Roadmap to Quantum Field Theory

Zeroth Lecture(s)

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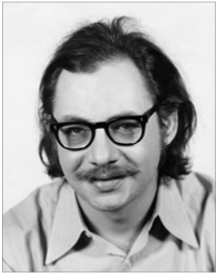
Career of a theoretical physicist consists in understanding the harmonic oscillator at progressively higher planes of abstractions.

Sidney Coleman



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Outline

1. Course Structure
2. Roadmap to Quantum Field Theory
3. Trichotomy of Waves Particles and Fields

Scope and Objective

This course aims to teach the bare bones of canonical quantization program for a system of fields, focusing on scalar fields. It will introduce Quantum Field Theory as an inevitable consequence of the union of quantum mechanics and relativity. The example of harmonic oscillator would be used to illustrate how particles and wave aspects of reality emerge from the underlying foundations of quantized fields. Notions of symmetries would be exploited to “build Lagrangians and interactions from scratch”. Time permitting; machinery of S-matrix would be developed within perturbative framework that would help us see how the violence of creation and destruction of elementary particle is as mundane and dirty as much it is pretty. It is mundane, because that is all that particles can do and actually do, all the time. It is pretty because it is a science that we have perfected to predict at extra-ordinary levels of accuracy. The dirty part is what you would know, when you get there (the S-matrix machinery).

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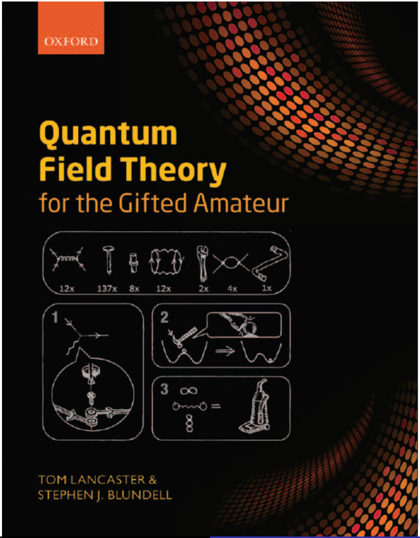
Textbook: Lancaster and Blundell



References

- Quantum Field Theory of Point Particles and Strings – Brian Hatfield
- Quantum Field Theory – Lewis Ryder
- First Book of Quantum Field Theory – Pal and Lahiri

Evaluation Commponents

- **Midsem:** 105 marks (90 min) 35% Closed book
- **Tutorials:** (3 best from 4) $25 \times 3 = 75$ 25 % Closed book
- **Comprehensive Examination:** 120 marks 40 % Open/Closed book

What is Quantum Field Theory

- Apply Quantum Mechanics to a system of fields (example: EM field)
- Promote physical observables to hermitian operators
- Identify cannonically conjugate variables and impose Heisenberg's equal time commutator conditions
- Find the complete set of commuting observables to label "appropriate" states in Hilbert space
- Use appropriate equation of motion to determine time evolution.

More or less correct answer but hardly educates!

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Shaunak's question to Angiras (Mundaka Upnishad 1.1.3

कस्मिन्नु भगवो विज्ञाते सर्वमिदं विज्ञातं भवतीति

Sir, what is it knowing which, everthing else becomes known?

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I would like to view this question from a reductionist perspective. It admits the existence of elementary conceptual building blocks to(from) which complex reality can be de(re)constructed. Quantum Field Theory is then this science of ultimate reduction (as of today!).

Inevitablity of Quantum Field Theory

आकाशात् पतितं तोयं यथा गच्छति सागरम् ।

All the water fallen from the sky, goes to the ocean.

We will try and appreciate that QFT, despite being as fancy as it is made out to be (and fancy for sure it is, thanks to the extra-ordinarily rich and profound possibilities it is capable of), is the most simple, economical, and logical consequence of any attempt at the synthesis of Quantum Mechanics and Relativity.

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Road 1: Can a classical radiation field ‘talk’ to a Quantum atom?

- Quantum Mechanics was developed for atomic systems.
- Would it lead to any theoretical inconsistency, if we treat radiation field classically, in its interaction with a quantum mehcanical atom?

All hell for sure breaks loose!

We can then use an arbitrarily convergent beam of radiation to know the position of electron with arbitrary precision, without affecting its momentum in anyway. In short, Heisenberg’s uncertainty comes to a certain end. For logical consistency, radiation field must be quantized.

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Road 2: "c"-ing thro' the Quantum Curtain! Or, how do we reconcile QM with relativity

- Treat space and time on "equal" footing. In NRQM time (t) is a parameter devoid of hermitian operator status, unlike X. This suggests two roads to "equality":
  (a) Promote t to operator status at par with X and hence let us propose 'relativistic' commutator involving $X^\mu = (cT, X)$ and $P^\mu = (H/c, P)$

$$[P^\mu, X^\mu] = i\hbar g^{\mu\nu}. \quad (1)$$

  - Assign. 1 Show that the commutator $[H, T] = i\hbar$ implies that that energy spectrum is continous $-\infty < E < \infty$ and unbounded from below.(**Hint:** How do stationary states $H|E >= E|E >$ evolve in time?)
  - Both these aspects contradict the observations. So option (a) is ruled out.

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(b) Since t cannot be promoted let us demote X from the status of an operator to a mere parameter x.

- x and t can now only show up as parameters of some some function $f(x,t)$. Should you want to impress (terrorize!) your wingies, use greek symbols $\phi(x,t), \psi(x,t), \zeta(x,t), \chi(x.t)$, but they all represent some kind of field.
- Just as a discrete system of particles is specified by giving all the positions and momenta, a system of fields is specified by giving field amplitudes $\phi(x)$ for all x and the corresponding field momenta. A field system is essentially and intrinsically a system of infinite DOF.

There is no getting away from fields as long as you insist on ‘c’-ing through the quantum curtain.

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Road 3: ‘Relativistification’ of Quantum Mechanics

- Relativity + Quantum Mechanics $\neq$ Relativistic Quantum Mechanics

  Not a surprize, really! $E = mc^2$ implies we can literally cook particles (mass) from energy and (under suitable circumstances) allow the particles to liberate their mass in the form of tremendous energy (sometimes with terrible consequence!). This means, creation and annihilation, just ships along with relativity. Hence your underlying fundamental theory should be intrinsically capable of describing arbitrarily large number of particles. Such a system better be a system with infinite number of degrees of freedom – a field theory, better still, Quantum Field Theory.

$$p + p = p + \bar{p} + p + p + p$$

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Road 4: Relativity at real tiny distances!

A ‘quiet’ particle arrested in the confnes of an extremely tiny box could be anything but relativistic!. Or, so do we think.

Assign. 2 Show that the supposedly lonesome electron in a sufficiently tiny box of size L ($L << \hbar/mc^2$) is merrily partying with hottest (only refers to the relativistic conditions!) of positrons and electrons. (**Hint:** Heisenberg’s uncertainty principle)

Relativity (when in company of QM) abhors loneliness!

Relativistic setting forces upon us a framework that should be capable of describing arbitrarily large number of particles. Only a system of fields with infinitely many degrees of freedom is capable of doing this.

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Road 5: Conventional notion of wavefunction is meaningless in relativistic setting!

- $|\psi(x)|^2$ gives the probability of finding a particle at x as a result of a measurement at a given instant.
- This requires the coordinate of electron to be at least in principle measurable with arbitrary precision in arbitrarily short time.
- Such a possibility is ruled out in a relativistic theory and is allowed only with amends that make field theory inevitable (Landau and Peierls, 1930)

Let us see how does this work(blackboard!).

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Curious case of a massless particle called Photon!

- We will show that any relativistic particle ($E \sim pc$) cannot be Localized to better than its de-Broglie wavelenth $\Delta q = \hbar/p$. If there is one particle that has right to be relativistic, it is photon!
- This means that notion of photon coordinates makes sense only when the characteristic scales of the problems are much larger than its de-Broglie wavelength. This however is the well-known classical limit corresponding to geometrical optics, where a ray description suffices.
- The fact the photon coordinates cannot be measured would be evident from the mathematical formalism that photon wavefunction cannot be used to construct a quantity that has a characteristic of probability density and satisfying necessary relativistic invariance conditions.

Curious case of a massless particle called Photon!

Isn't it curious that one of the hallmark of particle nature is localizability. Particle nature of light actually showed up upon its quantization but 'coordinates' of photons make sense only in classical limit, where the wave nature of light can explain ray optics as well as interference and diffraction.

Road 6: A casualty called Causality!

You will have a tut-test yesterday!

Whereas the statement is definitely an exagerration, it is indeed true that in the non-relativisitic framework there is violation of "microscopic causality". This can be rectified only in QFT.

Road 7: The many particle route

- Consider two particle quantum system described by 4 operators $\vec{x_1}, \vec{x_2}, \vec{p_1}, \vec{p_2}$, and a wavefunction $\psi_2(x_1.x_2, t)$. It gets cumbersome for a system of large number of particles
- What do you do if a $A \to B + C$? Is your n-particle framework equipped to handle $n + k$ particles where k is a positive integer. What do you do to terms involving A? Throw them and introduce new terms in Lagrangian involving B, C?
- A framework with fixed number of particles is not just clumsy but can't just handle more complicated situation.

Road 7: The many particle route

Even if relativistic treatment is not warranted, a system with large number of particles can be handled much more elegantly within the field theoretical framework. Arduous task of anti-symmetrizing and symmetrizing multiparticle wavefunction is just a piece of cake in field theory.This explains the ubiquitous and extensive use of field theory in the condense matter physics.

The great wave-particle dichotomy

Classical Connotations

Particles

A particle encodes the idea of localization in both space and time and hence a ‘local impact". Local impact means that the particle transfers its energy and momentum at a given point and instance of contact or impact with other particles.

The great wave-particle dichotomy

Classical Connotations

Waves

A wave on the other hand is a spread in both space and time. A snapshot of wave only captures its spatial spread and cannot convey its ability to transfer energy unless its temporal spread is taken into account. Owing to these differences, unlike a particle a wave transfers its energy and momentum simultaneously in a region of space at the same instant. You can imagine a spherical wave spreading outwards in a spherical enclosure and it will impact upon all the point at the spherical wall at the same time. So the impact is local in time but not in space.

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Demise of (wave-particle) mutual exclusivity!

Such an exclusivist conception of particles and waves is the first casualty of the process of quantization. A quantum particle such as an electron travels in all directions like a wave, but it impacts locally in space and time with other quantum particles(collapse of $|\Psi>$). This information about a quantum particle 'materializing" (for the want of a better word) for local impact at a space-time point while traveling like a wave, is encoded in its wave- function. In a spherical enclosure, when we release a lonesome electron it will impact locally, but as more and more members of their fraternity are released they will start showing the global impact pattern of a wave. It is this funny combination of classically exclusive attributes that makes quantum particle weird and incomprehensible.

The great wave-particle dichotomy

Demise of (wave-particle) mutual exclusivity!

Such an exclusivist conception of particles and waves is the first casualty of the process of quantization. A quantum particle such as an electron travels in all directions like a wave, but it impacts locally in space and time with other quantum particles(collapse of $|\Psi >$). This information about a quantum particle 'materializing" (for the want of a better word) for local impact at a space-time point while traveling like a wave, is encoded in its wave- function. In a spherical enclosure, when we release a lonesome electron it will impact locally, but as more and more members of their fraternity are released they will start showing the global impact pattern of a wave. It is this funny combination of classically exclusive attributes that makes quantum particle weird and incomprehensible.

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Field Particle Dichotomy

Classical Physics

Essentially connotes analytical mechanics and electrodynamics. In the former we discuss the kinematics and dynamics of particles, often under the influence of Gravitation, whereas in the latter we discuss the field configurations and the methods to obtain them.

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Field Particle Dichotomy

Given that both Gravitation and Coulomb's law are both $1/r^2$ law, isn't it surprising that in the former, the physics is dominantly about particle trajectories, whereas, in the latter, it is dominantly about field configurations

The answer my friend is lying in the scales!

Whereas $\vec{g}$ is practically constant for most terrestrial experiments, EM fields dance to the tune of table top experiments, curling and diverging, right before your eyes! This ensured that 'particles' and 'fields', forever remained partitioned in our mental pictures as mutually exclusive aspects of reality. A 'particle' is what dances to the tune of a 'field'. So when Einstein proposed the particle interpretation of EM fields in photon, the converse – fields aspects of particles such as electrons was unthinkable.Do not mistake wave aspects of electron with a field aspect. The framework of non-relativistic quantum mechanics 'comfortably' accommodates the wave-particle dualism, without any compelling need for a recourse to the underlying field reality. It is only when 'c'-through quantum curtain, that the field reality manifests in its full glory.

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What is the fundamental nature of reality? Fields or Particles?

Should we treat the classical field perspective of electromagnetic field (with weird particle attributes in the quantized version) as fundamental, or the classical particle nature of matter (with weird wave attributes upon 'first' quantization and field and particle attributes upon 'second' quantization) as fundamental.

What is the fundamental nature of reality? Fields or Particles?

Fundamental entities are those whose fields appear in Lagrangian. These fields also exhibit wave properties as the classical equation of motion happens to be a wave equation that admits harmonic solutions. Such a system of classical fields, upon quantization, exhibit a discrete spectrum of energy and corresponding states in an appropriate Hilbert space, with particle like attributes. Coefficients of polynomial terms (bilinear, trilinear and quartic) find interpretations as particle mass and particle charge, etc..

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‘Coming to terms’ with wave particle dualism

There are no straight answers and I have no illusions about offering one. What follows is a deeply personal perspective that has no obligation towards quenching your curiosity.

- Our binary and mutually exclusivist dissection of reality to particles and waves is a result of our classical (macroscopic) interaction with reality.
- We have no reason to believe that such an exclusive deconstruction of reality can be extrapolated down to its most fundamental layer. Doing so would be akin to (attempting to) extract individual marks of students, knowing only the average.
- ‘Objectivity’ and the ‘certainty’ of the macroscopic classical world is a consequence of whatever structural form reality takes at the bottom of the hierarchy of its complexity. If it means ‘uncertainty’ in canonically conjugate variables and

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