

## Physics 217: Introduction to Quantum Field Theory

Fall, 2003 Instructor: Michael Dine

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**Course information, homework, solutions, etc. will be available on my website: <http://scipp.ucsc.edu/dine> or follow the links from the department website.**

**Course Description:** This course is intended to provide an introduction to quantum field theory. The stress will be on developing the Feynman diagram method, and applying it to compute cross sections for a variety of physical processes, principally in Quantum Electrodynamics. We will also learn methods to handle the ultraviolet and infrared divergences which arise in perturbation theory.

**Note on the texts:** The principle text for the course will be Peskin and Schroeders “Introduction to Quantum Field Theory.” This text is, in my view, probably the best field theory text which presently exists. Peskin’s treatment is modern, self-contained, and provides a deep understanding of the essential physics. When one finishes this book, one is close to the research forefront.

I will supplement the book with handouts from other texts and articles from the current literature, as well as things I will prepare myself.

**Books on Reserve:** I have put a number of books on reserve, and strongly recommend you look at them. Steven Weinberg has recently produced a three volume text in field theory. I chose not to use this text because it is somewhat more difficult to read, and the treatment is a bit idiosyncratic. But for these reasons, I strongly recommend that you look at it. The treatment of many topics is exceptionally good. Weinberg is particularly interested in the significance of quantum field theory and the “grand principles” which underlie it. The introduction, which is mainly a historical review of the subject, is very interesting. Also on reserve is the text from the Landau and Lifschitz series. This has a good treatment of many topics in QED which you will have a hard time finding elsewhere (e.g. bound states, aspects of the infrared problem, etc.). Ramonds book, a Quantum Field Theory Primer, is easy to read and very accessible. It stresses the path integral method, which we will cover next quarter. The book by Itzykson and Zuber is not an easy read, but is comprehensive. It has good treatments of many particular topics, including very explicit two loop computations in QED, the goldstone phenomenon, and others. I have used the text by Mandl and Shaw in the past for this course, and it is quite readable. Many students find it more accessible and concise than Peskin, and I encourage you to use it to supplement your reading.

The two volume text by Bjorken and Drell was for many years the standard text in the field. It is now dated in many respects, but still has useful treatments of many problems. The first volume follows Feynman's original treatment of the subject, and goes through some useful computations. I will put other books on reserve from time to time as seems appropriate. I will frequently supplement the text with handouts from other texts as well as with my own notes. I have also put the text by Lowell Brown on reserve, which has good coverage of a number of topics which do not appear in other books.

**Homework, exams,etc:** There will be approximately six problem sets plus a take home final. The homeworks will be rather demanding. The subject matter is not really that difficult, but it is essential to review class notes and to keep up in the reading and the homework.

### Tentative Schedule

**Warmup: Read PS, chapter 1 and 2. Read handout by Wilczek on Quantum Field Theory.**

Sept. 25. Introduction. Quantization of the free Klein-Gordan and electromagnetic fields from a simple-minded perspective. Review of special relativity in four vector notation. Introduction to the Dirac equation. [I understand that you did not touch on the Dirac equation in quantum mechanics, and that many of you have not encountered it.]

Sept. 30, Oct. 2. More systematic development of the free Klein-Gordon field. This is the simplest type of field theory, and provides an opportunity to introduce a number of basic concepts. We will consider the classical Lagrangian and Hamiltonian descriptions of this field, and possible symmetries. Then we will turn to its quantization, imposing canonical commutation relation relations on the fields, decomposing the field into its normal modes (harmonic oscillators), constructing the Hilbert space, and considering issues such as Lorentz invariance. We will also introduce an object which is fundamental in the Feynman approach to perturbation theory: the propagator. This will give us a chance to discuss the question of causality. (PS, chapter 2.)

Oct. 7,9. The free Dirac field. Review of the four-component Dirac equation and its Lorentz transformation properties. Solution of the equation. Introduction of two-component, Weyl spinors. Spin sums. Quantization of the free field; fermion creation and annihilation operators. Structure of the Hilbert space. Construction of the propagator for the Dirac field. The discrete symmetries P,C, and T. (PS, chapt. 3.)

Oct. 14. Quantization of the Electromagnetic field. Coulomb gauge treatment. Lorentz covariance. Derivation of a Lorentz covariant propagator using gauge invariance. (MS chapter 5 (handout.)

Oct. 16. Feynman-Dyson perturbation theory. In this discussion, we will use the operator method, in a manner quite analogous to the usual treatment of time-dependent perturbation theory in quantum mechanics. The main new feature is a rearrangement of the terms in the expansion exploiting the time-ordering of operators which appears in that treatment. This leads to Lorentz invariant expressions. We will first consider (interacting) scalar field theory. We will develop the expansion of the time-development operator in the interaction picture in powers of the perturbation, and prove “Wick’s theorem,” the basic tool for developing the diagram expansion. We will exhibit the cancellation of the disconnected graphs. Extension of the methods to fermions, photons. (PS, chapter 4.)

**I may have to be at the ITP all or part of this week, so some rescheduling of these lectures will be required.**

Oct. 21. 23. Path Integrals. Feynman long ago gave an alternative formulation of quantum mechanics in terms of integrals over histories. This beautiful set of ideas is not terribly useful in quantum mechanics, but is a very powerful tool for many problems in quantum field theory. We will give an introduction to path integrals in quantum mechanics, and use them to give a quick derivation of Wick’s theorem. **Note: Depending both on how we are keeping to schedule and popular demand, we may postpone this for 218 next quarter.**

Oct. 28,30. Elementary Processes in QED. We will compute the cross sections for a number of processes.

- a.  $e^+e^- \rightarrow \mu^+\mu^-$  – develop trace technology. Analyze helicity structure.
- b.  $e - \mu$  scattering and crossing.
- c. Compton scattering.
- d. Scattering in an external field. (PS, chapter 5.)

Nov. 4,6. Radiative corrections: infrared problems. Radiative corrections exhibit infrared divergences associated with very low momentum processes and ultraviolet divergences associated with high momentum processes. The low energy divergences represent real, computable physical effects. Here we will consider bremsstrahlung. as an example of infrared difficulties (PS chapter 6.)

Nov. 13,18 [**Nov. 11 is campus holiday**]. Radiative corrections: ultraviolet problems.

- a. Electron self energy: in QED, we can try to compute the corrections in perturbation theory to the electron mass. We will see that these are divergent

and introduce the notion of regularization, the process of giving a definition to divergent, ill-defined quantities.

- b.* We will consider particular types of regulator. The most obvious one is a simple cutoff on momentum integrals, but we will see that this has difficulties. We will consider two other regulators: Pauli-Villars and dimensional regularization. Of these, the first is perhaps the nicest conceptually, but the second is far easier to use in practice.
- c.* In order to “learn our way around,” we will compute something physical: the anomalous magnetic moment of the electron. (PS 6,7.5.)

Nov. 20, 25. More radiative corrections. We will consider systematically the various divergences which arise at order  $\alpha$  in perturbation theory. We will study the photon self-energy and the vertex correction, as well as the electron self-energy. We will interpret the results of our computations in terms of the “renormalization” of the electron charge and mass. We will also study further the problem of infrared divergences and their cancellation. (PS, chapter 6.)

Dec. 2,4. Some formal developments. Basic notions of renormalization theory, illustrated with scalar field theory and QED. The LSZ approach to computing the S matrix. (PS, chapter 6).