QMBT in Condensed Matter
PGF5295 – IF - USP

Videos every Tue and Thurs.

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Course page (Moodle) (2020 →IF → PGF → PGF5295--2020→ Início)
https://edisciplinas.usp.br/course/view.php?id=79962
Youtube channel:
http://www.youtube.com/c/LuisGregorioDias

Course Contents (ideally):

- Formalisms:
  - 2nd quantization, Reps. in Quantum Mechanics, field operators.
  - Green’s functions at T=0 and T≠0.
  - Feynman Diagrams and Wick’s theorem.

- Physical systems in condensed matter:
  - (Interacting) electron gas: RPA.
  - Mean-field theories: Hartree-Fock, etc.
  - Models: Anderson, Kondo, Heisenberg, Hubbard.
  - Transport in mesoscopic systems.
  - BCS theory: superconductivity
  - Topological insulators and superconductors.

- “More is Different” paradigm (Anderson, Laughlin, and others).
  - Emergent phenomena in Physics.

Tentative timeline:

	SUN	MON	TUE	WED	THU	FRI	SAT	CALENDAR- PGF5295 -2nd sem 2020	
AUGUST	9	10	11	12	13	14	15		Bruus/Flensberg
	16	17	18	19	20	21	22	**Class 1** Course presentation/Review of Quantum Mechanics **Class 2** Indistinguishible particles, Fermions and bosons (C1)	Chap. 1
	23	24	25	26	27	28	29	**Class 3** Second quantization. Field operators. (C1) **Class 4** Non-interacting electron gas. Density of states (C2)	Chap 2
SEPTEMBER	30	31	1	2	3	4	5	**Class 5** Tight-binding model on a 1D lattice (second quantization). **Class 6** Mean-field theories (Hartree-Fock, etc) (C4)	Chapters 4-5
	6	7	8	9	10	11	12	**7 a 11/ set Semana da Pátria**	
	13	14	15	16	17	18	19	**Class 7** Representations: Schrödinger, Heisenberg and Interaction; **Class 8** Time-ordering, Fourier Transform.	Chapters. 8-9
	20	21	22	23	24	25	26	**Class 9** Green's functions at T=0, Lehmann representation. (C8) **Class 10** Equations of motion (Zubarev). (C9)	Chapters 6,7,10
	27	28	29	30	1	2	3	**Class 11** Anderson model. Linear response theory (C6) . **Class 12** Conductance in quantum dots. Kondo effect (C10)	Chapters 11-12
OCTOBER	4	5	6	7	8	9	10	**Class 13** Imaginary time Green's functions. Wick's theorem(C11) **Class 14** Feynman diagrams (pair interaction). (C12)	Chapters 11,14
	11	12	13	14	15	16	17	**Class 15** Feynman diagrams (momentum representation) **Class 16** RPA for the electron gas (C14)	N
	18	19	20	21	22	23	24	**Class 17** Electron gas: dielectric response from the electron gas (C6 e C14) **Class 18** Matsubara formalism (C11)	N
	25	26	27	28	29	30	31	**Class 19** Phonons (C3) **Class 20** Green's functions for phonons (C17)	Chaps 6,14
NOVEMBER	1	2	3	4	5	6	7	**Class 21** RPA and phonons: Cooper instability (C18) **Class 22** BCS theory (C18)	Notes
	8	9	10	11	12	13	14	**Class 23:** Berry phase. **Class 24:** Hall conductance and Chern number.	Notes
	15	16	17	18	19	20	21	**Class 25:** Topological insulators and quantum spin Hall effect. **Class 26:** Topological superconductors, Kitaev model. Majorana zero states.	Notes
	22	23	24	25	26	27	28	**Student's presentations**	Final projects
DEC	29	30	1	2	3	4	5	**Student's presentations**	Final projects
	6	7	8	9	10	11	12	**Student's presentations**	Final projects

- **Video available** (green)
- **Final project presentations** (yellow)
- **No video uploaded** (blue)
- **Holiday** (red)

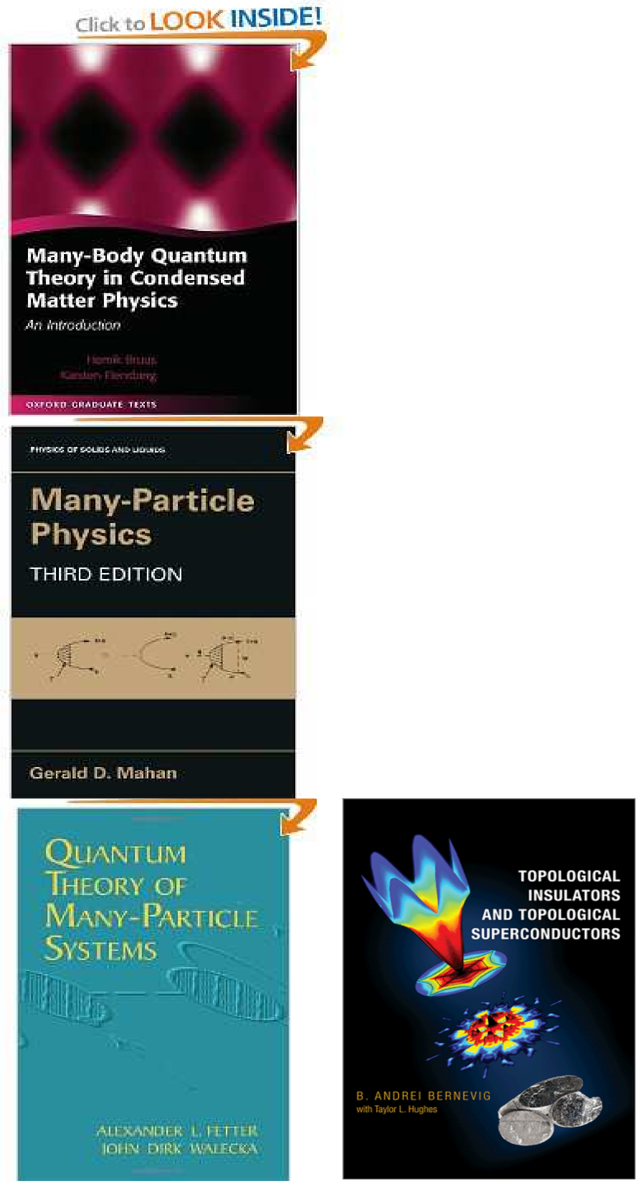
Bibliography:

- [Henrik Bruus e Karsten Flensberg, "Many-Body Quantum Theory in Condensed Matter Physics", Oxford University Press (2004).]

- G. D. Mahan, “Many-particle physics”, New York Plenum (1990).

- A. L. Fetter e J. D. Walecka, "Quantum Theory of Many-Particle Systems", Dover (2003) [ou McGraw-Hill (1971)]

- B. Andrei Bernevig, “Topological Insulators and Topological Superconductors”, Princeton (2013).



Grading and evaluation (rules of the game)

- **Class assignments** (70%):
  - Each class will have 1-3 assignments, which will be graded.
  - Assignments must be uploaded in the Moodle platform.
  - The assignments will be due a week after the class in which they are presented.
  - That means typically assignments will be due **every Tuesday and Thursday, at 23h55**.
  - Group discussions are ok. We will discuss the assignments during the *lives* (Weekly on Thursday or Friday).
  - Assignments by e-mail **WILL NOT BE ACCEPTED**!!
- **Final project** (30%):
  - Essay (5-10 pages) + Zoom Presentation at the end of the semester.
  - Topic to be chosen by the student and the instructor.

Final Project.

- Manuscript (topic to be chosen in common agreement with instructor).
  - Typically 5 to 10 pages (written preferably in Latex)
  - Introduction with a review of the basic literature.
  - Presentation of topic in an organized, clear manner.
  - “Know your audience”: Tailor your presentation to your target audience (e.g., other graduate students, non-speciallists on the subject).
  - DO NOT WRITE FOR THE EYES OF THE INSTRUCTOR ONLY!
- Oral Presentation (24/11 through 10/12):
  - 20 min seminar + questions (on Zoom).
  - The order of the presentations will be defined by a random draw.
  - Organize your seminar; beware of the time; master the subject.
  - BE clear and didactic (talk to your colleagues not to the instructor only!
  - Seminar attendance is **MANDATORY** to all students. (absences in your colleague’s seminar will affect your grade).

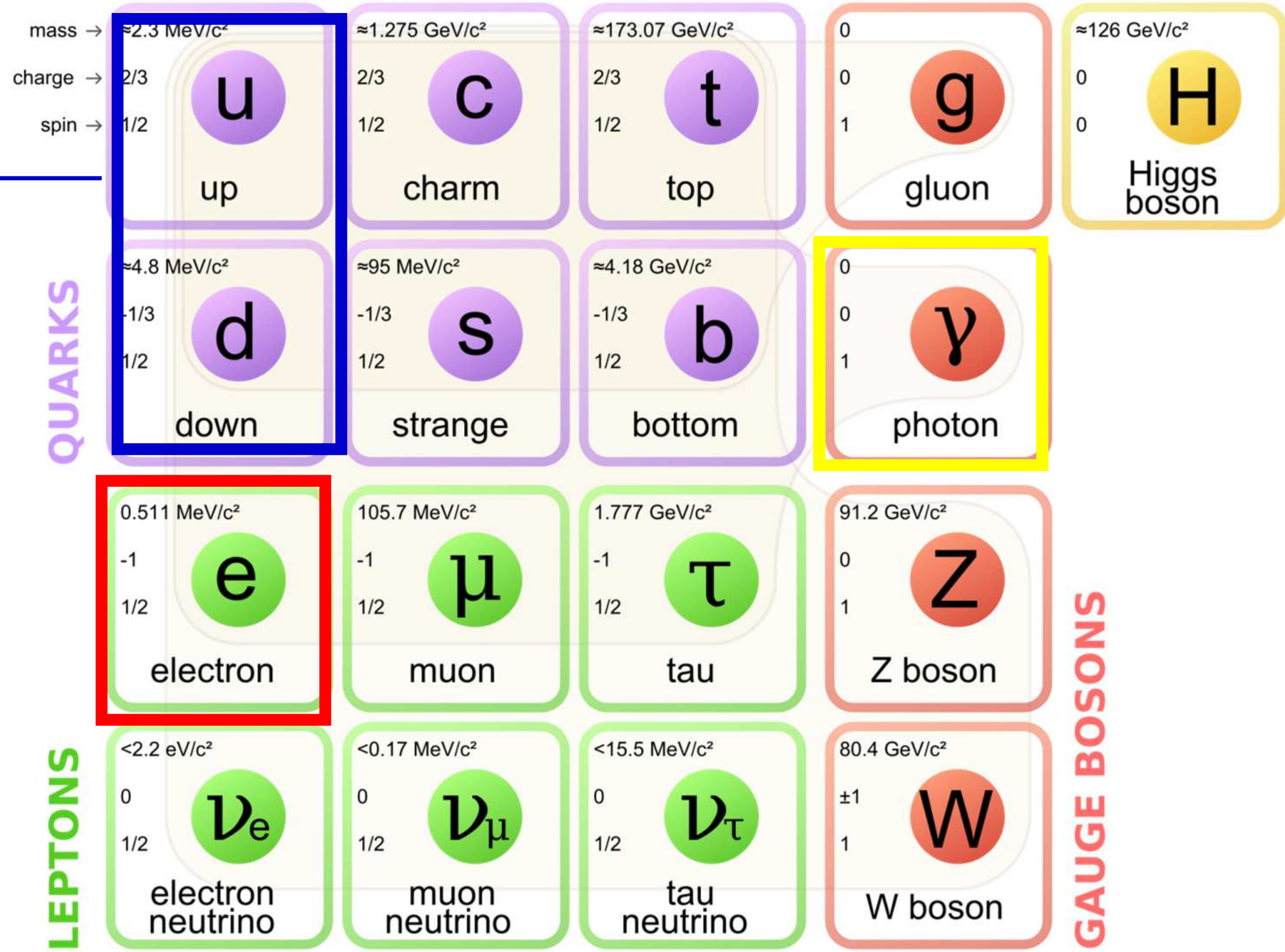
Final Project.

- (Some) Suggested topics

  - Strongly correlated systems (several possibilities)
  - Numerical Methods for correlated systems (DMRG, NRG, QMC, etc.).
  - Correlations in cold atoms traps (bosonic, fermionic).
  - GW method (RPA, etc.)
  - High-Tc superconductors (Cuprates, Pnictídeos,...)
  - “Magic angle” bilayer graphene.
  - “Topological matter” (several possibilities)
  - Majorana bound states/Non-abelian anyons/Topological computation.
  - Disorder effects (Anderson localization, Many-body localization).
  - Luttinger liquids.
  - etc., etc.

What is fundamental?

Nuclei



Standard Model Particles

Too much information!

All we need to make up all materials we have contact with is: electrons + nuclei

(and perhaps some photons?)

“More is Different!”

“ The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of simple extrapolation of the properties of a few particles.

Instead, at each level of complexity entirely new properties appear and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other.“

Phillip W. Anderson, “More is different”,
Science **177** 393 (1972)

“Theory of Everything”

R. B. Laughlin and David Pines, PNAS **97** 28-31 (2000)

$$\boxed{i\hbar\frac{\partial}{\partial t}|\Psi_{\rm all}\rangle = H_{\rm all}|\Psi_{\rm all}\rangle}$$

In our everyday life, “everything” is made of electrons and nuclei.

Kinetic energy
electrons e nuclei

$$H_{\rm all} = \boxed{\sum_j^{N_e}\frac{p_j^2}{2m_e}} + \boxed{\sum_\alpha^{N_n}\frac{P_\alpha^2}{2M_n}}$$

Attractive/repulsive interactions between electrons e nuclei

$$\boxed{-\sum_j^{N_e}\sum_\alpha^{N_n}\frac{Z_\alpha e^2}{|\mathbf{r}_j - \mathbf{R}_\alpha|}} \quad \boxed{+\sum_{j,k}^{N_e}\frac{e^2}{|\mathbf{r}_j - \mathbf{r}_k|}} \quad \boxed{+\sum_{\alpha,\beta}^{N_n}\frac{Z_\alpha Z_\beta e^2}{|\mathbf{R}_\alpha - \mathbf{R}_\beta|}}$$

electron-nuclei   electron-electron   nuclei-nuclei

Not included: - Light and photons in general (which can be important)
- *Gravity* - *Nuclear forces* , etc.

“Theory of Everything” does not predict everything!

$$\boxed{i\hbar\frac{\partial}{\partial t}|\Psi_{\mathrm{all}}\rangle = H_{\mathrm{all}}|\Psi_{\mathrm{all}}\rangle}$$

R. B. Laughlin and David Pines, PNAS **97** 28-31 (2000)

- Can only solve this equation exactly for small systems (N_e,N_n~10).

- Large systems: Much harder problem!

- Some <u>approximations</u> sometimes work well: Hartree-Fock, CI, DFT (+GGA, B3LYP), GW, etc.

"Theory of Everything" does not predict everything!

$$\boxed{i\hbar\frac{\partial}{\partial t}|\Psi_{\mathrm{all}}\rangle = H_{\mathrm{all}}|\Psi_{\mathrm{all}}\rangle}$$

R. B. Laughlin and David Pines, PNAS **97** 28-31 (2000)

- Exact solution only for $N_{e,h}$~10!
- Even if one *could* solve it, this equation (as is) does not predict several fundamental behaviors!

Conductance quantum in the quantum Hall effect (=e^2/h).
- Quantum magnetic flux (=hc/2e) in superconduting rings (or in the Josephson effect).
- Magnetic field generated by rotating superconductors (=e/mc).

Experimental measurement of some of the fundamental physical constants:
h, m and *c* !

Why???

These are *emergent* phenomena!

In short:

Robert Laughlin - Stanford
Nobel Prize winner – 1998

“We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance.”

David Pines
U.C. Davis

Robert B. Laughlin and David Pines, “Theory of Everything”
PNAS **97** 28-31 (2000)

1st assignment (due Aug. 25).

- Written essay on the papers:
  - Phillip W. Anderson, "*More is Different*", Science **177** 393 (1972).
  - Robert B. Laughlin and David Pines, "*Theory of Everything*", PNAS **97** 28-31 (2000).
  - Both papers are available in the website.

- What do I expect in this work?
  - Quality of the written presentation (ideas, fluency, etc.)
  - (Writing skills are very, very important in Physics research and many times are not emphasized in Physics courses)
  - A *critical reading* of the papers (and not only an "abstract").
  - An essay of 2-3 pages should be fine.
  - You may write it either in Portuguese or in English.
  - Upload a pdf on Moodle by Tuesday, Aug. 25 at 23h55.