SFT-2022
Lectures on Statistical Field Theories
Galileo Galilei Institute
Florence, 7-18 February 2022

Program of lectures

Mari Carmen Banuls (Max Planck Institute of Quantum Optics, Garching)
Introduction to tensor networks. (6h)

The term Tensor Network States (TNS) has become a common one in the context of numerical studies of quantum many-body problems. It refers to a number of families that represent different ansatzes for the efficient description of the state of a quantum many-body system. The first of these families, Matrix Product States (MPS), lies at the basis of Density Matrix Renormalization Group methods, which have become the most precise tool for the study of one dimensional quantum many-body systems. Their natural generalization to two or higher dimensions, the Projected Entanglement Pair States (PEPS) are good candidates to describe the physics of higher dimensional lattices. They can be used to study equilibrium properties, as ground and thermal states, but also dynamics. Quantum information gives us some tools to understand why these families are expected to be good ansatzes for the physically relevant states, and some of the limitations connected to the simulation algorithms.

Originally introduced in the context of condensed matter physics, these methods have become a state-of-the-art technique for strongly correlated one-dimensional systems. Their applicability extends nevertheless to other fields. These lectures will present the fundamental concepts behind TNS methods, the main families and the basic algorithms available.

<u>Material:</u>

Most of the content of the lectures, and references to introductory bibliography, can be found in these notes: https://drive.google.com/file/d/1FOWJwbwyErND7XCjF5fyQ1bGHGrKTaif/view

Nigel Cooper (University of Cambridge)
Quantum dynamics and topology. (6h)

These lectures shall give an introduction to the role of topology in the dynamics of quantum many particle systems. The focus shall be on topological band theory, and symmetry protected topological states. The topics to be covered are:
• Topological band theory and symmetry protected topological invariants;
• Adiabatic evolution and Thouless pumping;
• Floquet topological phases;
• Quench dynamics and far-from-equilibrium topology;
• Open quantum systems.

References to relevant background material can be found in:
N. R. Cooper, J. Dalibard, and I. B. Spielman, Rev. Mod. Phys. 91, 015005 (2019)

Valentina Ros (LPTMS-Orsay)
An introduction to (Many-Body) Localization. (6h)

The aim of these lectures is to introduce the concept of (Many-Body) Localization.
The first half of the lectures is an overview of the key features of localized systems as they emerge from analytical arguments, numerics and experiments [1,2,3], with some emphasis on the differences between localized systems and other systems which do not equilibrate (such as glasses or clean integrable systems). This is organized around the following 5 questions: (1) What does out-of-equilibrium mean in Many-Body Localization (MBL)? (2)What would equilibrium mean here, actually? (3) Why is MBL theoretically challenging, and why is it worth the effort? (4) How does disorder generate localization? (5) How can we understand this phenomenology in a unified framework?
The second half of the lectures focuses on the analytical arguments for the existence and stability of the localized phase, through a quick review of the diagrammatic/perturbative expansion discussed originally in the seminal work by P. W. Anderson for non-interacting systems [4], and subsequently extended to interacting systems [5].

References:

[1] R. Nandkishore and D. A. Huse, *Many-body localization and thermalization in quantum statistical mechanics.* The Annual Review of Condensed Matter Physics, 6(1), 15 (2015).
[2] D. A. Abanin, E. Altman, I. Bloch and M. Serbyn, *Colloquium: Many-body localization, thermalization, and entanglement.* Reviews of Modern Physics, 91(2), 021001 (2019).
[3] Review papers in the special issue of Annalen der Physik on Many-Body Localization, Annalen der Physik, 529(7), 1770051 (2017).
[4] P. W. Anderson, *Absence of diffusion in certain random lattices.* Physical Review, 109(5), 1492 (1958).
[5] D. M. Basko, I. L. Aleiner and B.L. Altshuler, *Metal–insulator transition in a weakly interacting many-electron system with localized single-particle states.* Annals of physics, 321(5), 1126 (2006).

Some extra material (exercises, list of references for specific topics, slides with plots) will be available at the following link: https://mycore.core-cloud.net/index.php/s/h1N9JQoE4oKqeNq
Ref. [1] would be a good reading to familiarise in advance with the concepts discussed in the lecture.

Subir Sachdev (Harvard University)
The quantum phases of matter. (10h)

The first part of the course will focus on phases of matter with fractionalization and emergent gauge fields. I will introduce there ideas in the simplest context of the 3-dimensional classical XY model. Then I will describe the two most common spin liquid phases of two-dimensional antiferromagnets: the Z_2 spin liquid and the chiral spin liquid.
The second part will consider phases of matter without quasiparticle excitations. I will describe the SYK model, and note its connections to the quantum theory of charged black holes. Then I will turn to theory of strange metals, and describe phases with a Fermi surface without quasiparticle excitations.

Prerequisites: I will assume knowledge of path integral methods of bosons and fermions, and a passing familiarity with the Landau-Ginzburg-Wilson theory of phase transitions.

Lectures notes: I will hand out a few chapters from my forthcoming book on "The Quantum Phases of Matter".

Kareljan Schoutens *(*University of Amsterdam)
Many-body physics and quantum computation. (10h)

There is an intriguing two-way interplay between quantum many-body physics and quantum computing (or, closely related, quantum simulation). In one direction, insight in quantum physics is crucial for the design of quantum hardware (say, qubit platforms) and for the quantum control needed to operate such systems. In the other direction, a sufficiently mature quantum computer is a splendid new addition to the toolbox that we employ for analyzing quantum many-body problems, in physics and (quantum) chemistry alike.
In these lectures I will address and illustrate both these perspectives. This course being too short for a systematic treatment, I will sketch the big picture and then delve into specific systems and protocols, the choice of which is a reflection of my own involvement in the field.

Preliminary content:

1. Qubits & quantum gates - shortcuts to multi-qubit gates
   [key words: resonant driving, adiabatic following, perfect state transfer (PST), n-bit Toffoli gate]
2. Quantum computing and simulation with Rydberg atoms – blockaded, facilitated and dressed regimes
   [key words: PXP chain and QMB scars, Hilbert crystals, susy lattice model]
3. Quantum materials and quantum chemistry on a quantum computer
   [key words: qubit mappings, hamiltonian simulation, state preparation]
4. Quantum Phase Estimation (QPE)
   [key words: quantum Fourier transform, ground state projection]
5. Variational quantum algorithms
   [key words: QAOA, VQE, simple molecule and spin-chain as examples]

References will be provided at a later stage and I will challenge the students with some exercises. Lectures 4 and 5 will feature simple illustrations using Cirq – interested students are urged to familiarize themselves with Cirq using the tutorials at https://quantumai.google/cirq/tutorials.