SFT-2020
Lectures on Statistical Field Theories
Galileo Galilei Institute
Florence, 3-14 February 2020

Program of lectures

Alexander Abanov (SUNY at Stony Brook)
Topology and geometry in condensed matter physics. Toy models. (8h)

It is often that in the condensed matter systems the degrees of freedom that appear due to spontaneous symmetry breaking or emergent gauge symmetry, have non-trivial topology. In those cases, the terms in the effective action describing low energy degrees of freedom can be metric independent (topological). We consider a few toy models illustrating topological terms of different types and discuss some of the physical consequences of topological terms. We will also discuss how topological terms originate from phases of fermionic determinants and represent quantum anomalies. In condensed matter physics, topological terms are useful in studies of charge and spin density waves, Quantum Hall Effect, spin chains, frustrated magnets, topological insulators and superconductors, and some models of high-temperature superconductivity.

Main reference: arXiv:1708.07192

Vedika Khemani   (Stanford)
Topology and Symmetry Breaking in Periodically Driven Systems. (6h)

Periodically driven (Floquet) quantum systems have emerged as a new topical research field in the study of many-body systems. Interest in them originates from the many novel possibilities to engineer versatile Hamiltonians and realize novel out-of-equilibrium phases of matter, often with no static analog. In this set of lectures, I will give an introduction to Floquet systems, and describe how these realize new phases of matter - both topological and symmetry breaking.

Plan of the course:
- Lectures 1-2: Introduction to Floquet formalism; topological phases in non-interacting Floquet systems.
- Lectures 3-4: Heating in many-body Floquet systems; Floquet many-body localization; eigenstate order.
- Lectures 5-6: Phases in a driven Ising chain; the time-crystal phase and its properties.

References:
- Khemani, Moessner, Sondhi, *A Brief History of Time Crystals,* arXiv:1910.10745.
- Harper, Roy, Rudner, Sondhi, *Topology and Broken Symmetry in Floquet Systems,* arXiv:1905.01317.

Joel Moore (UC, Berkeley)
Introduction to topological phases of electrons. (6h)

The purpose of this course is to give an introduction to various kinds of topological order and related properties. We will focus on explaining several of the most important examples and general concepts, rather than trying to give comprehensive classifications where those exist. Quantum or classical field theories often provide the most compact and universal description of the essential elements of a topological phase or phenomenon. In addition to well-established examples such as the quantum Hall effect, we will spend a considerable amount of time on.

Plan of the course:
- Lectures 1-2: basic mathematical notions and physical background of the integer and fractional quantum Hall effects. The Laughlin state and other examples of incompressible quantum liquids with topological order. First examples of Berry phases and quantum Hall physics on lattices. Brief comments on disorder.
- Lectures 3-4: Field-theoretic description of the integer and fractional Hall effects by Chern-Simons theory. Time-reversal symmetry and spin-orbit coupling. Topological insulators.
- Lectures 5-6: Topology in gapless matter. Weyl semimetals and their universal electromagnetic responses. Brief introduction to spin liquids. As time permits, new directions.

Some optional readings:
- For the course material: J. E. Moore, "Introduction to topological phases of electrons", in *Topological Aspects of Condensed Matter Physics*, Oxford University Press. These are notes from lectures at Les Houches, and videos are available online. There is some overlap with what I will cover in Florence, but I expect to cover some new topics and to supply revised notes closer to the meeting.
- A useful book for people who wish to know more about the mathematical background is M. Nakahara, *Geometry and Topology in Condensed Matter Physics.*
- It will be assumed that students know the basics of solid-state physics and field theory. A new book on solid-state physics that may be useful is *Modern Condensed Matter Physics* by S. M. Girvin and K. Yang.
- I will not have time to cover topological spin liquids in detail, but readers who would like to work through some examples I will mention in more detail can see the *Les Houches lecture notes* (on arXiv) jointly by A. Kitaev and C. Laumann.

Giuseppe Mussardo (SISSA, Trieste)
Two-dimensional conformal field theory: a primer. (12h)

Conformal Field Theory:
- Conformal Invariance
- Ward identity and primary fields
- Virasoro algebra and central charge
- Representation theory
- Casimir effect and other finite size phenomena
- Bosonic and fermionic fields

Minimal models
- Differential equations of the correlation functions
- Coulomb gas

- Modular invariance

Suggested pre-reading:
- John Cardy, *Scaling and Renormalization in Statistical Physics,* Cambridge University Press, Cambridge, 1996.
- A.Z. Patasinskij, V.L. Pokrovskij, *Fluctuation Theory of Phase Transitions,* Pergamon Press, Oxford, 1979.
- K. Huang, S*tatistical Mechanics,* John Wiley, New York, 1963.
- M.E. Peskin, D.V. Schroeder, *An Introduction to Quantum Field Theory,* Adison Wesley, New York, 1995.

Paola Verrucchi (ISC-CNR, Florence)
Quantum processes: from quantum computation to many-body physics, and back. (6h)

Any physical procedure that transforms a quantum state into another one can be legitimately called a "quantum process". It is not necessary that the procedure be a dynamical one, i.e. that it takes place in time; it is not necessary that the system which is described by the original state be the same as that described by the modified one; finally, it is not even necessary that the procedure itself be defined, as what matters is just the change in the state. Needless to say, then, the term may sound so general to be uselessly generic. On the other hand, just because of their general nature, quantum processes cannot be studied with the tools of quantum dynamics, and rather require a specific formalism. This goes under the name of "quantum operations" formalism, and it contains instruments such as trace-preserving maps, Krauss operators, positive-operator-valued measures, involving concepts like complete positivity, tomography, channel-state duality. It is a toolbox made up for studying open quantum systems, i.e. quantum systems with equally quantum environments, that has become particularly relevant in the last decades because of its use in the realm of quantum information and computation.

In these lectures we will first meet the quantum operations formalism in a setting where a very simple system, such as a qubit, goes hand-in-hand with an environment which is a, possibly very complicated, many-body quantum system. We will then introduce the fundamental elements of quantum computation, so as to understand why, and in what sense, the above picture fits within the analysis of quantum algorithms as dynamical processes. Finally, we will reverse our viewpoint, and show that quantum algorithms can be designed in such a way that they dynamically solve problems of many-body quantum physics.

Suggested readings
These books contain much more material than that considered during the course. However, they are excellent textbooks to which it is worth referring.
- Teiko Heinosaari and Mário Ziman, *The Mathematical Language of Quantum Theory,* Cambridge University Press, 2011.
- Michael A. Nielsen and Isaac L. Chuang, *Quantum Computation and Quantum Information,* Cambridge University Press, 2010.
- Ingemar Bengtsson and Karol Żiczkowski, *Geometry of Quantum States,* Cambridge University Press, 2017 (1st ed. 2006).

Other events

Monday 3 February 2020, 2.30 pm
Gong Seminar[‡]

Monday 3 February 2020, 5.30 pm
Welcome drink

Wednesday 5 February 2020, 3.30 pm
Seminar:
"J. Robert Oppenheimer: Shatterer of Worlds"
by Giuseppe Mussardo (SISSA, Trieste)

Tuesday 11 February 2020, ~3.00pm
Guided visit at "Villa Il Gioiello"

[‡]   Each student is invited to give a two-minute talk to present himself and his scientific interests.