Preprint typeset in JHEP style - HYPER VERSION

Non-perturbative Quantum Field Theory

An Erasmus Intensive Program

Abstract: The purpose of the course is to develop several methods that have been used over the years to deal with non-perturbative physics in quantum field theory. Such methods are rarely taught in today's graduate programs. Such methods complement modern approaches to non-perturbative physics using the holographic correspondence.

Contents

(each hour= 45 minutes).

1. Confinement in Quantum Chromodynamics (E. Kiritsis, 12 hours)

1. The string picture of hadrons (1 hour).
2. The Nielsen-Olesen vortex as stable confined magnetic flux (1 hour).
3. Generalities on the realization of global and gauge theories. Elitzur's theorem (1 hour).

4. Wilson loops and a criterion for confinement. Timelike loops, spacelike loops. The Wilson loop as a "gauge" of magnetic flux (1 hours).

5. Confinement in 2+1 YM theories (1 hour).

6. 't Hooft operators and their braiding with Wilson loops (1 hour).

7. Magnetic and electric fluxes in a box and duality relations (2 hours).

8. Confinement of quarks and monopoles (1 hour).

9. Deconfinement at finite temperature and the phase transition (1 hour).

10. Confinement with Dynamical Quarks (1 hour).

11. Dynamical Quarks at finite temperature (1 hour).

2. Chiral symmetry and chiral symmetry breaking (E. Kiritsis, 12 hours)

1. The pair-condensate instability (1 hour).

2. The Nambu-Jona-Lasinio model and dynamical chiral symmetry breaking (1 hour).

3. The chiral symmetry at finite temperature (1 hour).

4. Chiral anomalies and their implications (1 hour).

5. The $U(1)_A$ problem (2 hours) .

6. Instantons and the θ parameter (2 hours).

7. The chiral selection rule (2 hours).

8. Anomalies and the realization of chiral symmetry (the 't Hooft anomaly matching conditions) (2 hours).

3. Anomalies in gauge theories (N. Tetradis, 8 hours)

1. Anomaly matching in QCD. Persistence of mass. Complementarity. (4 hours)
2. Chiral gauge theories.(2 hours)
3. The trace anomaly. (1 hour)
4. The non-perturbative SU(2) (Witten) anomaly. (1 hour)

3.0.1 Bibliography for Kiritsis' and Tetradis' lectures

The main parts of thee two sections will be based on a combination of the old material of Preskill's lectures, [1] as well as from various other lecture notes and books.

The appropriate parts of Preskill's lectures are on

- Confinement and the associated order parameters,
- Chiral symmetry and its breaking
- Chiral anomalies and instantons
- Anomalies in general gauge theories and the 't Hooft consistency conditions
- Chiral gauge theories
- The trace and SU(2) anomalies
- Basic differential geometry and the relation to anomalies
- The large-N limit of gauge theories
- Lattice gauge theories

The lecture notes of E. Kiritsis' can be found below

- Review of the Nielsen-Olesen vortex from Trodden's TASI lecture notes.

- Confinement and the associated order parameters,
- Chiral symmetry and its breaking
- Chiral anomalies and instantons
- Anomalies in general gauge theories
- The 't Hooft consistency conditions
- Chiral gauge theories
- The trace and SU(2) anomalies

For the issue of confinement and the relevant order parameters the following lecture notes and papers maybe useful:

- Highly recommended are the two classic papers of G 't Hooft on magnetic confinement and twisted toroidal gauge theory partition functions
- The review of J. Greensite on confinement and lattice gauge theories as well his related lecture notes.
- The lecture notes of M. Creutz on confinement
- The review of G. 't Hooft on confinement, the $U(1)_A$ problem and instantons.
- Coleman's Erice Lectures, [2]. This has relevant chapters well explained for beginners for solitons, instantons and large N_c,

For the issue of chiral symmetry breaking, the $U(1)_A$ problem and instantons relevant references and reviews are

- Coleman's Erice Lectures, [2]. This has relevant chapters well explained for beginners for solitons, instantons and large N_c,
- The Physics Reports article of 't Hooft on instantons and the $U(1)_A$ problem, [5].
- The review of G. 't Hooft on confinement, the $U(1)_A$ problem and instantons.

For the topic of the anomaly matching conditions and how they can be used to check the realization of global symmetries in strongly coupled QFTs the following papers are recommended.

- The classic 't Hooft preprint from the Cargese lectures that describes the anomaly matching conditions.
- The paper of Coleman and Grossman that has proved the anomaly-matching conditions using S-matrix techniques.
- The two papers by Vafa and Witten on the breaking of global symmetries in vectorlike gauge theories and on the breaking of discrete symmetries.
- The paper by Weinberg and Witten on the basence of massless composite gauge fields and gravitons
- Weingarten's paper [8] on rigorous bounds on meson and baryon masses.

Finally a few other relevant lectures/books:

- Manohar's lectures on Large-N_c QCD, [7].
- Frishman's and Sonennschein's book [3]. It contains for our purposes, Instantons in QCD, magnetic monopoles and (baryon) solitons in the Skyrme model, Large N_c methods in QCD. It also contains relevant two dimensional physics namely, the 't Hooft solution of two dimensional QCD, and the physics of baryons.

4. Convergence of perturbation theory (R. Helling, 4 hours)

1. The Dyson argument: Why the perturbative series is not a Taylor series (1 hour)
2. Finite precision information from the perturbative series and the role of instantons (1.5 hours)

3. Asymptotic series and Borel resummation: Recovering exact results from the perturbative series (1.5 hour)

4.0.2 Bibliography for Helling's lectures

The main reference is [18] that contains more information that what is presented in the lectures. Additional references for further reading are [19] and [20].

5. Lattice gauge theories (E. Rabinovici, 8 hours)

1. The Wilson formulation. (2 hours)

2. The strong coupling expansion.(1 hour)

3. The character expansion (1 hour)

4. Z_N gauge theory and Kramers-Wannier duality. (1.5 hours)

5. Wilson loops and 't Hooft loops. (0.5 hours)

6. Phase diagrams of lattice theories. (2 hours)

5.0.3 Bibliography for Rabinovici's lectures

The standard review on basic lattice methods is [4]. Further relevant papers are [86], [87] on anomalies and their lattice realizations, the classic paper of Wilson on lattice gauge theory and quark confinement, [88], and papers on lattice models, gauge theories their phase structure and confinement, [89]-[95]

6. Supersymmetric non-perturbative dynamics (V. Niarchos, 16 hours)

6.1 Supersymmetric gauge theories in four dimensions (6 hours)

1. Introduction to supersymmetry, supersymmetric Lagrangians (2 hours)
2. Effective actions, holomorphy and symmetries, non-renormalization theorems (2 hours)
3. Phases of gauge theories (1 hour)
4. Exact beta-functions (1 hour)

6.2 N=2 supersymmetric gauge theories (5 hours)

1. The perturbative regime (SU(2)). (1 hour)
2. The exact quantum moduli space. (2 hours)
3. The BPS spectrum. (2 hours)

6.3 N=1 supersymmetric gauge theories (5 hours)

1. Perturbative N=1 Supersymmetric QCD, symmetries and vacua. (1 hour)
2. Non-perturbative sQCD in the various regimes (pure sYM, N_f¡N_c no vacuum, N_f=N_c confinement with chiral symmetry breaking, N_f=N_c+1 confinement without chiral symmetry breaking, $\mathrm{N}_f > N_c$+1) (2 hours)
3. The 't Hooft anomaly matching conditions in sQCD. (1 hour)
4. Seiberg duality: formulation, implications, checks. (1 hour)

6.4 New developments on Seiberg duality in diverse dimensions (1.5 hours)

1. Aspects of Seiberg duality for supersymmetric quantum field theories on three and four space-time dimensions will be presented. Emphasis will be given on new non-perturbative checks of these dualities and interesting open questions.

6.4.1 Bibliography for Niarchos' lectures

For those not fluent in susy, a crash introduction to basic susy via collected formulae.

The lecture notes of V. Niarchos' can be found below

- First Lecture
- Second Lecture
- Third Lecture
- Fourth Lecture
- Fifth Lecture
- Sixth Lecture

The lectures on non-perturbative methods in supersymmetric theories are based mainly on references [9] and [10]. Further references in this directions with different emphasis are given in [11]-[17]. On further developments and applications, the following references are useful, [64]-[67].

The slides of the last lecture can be obtained here.

7. Black branes in flat and AdS space (N. Obers, 5 hours)

1. Neutral and charged black branes, stress tensor, currents and thermodynamics. (1 hour)
2. Long-wavelength effective theory for black branes. (1 hour)
3. Stationary blackfold solutions. (1 hour)
4. Intrinsic and extrinsic perturbations of black branes. (1 hour)
5. Planar AdS black holes. (1 hour)

7.0.2 Bibliography for Obers' lectures

The basic lecture notes are in the introductory review [31] as well as the papers [32, 33, 34].

The lecture notes of N. Obers can be found below

- Ober's Lecture Notes

8. Hydrodynamic transport: theory and applications (M. Rangamani, 6.5 hours)

1. Relativistic hydrodynamics: introduction, variables, formalism (1 hour)
2. Constraints on hydrodynamic transport (2 hours)
3. Anomalous transport in fluids.(1 hour)
4. Superfluids and non-relativistic fluids (1 hour)
5. Phases of higher spin theories (the correspondence between the WN minimal models and higher spin gravity in AdS3 will be reviewed. The aim will be to establish a detailed dictionary between the CFT spectrum and states in the holographic dual. The spectrum of CFT will be discussed in some detail and phase transitions will be examined. Comparisons will be made with the behaviour of black holes in the higher spin theory and we will delineate the phase diagram of these WN minimal models). (2 hours)

8.0.3 Bibliography for Ragamani's lectures

Overview of the material can be found in references [35]-[37]. Constraints on fluid dynamics can be found in [38]-[43]. Anomalies in fluid dynamics are discussed in [44]-[48]. Finally references for superfluids and non-relativistic fluids can be found at [49]-[52].

- The Lecture Notes
- The slides of the last lecture can be obtained here.

9. Fluid/gravity duality (V. Hubeny, 6.5 hours)

1. Overview and context of fluid/gravity, basic set-up. (1 hour)

2. Planar Schwarzschild-AdS black hole, boundary derivative expansion. (1 hours)

3. Bulk metric and extraction of boundary stress tensor at higher orders. (1 hour)

4. Event horizon and entropy current. (1 hour)

5. Generalizations, applications, relation to the black-fold approach. (1 hour)

6. Causal holographic information and causal wedges in AdS/CFT. (The AdS/CFT correspondence has propelled AdS black holes into prominence as useful calculational tool in diverse branches of physics, but it also holds great potential for answering long-standing questions in quantum gravity by recasting them in non-gravitational language. The prerequisite for this program is good understanding of the dictionary between the two sides, which motivates the present exploration. We study the properties of a very natural gravitational construct – the causal wedge in AdS, pertaining to a specified spatial region on the AdS boundary – in order to obtain insight into its CFT dual. Along with the causal wedge we also consider the 'rim' of the causal wedge, as well as its area which we call the 'causal holographic information'.

   The construction is reminiscent of, but importantly distinct from, the correspondence between CFT entanglement entropy and area of extremal surface in AdS. After reviewing the causal wedge construction, we focus on interesting global properties of causal wedges in general time-dependent backgrounds.)

9.0.4 Bibliography for Hubeny's lectures

The lecture notes can be found in [36, 37]. Complementary lecture notes are in [41]. They all provide further guidance to the literature. For the causal issues relevant references are [39, 40].

The slides of the last lecture can be obtained here.

10. Non-Perturbative Aspects of RG Flows (Z. Komargodski, 6.5 hours)

1. Advanced aspects of SUSY in flat Space and a careful look at the stress tensor. (1 hour)
2. Coupling to nontrivial geometry, The connection to supergravity, preserving rigid supersymmetry on curved manifolds. (2 hours)
3. Examples and partition functions – checks of dualities and RG flows (1 hour).
4. Geometric Interpretation of the partition functions. (1 hour)
5. Effective String Theory (1 hour)

10.0.5 Bibliography for Komargodski's lectures

The main recent review of the subject is [63]. For some background in localisation good references are [73]-[75] and references therein.

- The Lecture Notes.
- The slides of the last lecture.

11. Instanton techniques in QFT (M. Bianchi, 6.5 hours)

1. Instanton solutions in Yang-Mills theory (1 hour)
2. Bosonic moduli and fermionic zero-modes (1 hour)
3. Instanton calculus in supersymmetric theories (1 hour)
4. Non-perturbative effects generated by instantons (1 hour)
5. Multi-instantons, ADHM construction and open strings (1 hour)

6. Unoriented quivers, dimers and their mass deformations. (After reviewing the dimer description of quiver gauge theories that govern the low-energy dynamics of unoriented D-branes at orbifold and other toric singularities, we will consider the effect of fluxes and of non-perturbative corrections induced by unoriented D-brane instantons. We will also discuss the role of 'specular duality' in this context and comment on recently proposed non-perturbative dualities among N=1 supersymmetric theories)

11.0.6 Bibliography for Bianchi's lectures

The introductory reference is Colemans' classic lectures [2], namely the chapter "The uses of Instantons" and the appendix "The double well done doubly well". Also the book [53] and the reviews [54]-[56]. For the quiver topic the relevant references are [76]-[78].

- The lecture notes from the first five lectures
- The slides of the last lecture can be obtained here.

12. Holographic methods in near-equilibrium physics (A. Starinets, 6.5 hours)

1. Thermodynamics and transport at weak and strong coupling (1 hour)
2. Holographic dictionary for near-equilibrium processes. (1 hours)
3. Finite-temperature correlation functions and spectral functions. (1 hour)
4. Holographic transport at strong coupling. (1 hour)
5. Universality of the shear viscosity/entropy density ratio. (1 hour)
6. Phenomenology of RHIC-LHC heavy ion collisions and holography (Experiments with heavy ion collisions at RHIC and LHC have revealed properties of hot and dense nuclear matter in the regime of intermediate QCD coupling. Theoretical understanding of these properties is a difficult task, often aggravated by the lack of necessary theoretical tools in the non-perturbative regime. We describe holographic approaches to the problem and review the current status of gauge-string duality calculations of the relevant physical observables.)

12.0.7 Bibliography for Starinets' lectures

The main papers that are relevant for the presentation are [21]-[26].

The lecture notes are below:

- First Lecture
- Second Lecture
- Third Lecture
- Fourth Lecture
- Fifth Lecture
- Sixth Lecture
- Seventh Lecture
- Eighth Lecture
- Nineth Lecture

The slides of the last lecture can be obtained here.

13. Holographic techniques for condensed matter systems (K. Schalm, 6 hours)

1. Strongly coupled phenomena in Condensed Matter (1 hour)
2. The holographic superconductor (1 hour)
3. Holographic Non-Fermi liquids (1 hour)
4. Stars and Stranger holographic metals (1 hour)
5. Semi-local quantum liquids (1 hour)
6. Holographic BCS theory. (New results will be presented which show that holographic fermions can themselves drive the transition to holographic superconductivity.) (1 hour)

13.0.8 Bibliography for Schalm's lectures

The main review papers that are relevant are [57]-[59] and original papers are [60]-[62].

The slides of the last lecture can be obtained here.

14. Inhomogeneous holographic thermalization. (B. Craps, 1.5 hours)

1. The sudden injection of energy in a strongly coupled conformal field theory and its subsequent thermalization can be holographically modeled by a shell falling into anti-de Sitter space and forming a black brane. Motivated by event-by-event fluctuations in heavy ion collisions, the inclusion of inhomogeneities in such a model will be discussed.

14.0.9 Bibliography for Craps's lectures

The main work that introduces the subject is [68].

The slides of the lecture can be obtained here.

15. What happens at the horizon of an extreme black hole?. (H. Reall, 1.5 hours)

1. The horizon instability of extreme black holes. (It was shown that a massless scalar field exhibits an instability at the horizon of an extreme Reissner-Nordstrom or Kerr black hole. Although the field and its derivatives decay outside the black hole, the first derivative generically does not decay at the horizon, and the second derivative generically blows up at late time on the horizon. I will review this instability, and explain recent work demonstrating that this instability occurs for any extreme black hole, and also occurs for linearized gravitational and electromagnetic perturbations. If time permits, I will discuss the effect of gravitational backreaction.)

15.0.10 Bibliography for Reall's lectures

The references to consulted for this topic are [69]-[71].

The slides of the lecture can be obtained here.

16. Gauged Non-linear sigma models (U. Lindstrom, 1.5 hours)

1. The target space of non-linear sigma models carries geometric structures that are closely related to the symmetries of the model. In particular the target space always has a Riemannian structure, possibly with isometries. It is interesting to gauge these isometries both for constructing quotients and for finding dual models. Other symmetries of the models, e.g., supersymmetries, may complicate the gauging. I will present important aspects of this process.

16.0.11 Bibliography for Lindstrom's lectures

The references to consulted for this topic are [72].

The slides of the lecture can be obtained here.

17. Spatially modulated phases in holography (J. Gauntlett, 1.5 hours)

1. There a wide variety of systems in nature that exist in spatially modulated phases which spontaneously break translation invariance. Common examples include charge density waves and spin density waves in which the charge density and spin density is, respectively, spatially modulated. Furthermore, it is also possible to have spatially modulated superconducting states of matter. The lecture will give an overview of how spatially modulated phases are holographically realised as novel black hole solutions. It is highly plausible that there are many spatially modulated ground states of holographic matter that are waiting to be discovered.

17.0.12 Bibliography for Gauntlett's lectures

The references to consulted for this topic are [79]-[85].

The slides of the lecture can be obtained here.

18. Novel applications of Derrick-like theorems (J. Sonnenschein, 1.5 hours)

1. Derrick's theorem and its integral generalizations proposed by Manton will be reviewed. Applications to D-brane actions will be described. An alternative method to check the stability of inhomogeneous static solutions of branes based on small geometrical deformations will be proposed.

18.0.13 Bibliography for Sonneschein's lectures

The slides of the lecture can be obtained here.

19. Holographic theories for QCD In the Veneziano Limit (M. Jarvinen, 1 hour)

1. A class of holographic models with physics comparable to the one expected from QCD in the Veneziano limit of large N_f and N_c with fixed $x = N_f/N_c$ are constructed. The models capture the holographic dynamics of the dilaton (dual to the YM coupling) and a tachyon (dual to the chiral condensate), and are parametrized by the real parameter x, which can take values within the range $0 <= x < 11/2$. The saddle point solutions are analyzed, and the phase diagram at zero temperature and density is drawn.The conformal window for $x \geq x_c$ is found, and the QCD-like phase with chiral symmetry breaking at $x < x_c$, where the critical value x_c lies close to four. Miransky scaling is also found as $x \to x_c$ as well as Efimov-like saddle points. By calculating the holographic beta-functions, the "walking" behavior of the coupling in the region near and below x_c is demonstrated.

   The zero temperature spectra of mesons and glueballs are analyzed as a function of x with the full back-reaction included. It is found that spectra are discrete and gapped (modulo the pions) in the QCD regime, for x below the critical value x_c where the conformal transition takes place. The masses uniformly converge to zero in the walking region $x \to x_c$ due to Miransky scaling. The ratio of masses all asymptote to non-zero constants as $x \to x_c$ and therefore there is no "dilaton" in the spectrum. The S-parameter is computed and found to be of $O(1)$ in the walking regime

The phase structure at finite temperature in the T, x plane is also analyzed and various 1st order, 2nd order transitions and crossovers with their chiral symmetry properties are identified. In the simplest case, it is found that for x up to the critical $x_c \simeq 4$ there is a 1st order transition on which chiral symmetry is broken and the energy density jumps. When approaching x_c from below, $x_f \to x_c$, temperature scales approach zero as specified by Miransky scaling.

19.0.14 Bibliography for Jarvinen's lectures

The relevant references are the following:

- A review of Improved Holographic QCD, the model for holographic YM, [96],
- Improved Holographic QCD at zero temperature, [97], [99].
- Improved Holographic QCD at finite temperature, [100]-[102].
- The bulk viscosity and drag force in Improved Holographic QCD at finite temperature, [103].
- Flavour dynamics and chiral symmetry breaking as tachyon condensation, [103]-[106].
- Holographic QCD in the Veneziano limit , [107]-[109].

The slides of the lecture can be obtained here.

References

[1] John Preskill's lecture notes available from his web page at Caltech, http://www.theory.caltech.edu/∼preskill/notes.html#qcd

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