Physics 82500, Quantum Field Theory, Spring 2009
Graduate School and University Center, CUNY

Peter Orland, Baruch College, CUNY,
646-660-6205, orland@nbi.dk

The course will be an introduction to relativistic quantum fields, scattering amplitudes and renormalization. Additional topics, such as the Lamb shift, formal renormalization proofs, the standard model of particle physics, lattice regularization, and non-perturbative methods will be deferred to the sequel to the course, PHYS 82600 (in the Fall 2009 Semester). I have made a point of include some interesting material in the first semester, in case the second course does not run. Regular homework will be assigned. There will be a midterm exam and a final exam.

Here is an outline of the topics covered:

1. Background Material
   (a) Relativity, Lorentz group;
   (b) Scalar wave equation;
   (c) Dirac equation, its plane-wave and hydrogenic-atom solutions;
   (d) Calculus of variations and functional differentiation;
   (e) Nonlinear theories, the Yang-Mills equations.
2. Quantized Fields
   (a) Scalar field quantization, vacuum state;
   (b) Dirac field quantization, Jordan-Wigner transformation;
   (c) Transition amplitudes in the presence of sources, propagators;
   (d) Feynman graph rules.
3. Elementary Processes
   (a) Decay rates and scattering theory;
   (b) Compton scattering and the Klein-Nishina formula;
   (c) Positronium decay.
4. Higher-Order Processes and Renormalization
   (a) Divergences in loop diagrams;

(b) Wick rotation and the connection with critical phenomena;

(c) Effective couplings at different scales, the renormalization group;

(d) Asymptotic freedom in Yang-Mills theories.

I'll probably go very quickly through 1.a.b., 2b. and 3c. to try to get through some of the more interesting material.

All course notes will be made available. There will be no required textbook. For the benefit of the student who wishes to read further, however, some field-theory books are listed below, with my comments, in no particular order:

- **Quantum Field Theory**, C. Itzykson and J.-B. Zuber, McGraw-Hill Inc. (1980). Now reprinted by Dover. A long overview of the subject, with a great deal on Heisenberg, interaction and functional methods. There is a good chapter on radiative corrections and the Lamb shift, and a modern discussion of gauge theories and their renormalization. This is one of the modern standard encyclopedic texts. Some of the discussion is not complete and the reader has to go the literature to fill in the gaps.

- **Quantum Field Theory I, II**, S. Weinberg. I would say that this book moves very slowly and, in my opinion, the derivations are unnecessarily cumbersome. On the other hand this is the most complete and pedagogical textbook available, and has the answers to almost any questions students may have. It may be a long time before a better encyclopedic text is available.

- **Diagrammatica**, M. Veltman, Cambridge University Press (1994). An introductory cookbook, advocating a (obviously) diagrammatic approach. The emphasis is on computing experimentally measured quantities. It overlaps a good deal with the CERN preprint article "Diagrammar", by 't Hooft, and Veltman, available on-line, which is excellent.

- **Renormalization**, J. Collins, Cambridge. This is an excellent review of renormalization and its applications in particle physics, for the student who already is familiar with functional integrals and the basics of field theory.

- **An Introduction to Quantum Field Theory**, M. Peskin and Schroeder, Perseus books (1995). Seems pretty good at explaining the basic points. Oriented towards standard-model phenomenology.

- **Introduction to the Theory of Quantized Fields**, N. N. Boguliubov and D. Shirkov, Wiley Interscience (Second edition 1980?). The first edition was a remarkably modern book, in its treatment of naive degrees of divergence, overlapping divergences and the renormalization group; this in 1957! There are many other topics discussed, such as Schwinger-Dyson equations and dispersion relations. However, few applications of loop calculations are discussed in detail, and the regularization methods are clumsy. The second edition contains a discussion of gauge theories and path integrals.

- **A Field Theory Primer**, P. Ramond, Benjamin/Cummings (1980?). A very good cookbook, using path integrals and dimensional regularization (though there is a brief introduction to the zeta-function method). This will tell you how to calculate, but not what you are calculating.

- **Relativistic Quantum Mechanics** and **Relativistic Quantum Fields**, J. Bjørken and S. Drell, McGraw-Hill Inc. (1966?) The first volume develops Feynman rules heuristically and does a good job with tree and one-loop calculations in quantum electrodynamics, including the Lamb shift. The second volume covers the interaction representation and the renormalizability of quantum electrodynamics (which is now outdated), and has an introduction to dispersion relations. In the seventies, this was *the* book used in field theory courses.

- **Advanced Quantum Mechanics**, F.J. Dyson, available on the web. Wonderful introduction to QED, from the early fifties. Good discussion of the Lamb shift.

- **Advanced Quantum Mechanics**, J.J. Sakurai, Addison-Wesley covers most the material in Dyson's manuscript, above, from a more elementary viewpoint. Starts with background material in atomic physics. Some good discussion of the weak interactions (pre-standard-model), parity violation V-A theory. Avoid the Aharonov-Bohm discussion; a better treatment is in Sakurai's quantum-mechanics text.

- **PCT, Spin and Statistics and all That**, Streater and Wightman. The axiomatic (rigorous) approach to Hamiltonian field theory. I don't see that there has been much progress in this field since 1960, though people still write Ph.D. dissertations about it.

- **Quantum Physics**, Glimm and Jaffe, Springer. An introduction to Euclidean constructive field theory and statistical mechanics. Unfortunately the rigorous methods of this book had some initial success, but have not progressed much since the mid-1980's.

- **Classics Illustrated: Field Theory**, P. Cvitanović, Nordita Lecture Notes (1983). The identity of this manuscript lies somewhere between a book and a preprint (there is no index, for example), and is not widely available. No calculations, but uses a physical diagrammatic approach to field theories. There is a wonderful discussion of the physical meaning of Ward identities and Fadeev-Popov ghosts in this context.

- **Elementary Particle Physics**, S. Gasiorowicz (1966). The first part of the book is an excellent introduction to quantum electrodynamics and other field theories. The remainder of the book discusses strong and weak interactions, which though good, is out of date, due to the advent of gauge theories and further experiments.

- **Introduction to Particle Physics and Field Theory**, T. D. Lee, Harwood Academic Publishers (Revised First Edition 1988). This book contains a good introduction to field theory, more modern (for example there is plenty of discussion of gauge theories), though not as detailed as that in Gasiorowicz's book. There is much excellent discussion on the applications to particle physics, to which this book is probably the best introduction at the graduate level.

- **Quantum Field Theory**, by W. Siegel. A web-book. Much of this looks good, though it seems heavily oriented towards supersymmetric theories. If you love supersymmetry, this might be for you. I looked at the discussion of the Landau rules, which is very nice.

- **Quantum Field Theory and Critical Phenomena**, J. Zinn-Justin, Oxford University Press (Second Edition 199?) An immense collection of very useful stuff.

- **Field Theory the Renormalization Group and Critical Phenomena**, D. Amit, World Scientific. Good pedagogical volume on the renormalization group and critical phenomena. Before reading this or Zinn-Justin's book above, I would look at Ma's book, below.

- **The Modern Theory of Critical Phenomena**, S.-K.Ma, Benjamin (1973). Wonderful introduction to what critical phenomena and the renormalization group are all about.

- There are also older books by Mandl (1st edition), Lurie, Roman and Schweber on QED. The first two are good (Mandl has a 2nd edition with Shaw, which I haven't looked at). Run from the last two!

- Review articles, like Abers and Lee, Marciano and Pagels, Wilson and Kogut, (all Physics Reports) for further reading.