Introduction to Quantum Field Theory

The *Introduction to Quantum Field Theory* is a two-semester course. Content-wise, this is a continious 29-week long course, but for administrative purposes it is split in two:

- PHY 396 K -- Quantum Field Theory I, usually taught in the Fall, and
- PHY 396 L -- Quantum Field Theory II, usually taught in the Spring.

Physics-wise, the split is rather arbitrary, so *students seriously interested in the Quantum Field Theory should take both halves of the course*.

Unfortunately, the UT Physics Department is unable to offer the QFT II class every year, so the students who took QFT I (396 K) last Fall (2015) will have to wait for the Spring of 2017 for the QFT II (396 L) course.

This document is the syllabus for the whole course as taught in the academic years 2015/16/17 (that is, **396K** taught in Fall 2015 and again in Fall 2016, and **396L** taught in Spring 2017) by **Dr. Vadim Kaplunovsky**. Note that future offering of the Quantum Field Theory course may vary.

Prerequisite Knowledge

The formal pre-requisites for the QFT (I) class is graduate standing and the PHY 389 K class (graduate Quantum Mechanics (I)). However, what I care about is your knowledge rather than your status or grades. **If** you have the pre-requisite knowledge — however you have learned it — I'll sign the paperwork to let you into my class even if you are an undergraduate student.

Understanding Quantum Field Theory requires serious knowledge of quantum mechanics at graduate or *advanced* undergraduate level. Besides the QM basics — like knowing how to solve the hydrogen atom — you must be familiar with the multi-oscillator systems, the rotational symmetry and the angular momenta as its generators, the identical particles, the perturbation theory, and the basics of scattering theory. For the UT undergraduate students, you should complete the undergraduate QM sequence of 373 + 362K + 362L classes before taking the QFT class. For students who have learned their QM elsewhere, you need either 120 hours of undergraduate QM classes (not counting the inroductory *Modern Physics* class), or basic undergraduate QM followed by a gradute-level QM class. In any case, read J. J. Sakirai's book *Modern Quantum Mechanics* in the summer; if you understand everything in it, you are ready for my QFT class, but if the book looks all Japanese to you, you should beef up your Quanum Mechanics before taking Quantum Field Theory.

Besides QM, you would need good undergraduate-level knowledge of Classical Mechanics (the Lagrangian, the Hamiltonian, the canonical variables, etc.), Classical Electrodynamics (the vector potential **A**, the gauge transforms, the EM stress-energy tensor, etc.), and basic special relativity (the Lorentz transforms, the 4–vectors, and the tensors). Make sure you are familiar with both 3D and 4D index notations, so expressions like $\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu}$ do not confuse you or slow you down. You do not need general relativity for the QFT classes. In terms of the UT undergraduate classes, the 336 + 352K + 352L classes should give you adequate background.

The undegraduate-level Statistical Mechanics would be very useful for the second semester of QFT (**396L**), but you would not need it for the first semester (**396K**).

Finally, on the Math side, you would need basic complex analysis, especially the contour integrals and how to take them. You are also advised to learn a bit of continuous group theory, but this is not a pre-requisite. In class, I shall explain the basics of continuous groups, their generators, and the representations from scratch, but it would help if you already know something when I do.

Course Content (QFT I and QFT II combined)

Bosonic Fields:
: Classical field theory; relativistic fields; identical bosons and quantum fields; Klein-Gordon propagator and relativistic causality; quantum electromagnetic fields and photons.

Fermionic fields:
: Lorentz symmetry and spinor fields; Dirac equation and its solutions; second quantization of fermions and particle-hole formalism; quantum Dirac field; Weyl and Majorana spinor fields.

Symmetries in QFT:
: Continuous symmetries and conserved currents; spontaneous symmetry breaking and Goldstone bosons; local (gauge) symmetry and QED; Higgs mechanism and superconductivity; non-abelian gauge symmetries and the Yang-Mills theory; discrete symmetries.

Interacting Fields and Feynman Rules:
: Perturbation theory; correlation functions and Feynman diagrams; S-matrix and cross-sections; Feynman rules for the QED, QCD, and other important firld theories.

Quantum Electrodynamics:
: Some elementary processes; radiative corrections; infrared and ultraviolet divergencies; renormalization of fields and of the electric charge; Ward identities.

Functional Methods:
: Path integrals in quantum mechanics; "path" integrals for classical fields and functional quantization; functional quantization of QED; QFT and statistical mechanics; quantum symmetries and conservation laws.

Renormalization Theory:
: Systematics of renormalization; `integration out' and the Wilsonian renormalization; `running' of the coupling constants and the renormalization group.

Non-Abelian Gauge Theories:
: Non-abelian gauge symmetries and the Yang-Mills theory; interactions of gauge bosons and Feynman rules; Fadde'ev-Popov ghosts and BRST; renormalization of the YM theories and the asymptotic freedom; chiral gauge symmetries; the Standard Model; confinement and other non-perturbative effects.

In the first semester (the 396 K class) I shall cover the bosonic and the fermionic fields, the symmetries (including the Higgs mechanism and the non-abelian gauge symmetries at the semi-classical level), the perturbation theory and the Feynman graphs, and the elementary processes in QED. The remaining subjects will be covered in the second semester (the 396 L class).

Textbooks

The primary textbook for this course (both semesters) is *An Introduction to Quantum Field Theory* by Michael Peskin and Daniel Schroeder. To a large extent, the course is based on this book and should follow it fairly closely, but don't expect a 100% match.

Since both the course and the main textbook are introductory in nature, many questions would be left an-answered. The best reference book for finding the answers is *The Quantum Theory of Fields* by Steven Weinberg. The first two volumes of this three-volume series are based on a two-year course Dr. Weinberg used to teach here at UT — but of course they also contains much additional material. To a first approximation, Dr. Weinberg's book teaches you everything you ever wanted to know about QFT and more — which is unfortunately way too much for a one-year intodductory course. (Weinberg's volume 3 is about supersymmetry, a fascinating subject I sometimes teach, but I won't cover it in this class.)

I have told the campus bookstore that I use Peskin's book as a textbook for both 396 K and 396 L (Fall 2015, Fall 2016, and Spring 2017), Weinberg's vol.1 as a supplementary texbook for the 396 K (Fall 2015 and Fall 2016) and vol.2 as a supplementary textbook for the 396 L (Spring 2017). I hope the store have stocked the books accordingly, but you should buy them while the supply lasts.

Homeworks and Grades

The homeworks are absolutely essential for understanding the course material. Often, due to the time pressure, I will explain the general theory in class and leave the examples for the homework assignment. It is extremely important for you to work them out by yourselves; otherwise, you might think you understand the class material but you would not! *Be warned: The homeworks will be very hard.*

I shall post homework assignments each week on page http://bolvan.ph.utexas.edu/~vadim/Classes/2016f/homeworks.html (for the Fall 2016 and Spring 2017 classes). The solutions will be linked to the same page after the due date of each assignment.

The homeworks are assigned on the honor system: I shall not collect or grade the homeworks, but you should endeavor to finish them on time and check each other's solutions.

The solutions to previous years' homeworks — often quite similar to this year's — are available on the web, even on my own web server. On the honor system, I will keep them available at all times. But you should do your best to do the homework yourself, and only then read the solutions I post.

There will be separate final grades for each semester. Each grade is based on two take-home tests, one in the middle of the semester, the other at the end; the mid-term test contributes half of the grade and the end-term test the other half. There will be no in-class final exams.

- Fall 2016 mid-term exam will be given to students On October 25 and due on November 1.
- Fall 2016 final exam will be given to students on December 1 (last class) and due on December 8.
- Spring 2017 mid-term exam will be given to students in late March and due a week later.
- Spring 2017 final exam will be given to students on May 4 (last class) and due on May 11.

Lectures (Fall 2016 and Spring 2017)

Regular Lectures

- Four hours a week, both semesters.
- Fall 2015 semester:
  - Tuesdays and Thursdays, 3:30 to 5:30, in room RLM 5.114.
  - **No lecture on August 25** (first week's Thursday): I'll be out of town.
First lecture on August 30 (Tuesday)
- Spring 2017 semester:
  - Tuesdays and Thursdays, 3:30 to 5:30, room TBA.
- All missed lectures will be made-up.

Make-up and Supplementary Lectures

Besides the regular lectures, I shall give a few supplementary lectures about subjects that are somewhat ouside the main focus of the course but are interesting for their own sake, such as magnetic monopoles or superconductivity. The students are strongly encoraged to attend the supplementary lectures, but there is no penalty for missing them. The issues covered by supplementary lectures will not be necessary to understand the regular lectures and will not appear on exams.

The schedule for the make-up and supplementary lectures will be worked out in the first week of each semester and posted right here. Expect 5 to 7 lectures each semester, roughly a leacture evry two or three weeks.

Fall 2016 semester:

- The supplementary lectures will be on Wednesdays, from 1 to 2 PM, in room RLM 9.222 (the brown bag room).
- Tentatively, the lectures will be on **9/14**, **9/28**, **10/12**, **10/19**, **11/9**, **11/16**, **11/30**.
- Lecture on **9/14**: *Seeing classical motion in QM and classical fields in QFT.*
- Lecture on **9/28**: *Field theory of superfluidity.*
- Lecture on **10/12**: *More Superfluidity.*
- Lecture on **10/19**: *Spinor fields in different spacetime dimensions*.
- Lecture on **11/9**: *Resonances and unstable particles*.
- *Lecture on **11/16**: Spin-statistics theorem.*
- *Lecture on **11/30**: Superconductivity.*

Spring 2017 semester:
TBA

Lecture Log

For students' convenience, I shall keep a log of lectures and their subjects on a separate web page http://bolvan.ph.utexas.edu/~vadim/Classes/2016f/lecturelog.html (for the Fall 2016 and Spring 2017 classes). Since the pace of the course may change according to the students' understanding, I will not make a complete schedule at the beginning of the class. Instead, I will simply log every lecture after I give it. This way, if you miss a lecture, you will know what you should read in the textbook and other students' notes.

Office

- *Office Location: RLM 9.314A.*
- *Office hours: Wednesdays 2:30 to 3:30 and Thursdays 2 to 3.*
- *At other times, the students are welcome whenever I'm in my office and not too busy. The best times to look for me are late afternoons and early evening hours.*
- *E-mail: vadim@physics.utexas.edu.*
  Please use email for simple homework questions or administrivia. Complicated physics questions should be asked in person.
- *Office phone: (512) 471-4918.*

Last Modified: December 8, 2016.
Vadim Kaplunovsky

vadim@physics.utexas.edu