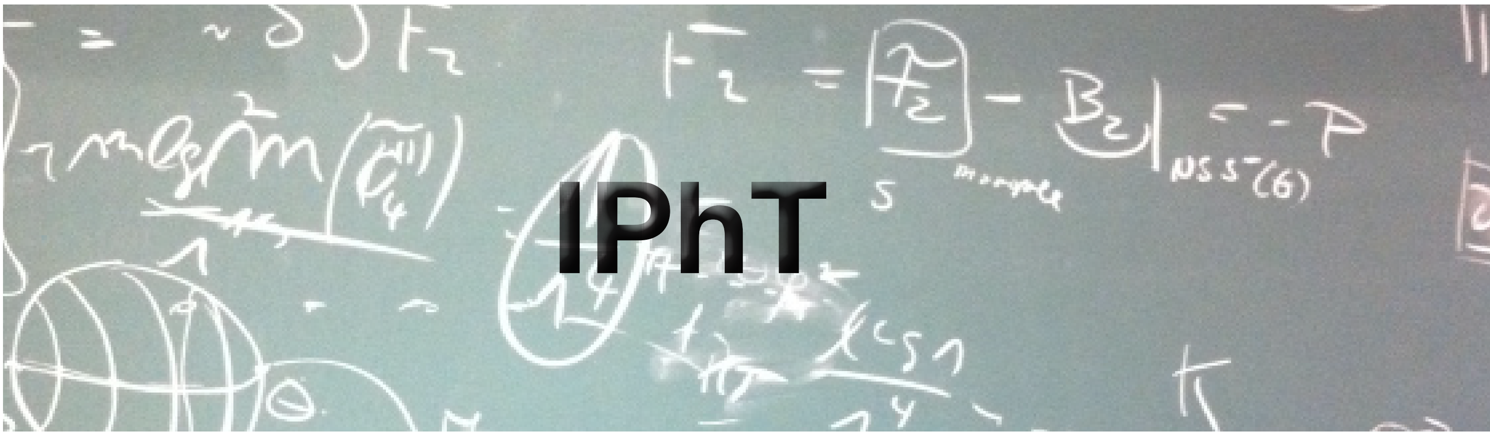
Institut de Physique Théorique



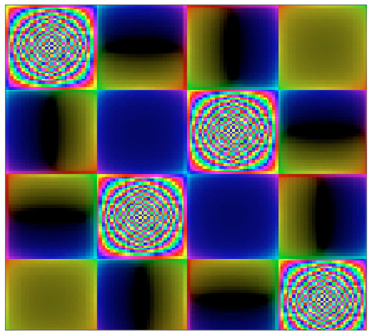
At the Institut de Physique Théorique, a wide range of research projects are pursued. They extend from the study of fundamental interactions, with the aim of understanding the primordial universe, to the modeling of biological structures. They also include the mathematical analysis of complex systems in statistical mechanics and in field theory. This diverse range of systems are united by the underlying mathematical forms used to describe them.

Commissariat à l’énergie atomique
et aux énergies alternatives
Direction de la Recherche Fondamentale
Saclay

Mathematical Physics

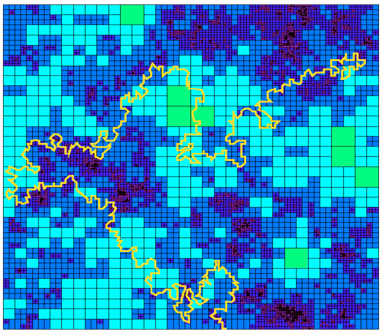
Quantum chaos, dynamical systems & field theory

The dynamics of very simple systems can lead to complex paths at long times. For example, the trajectories of a particle in a stadium shaped billiard are unstable and they eventually fill all of the billiard. This system has a quantum analogue: a wave propagating inside a cavity of the same shape. The semi-classical approach allows the analysis of the stationary modes and their localization properties by taking into account the long-time properties of the classical system. These kinds of simple mathematical models allow us to understand various physical systems, such as electrons in mesoscopic two-dimensional systems, propagation of light in optical fibers, acoustic cavities, or propagation of seismic waves. From a theoretical point of view, for systems with an infinite number of degrees of freedom, the renormalization group turns out to be an invaluable tool for rigorous analysis of perturbative quantum field theories. This vast field of research is thus on the border between mathematics and physics, with many and varied applications, ranging from turbulence to quantum decoherence.



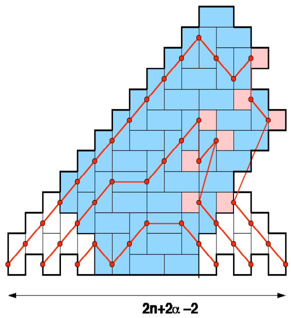
Combinatorial statistical physics

Statistical physics involves a precise counting of the states and configurations of a system, and thus is intimately related to combinatorics. The link between critical phenomena on 2d regular lattices and their “gravitational” version on fluctuating lattices is the key to the solution of a number of problems in statistical mechanics (polymers, hard-core particles) and in mathematics (three-color problem, meanders). This relation has been revisited in a rigorous fashion in the continuous probabilistic approach to quantum gravity. The study of the laws obeyed by random matrices allows us to discover new invariants of enumerative algebraic geometry which include and generalize some invariants (Gromov-Witten, knot, etc.), and more generally to explore the asymptotic expansion of integrable systems. The combinatorial approach is an alternative to traditional approaches like field theory and matrix models. For example, cutting the graphs into trees is a powerful way to determine the statistics of internal distances on random lattices.



Conformal theories & integrable systems

Integrable systems possess many conserved quantities. They are useful for studying non-perturbative phenomena in systems which are subject to strong statistical or quantum fluctuations. Their analysis uncovers remarkable algebraic and geometric structures, with applications ranging from physics to pure mathematics. This is equally the case for conformal field theories, which are central to the construction of string theory and which are also the perfect tools for studying critical 2d statistical systems or 1d quantum systems. They are also used to characterize certain stochastic and fractal growth processes, that are universal. Integrable models also occur in the study of supersymmetric gauge theories, where they are used to explore the strong coupling regime and to prove that these theories are dual to string theories in curved space-time.



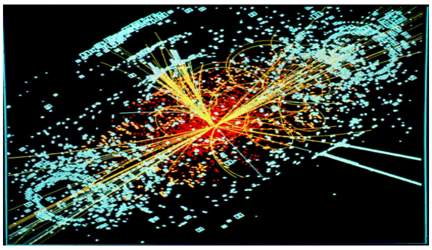
String theory & quantum gravity

The De Broglie wavelength of a particle moving in a region of high energy density or near a black hole is very large, and can be of the same order as the curvature radius of the spacetime. In such circumstances the classical laws of gravity are altered by quantum effects. The best candidate for a quantum theory of gravity is string theory, in which the particles are replaced by extended objects. Our researchers study string theory in various geometric configurations, both by using algebraic and differential geometry techniques to study its compactifications and by using supergravity techniques to attack longstanding problems like Hawking’s information paradox or the microscopic origin of black hole entropy. They also use the gauge/gravity duality to study strongly-coupled systems similar to the quark-gluon plasma produced at the LHC or to those appearing in condensed matter physics.

Particle physics - Astrophysics

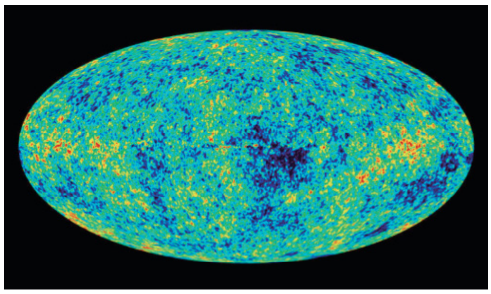
The Standard Model & beyond

The Standard Model describes the fundamental building blocks of matter (quarks and leptons) and their interactions. Particle accelerator experiments have been testing it for the last thirty years with unprecedented accuracy. One of the key elements of this theory, the Higgs field, whose role is to provide a mass to the elementary particles, is under high scrutiny at the Large Hadron Collider (LHC) at CERN. Despite its success in describing a host of experimental results, the Standard Model fails to explain observations such as the existence of dark matter, the matter-antimatter asymmetry, the acceleration of the expansion of the Universe, and the smallness of neutrino masses. Moreover, certain theoretical conundrums find no explanation within the Standard Model, e.g. the quantum instability between the electroweak scale and the Planck scale, at which gravitational interactions become strong. Physics beyond the standard model strives to give answers to these puzzles by envisaging more fundamental theories involving new particles and their interactions, or employing model-independent techniques with which one can extract information relevant to those theories directly from experimental data (high-energy collisions, cosmic rays, cosmological observations, neutrino oscillations, rare decays...). Several key phenomena such as the dynamics of the electroweak symmetry breaking, the nature and properties of dark matter, the origin of the mass of neutrinos, and also the nature of dark energy are under study using these complementary approaches.



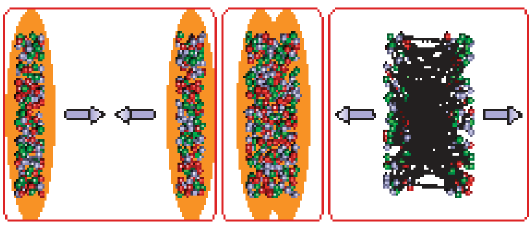
Cosmology

Cosmology aims to retrace the history of our Universe since the Big Bang, in order to understand its content as well as its large scale structure. The astrophysical objects that we observe today (galaxies, clusters of galaxies...) are due to the gravitational collapse of small density irregularities that appeared in the primordial universe. Our research topics range from studies of the primordial universe (statistical properties of the initial fluctuations, generation of gravitational waves or magnetic fields...) to studies of the gravitational dynamics of large-scale structures in the recent universe (spatial distribution of galaxies...). These theoretical predictions are confronted with observations to constrain cosmological scenarios (measurements of the temperature fluctuations of the cosmic microwave background, of the distribution of clusters of galaxies, of the distortion of the images of background galaxies by the gravitational potential along the line of sight...). Observational cosmology also confronts particle physics with numerous problems. The nature of dark matter, of dark energy, the origin of the matter-antimatter asymmetry, the nature of the inflaton and the space-time cosmological structure, are all questions which physicists are attempting to answer.



Quantum chromodynamics & hadronic physics

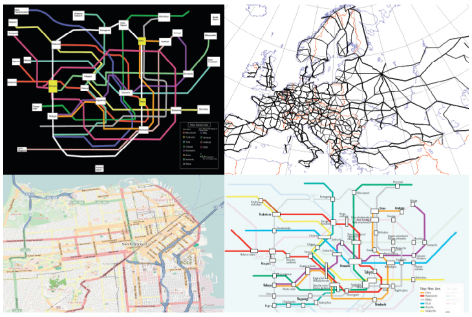
Quantum chromodynamics (QCD) is the fundamental theory that underlies the strong nuclear interactions. It governs the short-distance interactions of quarks and gluons, which are the constituents of protons and neutrons. QCD explains the confinement of quarks and gluons inside these particles. Understanding the strong interactions is crucial to the analysis of data collected by experiments running at the Large Hadron Collider (LHC) at CERN. QCD interactions have the remarkable property of becoming weaker at shorter distances, which allows the use of a perturbative approach to study high-energy processes. Conversely, it becomes stronger at long distances. This strong-coupling regime motivates the study of effective theories, or of related theories with additional symmetry, such as maximal supersymmetry, and of dual string pictures. QCD may also require non-perturbative techniques in situations involving a large number of particles, even at weak coupling. This happens in the wavefunction of a proton or nucleus: the gluon density increases rapidly with energy until it saturates, a situation that can be handled by the so-called ‘color glass condensate’. At high temperatures, nuclear matter undergoes a deconfinement transition to form a quark-gluon plasma. Its properties can be studied in ultra-relativistic heavy-ion collisions at the LHC and at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven.



Statistical physics- Condensed matter

Non-equilibrium & disordered systems

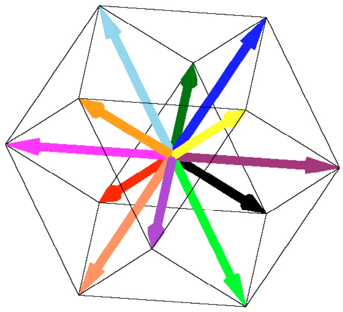
The new frontier in statistical physics is to build a general theory of systems out of equilibrium, continuously evolving with time. No theoretical framework is available that would encompass the physics of systems interacting with their environment through continuous exchanges of charge, spin, energy, or momentum. Yet, in nature, heat and matter fluxes are ubiquitous and systems far from equilibrium are the majority rather than the exception. Artificial devices (complex networks, urban patterns) as well as living matter provide us with prominent examples. The IPhT is a major actor in the study of these crucial issues. A global perspective of time-dependent processes involving a large number of interacting elementary constituents requires elaborate theoretical tools that can be developed using techniques of quantum field theory, conformal symmetries, Schramm-Loewner evolution and integrable systems.



Exact solutions of models far from equilibrium have allowed us to determine rare event statistics and large deviation functions that play the role of nonequilibrium thermodynamic potentials. Sophisticated renormalization procedures, at the level of the configuration space and its dynamics, have been developed to characterize the evolution and phase transitions in random systems (spin glasses, polymers, colloids). All these methods are now applied very successfully to interdisciplinary subjects such as computer science (constraint satisfaction, error correcting codes, analysis of search algorithms) and biology (genetic and evolutionary models). The study of various networks, smart-grids, and their evolution in space and time have fundamental applications in epidemiology and in controlling the spread of infectious diseases. Finally, the quantitative study of geographic and urban networks using the mathematical apparatus of statistical mechanics is a rapidly developing theme that offers a promising cross-disciplinary perspective.

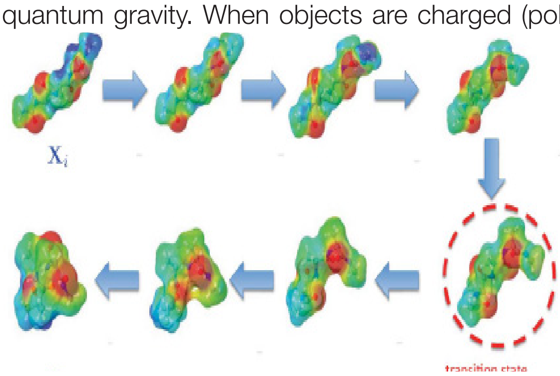
Quantum systems & condenser matter

The physics of condensed matter deals with spectacular quantum phenomena that occur at the macroscopic scale, when the temperature is low enough. Superconductivity, or conduction of electrical current without resistance, superfluidity, or frictionless flow, the Kondo effect, the fractional quantum Hall effect, in which the charge carriers are split as a result of interactions and quantum fluctuations, are examples of these fascinating and remarkable phenomena. Following their experimental observation, these quantum phenomena are studied theoretically by methods of quantum field theory, combined with advanced numerical techniques. These models, defined at the microscopic scale, are still poorly understood at the macroscopic scale when the interactions between the electrons become too strong. Low-dimensional magnets, as well as non-equilibrium systems, are also studied in depth at the Institute.



Soft matter & biological systems

Polymers provide physical realizations of stochastic processes such as Brownian motion or self-avoiding random walks. Other types of stochastic processes control the functioning of molecular motors and the folding of proteins. Some universal aspects of membranes (flexible films, biological membranes) are closely related to the random geometries studied in string theories and quantum gravity. When objects are charged (polyelectrolytes, charged membranes) or possess internal degrees of freedom, their physical and geometrical properties may be deeply modified: new phases may appear. Random polymer physics governs the complex interactions between chemically different monomers in biopolymers. One can study the denaturation of DNA or protein folding and RNA within this framework. For the latter, the classification of folded forms can be done using tools of topology (genus, Euler characteristic), leading to the development of powerful algorithms for structure prediction. In addition, most biopolymers carry charges, and the Coulomb interaction determines their universal properties of aggregation and solvation in the cell.



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From yesterday to today...

In 1947, barely two years after the creation of the Commissariat à l'énergie atomique (CEA), a group of scientists working in the physics and chemistry departments, at the Fort de Châtillon, manifested their inclination towards mathematical abstraction and modeling. For example, Jacques Yvon did not hesitate to study "an infinite planar reactor without a reflector"! Every week, one afternoon was devoted to "pure theoretical physics". In 1950 the group was joined by Claude Bloch and Philippe Meyer, where initial work on neutron physics rapidly expanded to nuclear physics and statistical mechanics.

In 1959 the "theoretical physics team" still belonged to the Service de physique mathématique (part of the Département d'études des piles) which was charged with the task of developing theoretical and numerical models of nuclear reactors. The research team published papers on nuclear physics, the many-body problem and superconductivity. Soon particle physics became a substantial part of the research programme too.

In 1963, the Service de Physique Théorique (SPhT) was created and consisted of about 20 physicists employed by the CEA. From the outset, they were joined by PhD students and, in 1964, by physicists employed by the national research center (CNRS). Soon after it had moved to the Orme des merisiers in 1968, field theory became the major subject of research in the laboratory. In the following decades research developed in the fields of conformal theories, matrix models, nuclear and particle physics, astrophysics, string theory, condensed matter physics, and biological systems.

On January 1, 2008, the Service de Physique Théorique acquired a new status and became the Institut de Physique Théorique (IPhT). To date, more than 500 physicists have worked in the Institute, without counting numerous foreign visitors, among which brilliant post-docs and eminent scientists. The visitors contributed strongly to the scientific activity and they established strong ties with physicists from laboratories worldwide. Building on the success of the Institute, many of its researchers have reached out to prestigious universities and laboratories in France and abroad.

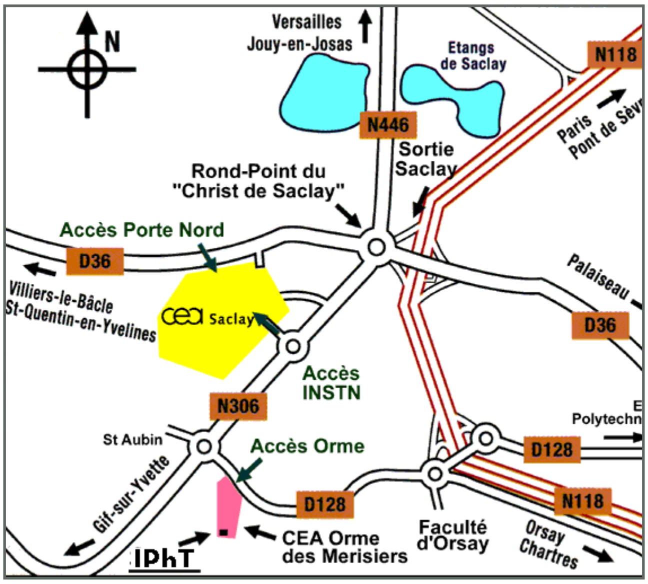
The output of the Institute includes over 11000 publications, about 150 books and over 250 PhD thesis and habilitations. In addition to this, there is the production, the organization and scientific animation of international meetings and seminars, as well as numerous summer schools (notably, the IPhT has played a key role in the development of the Ecole des Houches). Following a tradition established by A. Abragam, C. Bloch, A. Herpin, A. Messiah and M. Trocheris, researchers of the IPhT give lectures in laboratories and universities both in France and abroad, as well as in the Grandes Ecoles (Ecole normale supérieure, Ecole polytechnique,...). Lessons are given on the YouTube channel IPhT-TV. A fair number of these lectures have become classical reference books, namely those of Messiah, Mehta, Gaudin, Itzykson-Zuber, Itzykson-Drouffe, Des Cloizeaux-Jannink, Blaizot-Ripka, Negele-Orland, Zinn-Justin, Balian, Di Francesco-Mathieu-Sénéchal, etc.

Throughout its history, the research carried out at the Institute has been awarded over one hundred scientific distinctions, including foreign awards, like CNRS medals, and numerous awards from the Academy of Sciences and the French Physical Society. Members of the IPhT have served or serve in national academies in France and abroad. A lot of members of the IPhT have been winners of European Council grants (ERC).

Within the CEA, the IPhT is attached to the Direction de la Recherche Fondamentale (DRF) with one third of its workforce belonging to the CNRS, the IPhT became URA (Associated Research Unit) then the UMR (Joint Research Unit) 3681 of the National Research Center, thereby strengthening its ties with this institution. The Institute also hosts academics and researchers from other laboratories and participates in several networks of the European Community and in international exchange programmes through which it develops collaborations with foreign physicists.

Although it was not originally planned when the CEA was created, the Institut de Physique Théorique developed because first its members, and shortly later the administration of the CEA, felt that it was needed. The key of its success lies in the unpredictable convergence of new ideas and in the multi-disciplinary research pursued there for more than 50 years.

By RER



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