Curriculum Teorico Generale

A short presentation of research lines and why you should enroll in it

July 12th, 2023

Introduction

The curriculum is the right one for students interested in **every** aspect of theoretical physics:

- Theoretical physics of fundamental interactions
- General relativity and theoretical astrophysics
- Theoretical aspects of condensed matter
- Statistical mechanics and complex systems
- Computational physics and machine learning
- Mathematical physics
- Theoretical modelling of biological systems

Research lines related to

- Theoretical physics of fundamental interactions
- General relativity and theoretical astrophysics
- Theoretical aspects of condensed matter

have been already presented.

Below are briefly described research line related to

- **Statistical mechanics and complex systems**
- **Computational physics and machine learning**
- **Theoretical modelling of biological systems**

Introduction

Curriculum Teorico Generale is very **flexible** as it needs to cover every aspect of theoretical physics:

- leaves a lot of freedom in the choice of the courses
- 2 free choice courses (as in any curricula)
- 6 other courses to be chosen in large groups (3 in group A, 2 in group B an 1 in group C)

In the last years, roughly half of the students of the Laurea Magistrale in Physics have enrolled in it

The curriculum Teorico Generale is formally in Italian, but

- only one course is taught in Italian,
- a student not speaking Italian can easily organize its own *Piano Formativo* containing only courses taught in English.

Mandatory courses

- Introduction to quantum field theory (6 cfu)
- Condensed matter physics (6 cfu)
- Physics laboratory 1 & 2 (15 cfu)
- Mathematical physics or Group theory in math phys (6 cfu)
- English language (4 cfu)

Group A

- Statistical mechanics and critical phenomena (1 year, 1 sem)
- General relativity (1 year, 1 sem)
- Theory of fundamental interactions (1 year, 2 sem)
- Meccanica statistica del non equilibrio (1 year, 2 sem)
- Nonlinear waves and solitons (1 year, 2 sem)
- Statistical mechanics of disordered systems (2 year, 1 sem)
- Quantum field theory (2 year, 1 sem)
- Statistical physics and machine learning (2 year, 1 sem)

All courses have 6 cfu. **3 courses** must be chosen from this group.

Group B

- those in group A plus the following
- 1 year, 1 sem: Computing methods for physics, Nonlinear and quantum optics
- 1 year, 2 sem: Theoretical biophysics, Gravitational waves, compact stars & black holes, Neural networks, Strong interactions & QCD, Condensed matter physics II, Superconductivity & superfluidity, Advances machine learning for physics, Physical cosmology
- 2 year, 1 sem: Many body physics, Physics of complex systems, Quantum information and computation, Phenomenology of the standard model, Theory of stochastic processes, Physics of solids

All courses have 6 cfu. **2 courses** must be chosen from this group.

How to submit the personal curriculum (Piano Formativo)

A technical presentation at the end of September, before the opening of the Piano Formativo submission, to illustrate the actual rules

We leave a lot of freedom to the student as long as very reasonable choices are made:

- distribute courses evenly over the 3 semesters
- take courses in the “right order” according to their content
- justify any non-standard choice

These rules will be made explicit in the September presentation

At present, you just need to decide whether

Teorico Generale is the right curriculum

for your interests, according to our research lines

Research lines

Theoretical research lines in fundamental interactions will be presented within the Fundamental Interactions curriculum.

Theoretical research lines in condensed matter will be presented within the Condensed Matter Physics curriculum.

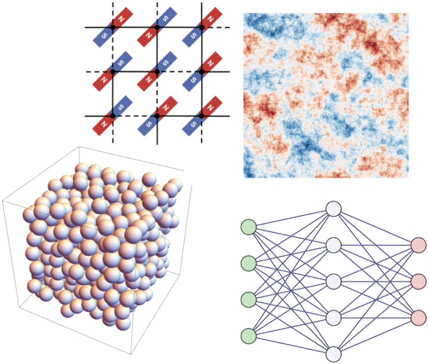
Following is a very short sketch of the remaining research lines in the Theoretical Physics Group (Gruppo Teorico)

Statistical physics of disordered systems... (Chimera group)

Group members: Angelini, Cammarota, Marinari, Negri, Parisi, Ricci-Tersenghi, Zamponi (Sapienza) + Leuzzi, Rizzo (CNR) + 7 Post-doc + PhD students

Study several models where disorder and frustration lead to complex physical behaviour:

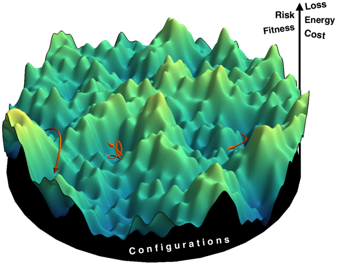
- Spin glasses
- Structural glasses
- Hard spheres jamming
- Artificial neural networks
- Etc...



...and applications (Chimera group)

Applications to many different fields

- Glassy dynamics, relaxation in complex energy landscapes with many metastable states
- Optimization and constraint satisfaction problems
- Statistical inference and machine learning
- Neural networks and statistical models of learning and memory
- Ecological models



In all these applications phase transitions play a key role and the approach based on statistical physics is the most effective!

Systems with Negative Temperature

Do negative absolute temperatures matter physics? It is now possible to provide evidence that we can certainly answer positively to this vexata quaestio. Since more than half a century ago it has been realized that for some interesting physical systems entropy is a non monotonic function of energy, here an incomplete list: $2d$ incompressible fluids, nuclear magnetic chains, lasers, cold atoms and optical waveguides.
It is possible to show that negative absolute temperatures are consistent with equilibrium as well as with non-equilibrium thermodynamics. In particular, thermometry, thermodynamics of cyclic transformations, ensemble equivalence, fluctuation-dissipation relations, response theory and even transport processes can be reformulated to include them, thus dissipating any prejudice about their exceptionality, typically presumed as a manifestation of transient metastable effects.

Response and flux of information in non-equilibrium dynamics

It is well known that entropy production is a proxy to the detection of non-equilibrium, i.e. of the absence of detailed balance; however, due to the global character of this quantity, its knowledge does not allow to identify spatial currents or fluxes of information among specific elements of the system under study. In this respect, much more insight can be gained by studying transfer entropy and response, which allow quantifying the relative influence of parts of the system and the asymmetry of the fluxes.

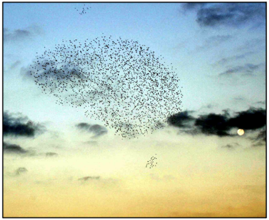
Statistical mechanics of integrable systems

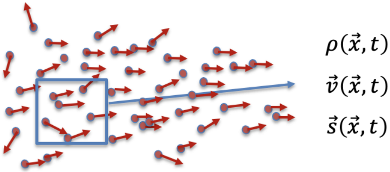
Statistical mechanics allows us to understand the features of macroscopic objects, including intriguing phenomena such as criticality and scale invariance. It is then quite natural to wonder about the origin of such a great success. A paradigmatic and historically crucial example for the problem of statistical mechanics foundations is the celebrated Fermi-Pasta-Ulam-Tsingou (FPUT) problem. Even after many years the true relevance of chaos to legitimate statistical mechanics is still an open issue. Two main different points of view may be traced back to two opposite schools:
i) the "chaotic" one according to which a key role is played by the dynamics and, consistently, the presence of chaos is regarded as the basic ingredient for the validity of the statistical mechanics;
ii) the "traditional" one, following the original Boltzmann's ideas (and then developed by Khinchin, as well as to Mazur and van der Linden) which stresses the role of the large number of degrees of freedom.

A realistic approach to the study of physical phenomena requires the formulation of sufficiently rich mathematical models reflecting their complexity, and a fundamental element of such complexity is nonlinearity. An important progress has been recently made with the discovery that extreme nonlinear wave phenomena in nature, such as anomalous (rogue) wave dynamics and multidimensional wave breaking are described, to leading order, by nonlinear integrable PDEs. Then exact algebraic and analytic techniques can be used to study these nonlinear phenomena, with applications in several branches of physics, like water waves, nonlinear optics, plasma physics and Bose-Einstein condensates.

People: Calogero, Santini + 1 post-doc

Collective Behaviour in Biological Systems (Cobbs)





- Living assemblies display collective patterns on the large scale
- Statistical Physics can be used to describe/understand them
- Statistical inference $\rightarrow$ data based modelling
- Stochastic dynamics + field theory of collective motion

People: Irene Giardina, Andrea Cavagna + Cobbs group
www.cobbs.it

Summary

The research lines presented above represent a good part of the activities of the Theoretical Physics Group (Gruppo Teorico), but they are not exhaustive!

They are meant to give an idea of the research fields where members of the Theoretical Physics Group are active.

You should consider enroll in the curriculum Teorico Generale if you would like to work on any of the above fields of research or on something very much related.

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