$\boxed{\text{Rough guide to the course Quantum Field Theory}}$

Getting started

Step 1: start by reading pages *xix–xxi* of the textbook by Peskin & Schroeder, where the relevant conventions of the textbook are listed. These conventions involve the use of so-called natural units ($\hbar = c = \mu_0 = \epsilon_0 = 1$) by absorbing these constants in the relevant fields and quantities. As a result, a single scale remains: mass. Please familiarize yourself with these conventions and treat Chapter 1 of the textbook as reading material, as recommended by the authors.

Step 2: in case you want to prepare for the course, you could refresh your knowledge about

- special relativity (mainly Lorentz transformations),
- complex contour integrations (mainly the residue theorem),
- the Klein-Gordon equation (if you have seen it before).

Optimal way to follow the course

Using the textbook by Peskin & Schroeder in combination with the weekly updated reader will be sufficient to efficiently follow the course ... *provided that you don't fall behind!* Throughout the reader you will encounter circled numbers. These numbers match the markers listed in the storyline of the course given below.

A birds-eye view of the storyline of the course

$\boxed{\textit{Part 1, the free Klein-Gordon field}}$: the first four weeks cover Chapter 2 of the textbook by Peskin & Schroeder. Its contents can be described in a sketchy way as follows.

1. Why field theory $\leftrightarrow$ Compton wavelength
2. Wave equations as equations of motion for the fields:
   a) describe this by means of the Lagrangian formalism for continuous systems, which is particularly suitable for discussing symmetries
   b) make sure that the associated action is Lorentz-invariant (relativity principle)
3. Noether's theorem: continuous symmetries from fundamentally unobservable quantities $\leftrightarrow$ conserved currents and charges $\Rightarrow$

a) energy, momentum and angular momentum in field theories, which are crucial for performing quantization and determining the particle interpretation

b) conserved charges such as particle number or electromagnetic charge, which will feature prominently in the description of fundamental interactions in nature

4 Quantization of the free Klein-Gordon theory (to be repeated later for the other, more complicated higher-spin theories):

a) canonical quantization (like $\left[\hat{x}, \hat{p}_x\right] = i\hbar\hat{1}$)

b) demand the energy spectrum to be bounded from below

c) demand causality $\rightarrow$ antiparticles

$\xRightarrow{b) + c)}$ bosonic commutation relations

d) the vacuum and free spin-0 particle states $\leftrightarrow$ plane-wave solutions

e) inversion of the Klein-Gordon equation (Green's functions and the Feynman propagator), to be used for performing calculations in interacting scenarios

Part 2, interacting scalar fields and Feynman diagrams : the next roughly five weeks cover large parts of Chapters 4 and 7 as well as a few aspects of Chapter 10 of the textbook by Peskin & Schroeder. Its contents can be described in a sketchy way as follows.

5 Weakly coupled field theories as a starting point for perturbation theory:

a) dimensional analysis and smallness of interactions

b) effective field theories $\leftrightarrow$ integrating out physics, parametrizing ignorance

c) ϕ^4-theory (which is part of the Higgs model) and the scalar Yukawa theory (which resembles the theory that describes the interactions between fermions and scalars)

6 Perturbation theory for interacting quantum field theories:

a) scattering matrix (S-matrix)

b) Wick's theorem

c) diagrammatic notation for time-ordered vacuum expectation values of interaction-picture fields $\Rightarrow$ Feynman diagrams and Feynman rules

7 Plane-wave amplitudes for decay processes and scattering reactions:

a) fully connected Feynman diagrams

b) amputation procedure

c) Feynman rules for incoming/outgoing particles

d) drawing conventions for particles and antiparticles

e) non-relativistic limit $\Rightarrow$ forces and force carriers

8 From amplitudes to probabilities:

a) decay widths

b) cross sections for scattering reactions, including a bit of kinematics

9 Dealing with energy eigenstates in the interacting theory:

a) establishing the link between Green's functions and time-ordered vacuum expectation values of interaction-picture fields

b) dressed states (Källén−Lehmann spectral representation)

c) perturbative loop corrections $\Rightarrow$ tricks and analytical structure

d) LSZ reduction formula $\Rightarrow$ scattering amplitudes derive from Green's functions

e) optical theorem

10 Dealing with infinities in loop corrections:

a) quantifying (regularizing) infinities

b) the concept of energy-dependent parameters (renormalization-group equations)

c) correct starting point for setting up the perturbative series (renormalization)

d) the mass of a scalar particle is not naturally protected against high-scale physics

e) power counting $\leftrightarrow$ renormalizability, i.e. when infinities have no effect on the predictive power of the theory considered

Parts 3+4 = Parts 1+2 for matter fermions instead of scalars : during the next three weeks Chapter 3 and § 4.7 of the textbook by Peskin & Schroeder will be covered. Its contents can be described in a sketchy way as follows.

11 The free Dirac theory:

a) representations of the Lorentz group $\leftrightarrow$ representations of the rotation group

b) Dirac's trick and algebra

c) reducibility of the Dirac representation $\Rightarrow$ chiral eigenstates (Weyl spinors)

d) Dirac-field currents $\Rightarrow$ building blocks for fundamental interactions

e) Dirac equation and its symmetries

f) plane-wave solutions and helicity $\xleftrightarrow{\text{mass}=0}$ chirality

g) quantization of the free Dirac theory (repeating part 1)
$\Rightarrow$ fermionic anticommutation relations

h) spin-1/2 particle interpretation and Feynman propagator

i) discrete symmetries (such as parity) $\leftrightarrow$ fundamental interactions

12 Part 2 repeated for spin-1/2 Dirac fermions:

a) Wick's theorem revisited

b) extra Feynman rules

c) extending the arrow convention

d) trace technology

Part 5, Quantum Electrodynamics (QED) : during the last two weeks the QED parts of Chapters 4, 5 and 7 of the textbook by Peskin & Schroeder will be covered as well as material that is not treated in this form in the textbook. Its contents can be described in a sketchy way as follows.

13 The electromagnetic theory:

a) gauge freedom, gauge fixing and charge conservation

b) charged Dirac fermions in an electromagnetic field $\Rightarrow$ minimal substitution and the QED Lagrangian

c) QED from local gauge invariance (gauge principle) $\Rightarrow$ fundamental postulate for describing all non-gravitational interactions in nature as gauge interactions (incorporated in the Standard Model of electroweak and strong interactions)

d) quantization of the free electromagnetic field and its complications $\Rightarrow$ massless spin-1 photons: the gauge bosons that mediate the electromagnetic force

14 Calculating with QED:

a) Part 2 repeated for QED $\Rightarrow$ extra Feynman rules, more trace technology

b) protected masses in QED $\Rightarrow$ fermions are protected by chiral symmetry, photons remain massless as a result of gauge invariance

c) the Ward–Takahashi identity in QED, i.e. gauge invariance as seen in Green's functions and scattering amplitudes

d) the "running" electromagnetic coupling (charge screening)

e) the issue of gauge-invariant regularization $\Rightarrow$ dimensional regularization