“In jeden Quark begräbt er seine Nase.” — Goethe

**General prerequisites:**
Relativistic quantum mechanics at the level of P601. Dirac and Klein-Gordon theory, hole theory, quantization of radiation, scattering theory, elementary group theory.

**Books:**
This is a comprehensive list. We will use only a couple of these!

**Basic:**
- Berestetskii, Lifschitz, Pitaevskii
- Bjorken and Drell, vol 2
- Bogoliubov and Shirkov
- L. Brown Cheng and Li (highly recommended)
- Coleman, *Aspects of Symmetry* (highly recommended)
- B. deWit and J. Smit, *Field Theory in Particle Physics*
- Feynman, *QED* (general background)
- W. Greiner and J. Reinhardt *Quantum Electrodynamics*
- M. Kaku, *Modern Introduction to Quantum Field Theory*
- Mandl and Shaw *Quantum Field Theory*
- Pais, *Inward Bound* (historical)
- Ramond, *Field Theory*, revised second edition
- Ryder, *Quantum Field Theory*

**Statistical:**
- Abrikosov, Gorkov, and Dyalozhinskii, *Methods of QFT in Statistical Physics* (Dover)
- D. Amit, *Field Theory, the Renormalization Group, and Critical Phenomena*
  (revised second ed.)
- C. Domb and M. Green, *Phase Transitions and Critical Phenomena*, vol. 6
- E. Fradkin, *Field Theory of Condensed Matter Systems*
- N. Goldenfeld, *Lectures on Phase Transitions and the Renormalization Group*
- Itzykson and Drouffe, *Statistical Field Theory*
- Ma, *Modern Theory of Critical Phenomena*
- Negele and Orland
- Parisi *Statistical Field Theory*
- V. Popov, *Functional Integrals in QFT and Statistical Physics* (Reidel, 1983)
- Zinn-Justin, *Quantum Field Theory and Critical Phenomena*

**Advanced:**
- R. Balian and J. Zinn-Justin, eds., *Methods in Field Theory*
- J. Collins, *Renormalization*
- Itzykson and Zuber
- Kapusta, *Finite-temperature Field Theory*
- Muta *Quantum Chromodynamics*
- Nash, *Relativistic Quantum Fields*
Pokorski *Gauge Field Theory*
Peskin, Weinberg, all great field theorists (to be written)

**Specialized:**
R. Baxter, *Exactly Solved Models in Statistical Mechanics*
F. Berezin, *The Method of Second Quantization*
N. Birrell and P. Davies, *Quantum Fields in Curved Space*
M. Creutz,
H. Georgi, *Weak Interactions and Modern Particle Theory* (Benjamin, 1984)
J. Glimm and A. Jaffe, *Quantum Physics*, second ed. (Springer)
A. Polyakov, *Gauge Fields and Strings*
Treiman, Jackiw, Gross, *Current Algebra and its Applications*
Outline
[Optional sections in brackets]

General Reading
. Mandl and Shaw, ch. 1–10.
. Peskin, ch. 1–6.

0. Historical overview: six decades of confusion.
1. An essay: how we now think about renormalization. The renormalization group.

Part one: Free Fields
“In any case, [physics] is too difficult for me, and I wish I had been a movie comedian or something of the sort and had never heard of physics.” — W. Pauli
[A. CPT and the axioms of QFT.]
4. Proca theory. Photon fields in Lorentz gauge. Gupta-Bleuler mechanism and a hint about BRST.

Part two: diagrammatic perturbation theory
“If all else fails, immortality can always be assured by spectacular error.” — John Kenneth Galbraith
[B. Temperature Green functions.]
7. Feynman rules for Yukawa theory; for QED.
8. Elementary QED processes: $e^+e^- \to \mu^+\mu^-$. Traceology. $e^+e^- \to$ hadrons. Quarkonium. Crossing symmetry. Mandelstam variables.

Part three: renormalized perturbation theory
“There is a concept which corrupts and upsets all others. I refer not to Evil, whose limited realm is that of ethics; I refer to the Infinite.” — Borges, Avatars of the Tortoise
13. Scattering theory with adiabatic switch; 3 toy models and their divergences; the necessity of mass renormalization; counterterms and the Main Idea of renormalized perturbation theory.
14. Good scattering theory: the LSZ formula; the necessity of wavefunction renormalization; justify the connected/amputated prescription for S-matrix elements.
Physics 633: Quantum Field Theory II
P. Nelson

A continuation of P632. We will finally come to grips with renormalization in a systematic way.

General Reading
- Peskin, ch. 7–13.
- Brézin, LeGuillou, and Zinn-Justin, in Domb and Green vol. 6.
- Cheng and Li, divers.
- Coleman, ch. 3 and 5.
- LePage article, cited below.
- Mandl and Shaw, ch. 9–13
- Pfeuty and Toulouse, ch. 1–4.
- Ramond, divers.
- Shenker article cited below.
- Weinberg article in Zichichi book.
- Zinn-Justin, ch. 1–2, 4–7, 20–21.
- Polyakov, ch. ??

Outline
[Optional sections in brackets]

"It's important to distinguish the Landau Ghost from 'The spirit of Landau'. The latter just means we do whatever we want without explaining anything and it works." – R. Shankar

0. Summary of all our notation and useful formulas.
15. Introduction: QFT resembles critical classical equilibrium statistical mechanics. The basic facts about phase transitions. Correlation length is like mass.
16. Universality; analogies to hydrodynamics, elasticity, Ginzburg-Landau theory; critical exponents.
[B. Unitarity; unstable particles.]
20. Regularization: cutoff vs dimensional. Gell-Mann–Low. A renormalization point is necessary but arbitrary. Infrared freedom of QED.
21. Scale invariance, its loss and restoration. Callan-Symanzik equation. Solution of the RGE.

Part four: path integrals
22. Functional integrals in QM. Hamiltonian form. Scalar field theory.
[...and conformal field theory.]
25. Gauge theories in functional integral form; Faddeev-Popov procedure.

Part five: hidden symmetry

"Whenever I'm faced with a choice between two evils, I like to choose the one I haven't tried yet." — Mae West


28. Renormalization and symmetry in the O(N) linear sigma model: an explicit calculation. Goldstone modes remain massless to one loop.

29. Effective action. The Maxwell construction and convexity of \( \Gamma \). The 1PI expansion of \( \Gamma \). "Secret symmetry gives us secret renormalizability." Trouble with perturbative evaluation of \( \Gamma \) and its resolution. Loop expansion is semiclassical expansion. One-loop evaluation of \( \Gamma \). Jackiw's algorithm. Quantum Goldstone theorem.

Part six: renormalization group

"All these are young adventurers, who produce their performance to the wise ear of Time, who ten years hence, out of a million of pages reprints one." — R. W. Emerson

30. Tiptoe through the two-loops. Overlapping divergences. A nontrivial example.

31. Why renormalization works: Return to the exact RG transformation. Gaussian fixed point; power counting; linearized RG flow; contractive property; how renormalizability follows. Toy model of RG equations. "Triviality" of \( \phi^4 \). General notion of fixed point and relevant/marginal/irrelevant classification. Wilson–Fisher fixed point.


33. Corrections to scaling = renormalization of composite operators. Running of the Fermi coupling constant \( G_F \).

34. Valedictory.

"Never prophesy — especially about the future." — Sam Goldwyn
Literature References


V.I. Arnold, Geometrical methods in the theory of ordinary differential equations [Basic Poincaré theorem about combing vector fields.]

C. Callan, in Methods in field theory, ed. R. Balian et al. [The C-S equation and renormalizability of $\phi^4$.]


L. Faddeev, Theor. Math. Phys. 1 1. [Hamiltonian justification of the Faddeev-Popov procedure.]

R. Feynman, Phys. Rev. 80 (1950) 440. [Path integral in qft.]

R. Feynman, Lectures on Gravitation (Caltech, 1962) [Einstein’s theory obtained from spin-2 quanta.]


R. Feynman, in Magic without magic, ed. J. Klauder (Freeman, 1972). [On FP ghosts and YM theory.]


D. Friedan, Ann Phys 163 (1985) 318. [Renormalization of general nonlinear sigma models.]


G. Gallavotti, Rev. Mod. Phys. 57 1985 471. [Perturbative renormalization from Wilson viewpoint.]

M. Gell-Mann and F. Low, Phys. Rev. 95 (1954) 1300.


J. Goldstone, A. Salam, and S. Weinberg, PR 127 (1962) 965. [Effective potential; 3 proofs of Goldstone theorem.]


K. Hopp, CMP 2 (1966) 301. [proof of renormalizability.]


J. Iliopoulos, C. Itzykson, and A. Martin, RMP 47 (1975) 165.

C. Itzykson, H. Salinou, J.-B. Zuber, eds: Conformal Invariance and Applications to SM


J. Kogut, Rev. Mod. Phys. 51 (1978) 699. [Lattice gauge theory and RG ideas.]


T. Kugo and Ojima, Suppl. Prog. Theo. Phys. 66. 1. [The operator meaning of the BRST mechanism.]

L. Landau, A. Abrishkoev, and I. Khaltativkii, Doklady Akademiai Nauk 95 (1953) 497. [Running of charge in QED; origin of RGE.]


R. Peierls, PR 53 (1938) 918 [SSB is possible for discrete symmetries].

M. Peskin, in Recent Developments in QFT and Statistical Mechanics, ed. J.-B. Zuber and R. Stora (North Holland, 1983). [Chiral symmetry breaking]


J. Schwinger, Phil. Mag. 44 (1953) 1171. [Anticommuting variables]


S. Shenker, in Recent Developments in QFT and Statistical Mechanics, ed. J.-B. Zuber and R. Stora (North Holland, 1983).


F. Wegner, in Domb and Green v.6.


S. Weinberg, “Why the RG is a good thing,” in Asymptotic realms of physics, ed. A. Guth et al.


K. Wilson, PR 179 (1969) 1493; PR D2 (1970) 1473, 1478; PR D3 (1971) 1818. [“dimension of a field is changed by interactions”]