobel for the standard model.) It is not an introductory book, but it is a superb reference on any subject of field theory you need to know about and everybody working in quantum field theory should own the first two volumes. Vol. III is on supersymmetry, which is far beyond what we will cover.

(c) Matthew Schwartz, *Quantum Field Theory and the Standard Model*. This book just came out, and looks great. Its order of presentation doesn’t quite serve my purposes, but particle physicists should check it out.

(d) Ramond, *Field Theory: a Modern Primer*. In particular I recommend the second edition. The early chapters of this book are very nice indeed. It has a good intro to spinors and fermions, and an excellent discussion of path integral techniques and perturbation theory, from a fairly modern point of view. Its treatment of renormalization is very old-fashioned, but that’s true of most treatments that you will find. Overall I think this is an excellent book to have around.

(e) Itzykson and Zuber, *Quantum Field Theory*. A classic of thoroughness and inscrutability. That said, it is very complete, and if you are serious about QFT from a particle physicist’s perspective, you really should own this. This has been made much easier as Dover has just re-released it in paperback at a more humane price.
(f) Banks, *Modern Quantum Field Theory*. This is a slim little book written from a particle physicist’s point of view. The approach is quite modern and it covers a variety of topics with unusual insight.

(g) Mandl and Shaw, *Quantum Field Theory*. The edition has been revised, though it costs a pretty penny new. A lot of students like this book, and I found it useful when I took this course – it’s slim, in paperback, basic, and very straightforward. The emphasis is entirely on the particle physics point of view. As a primary text it’s too old-fashioned for my purposes, especially when I hit renormalization, but you may find this quite useful for the first part of the course.

(h) Ryder, *Quantum Field Theory*. A readable and fairly modern introduction to QFT, again from the particle physics point of view. I find it intellectually a bit light, and people who have read it more closely than I have found some serious mistakes, so caveat lector.

4. Books from a quantum condensed matter point of view. There should be other, recent, modern approaches as well.


(b) Fetter and Walecka, *Quantum Theory of Many-Particle Systems*. Covers very similar ground as AGD; also a very nice book, though again rather dated, and now thankfully printed by Dover so you can afford it. I have been known to steal problems out of it from time to time.

(c) Wen, *Quantum Field Theory of Many-Body Systems*. This book studies quantum field theory from the point of view of quantum condensed matter physics. It goes from quite elementary to quite advanced; the applications are very modern (quantum hall effect, quantum spin liquids, and topological order – these involve some very advanced concepts in QFT, some of which emerged from string theory, and also are central in some very interesting ideas
for building quantum computers). I’ve spent more time reading the more advanced parts so I haven’t totally vetted it for pedagogy.

5. **Books from a statistical physics, or combined statistical/quantum physics point of view.**

   (a) Amit, *Field Theory, the Renormalization Group, and Critical Phenomena*, a classic text applying field theory techniques to statistical physics.

   (b) Le Bellac, *Quantum and Statistical Field Theory*. Somewhat after the fashion of Amit. I have not read this book in great depth, but (a) people I know have liked it quite a lot, and (b) it’s one of the few books which gives weight to both quantum and statistical physics, and (c) I have stolen buits from it in constructing my lecture. It goes in a different order than I like to go, starting in the first half with statistical physics and then moving to QFT. Those with an interest in stat mech may find it useful.

   (c) Kardar, *Statistical Physics of Fields*. What I have read of this I have really liked. The material through Chapter 5 will be relevant, though the perspective and order is different from what I will do here.

   (d) Itzykson and Drouffe, *Statistical Field Theory*, vols. 1-2. Volume 1 is more relevant to this course: I enjoyed it when I read it in grad school, but as with Kardar, the outline and perspective is very different from what I will do in this course.

   (e) Zinn-Justin *Quantum Field Theory and Critical Phenomena*. An encyclopedic tome dealing with QFT as practiced in particle and statistical physics. A very good reference for lots of things, but rather formal/mathematical and less useful to learn from.

   (f) Cardy, *Scaling and renormalization in statistical physics*, This is also nice to have if you are contemplating a future in string theory.