LAWS OF PHYSICAL SYSTEMS

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Summary

In this chapter an overview of physical systems and laws is presented. The structure of the related chapters allows us to see two broad tendencies in the subject: reductionism and emergent phenomena. After a brief description of the reductionism and emergent phenomena trends in physics, their confrontation and implications, we describe briefly the content of the related chapters and how they fit into this context. The topics of all these contributions are found to be part of a kind of unified theories; thus a description of how they enter in these theories is also discussed. Basic ingredients of these unified theories, as different processes in particle physics and general relativity and the necessity to quantize general relativity, are also introduced and a description of the two principal proposals for a quantum theory of gravity, namely string theory and loop quantum gravity is given. Finally, several examples of collective emergent phenomena are also outlined.

1. Introduction

A central philosophical concept that has pervaded our way of thinking in understanding physics is *reductionism*. The search for the most elementary ingredients that constitute our Universe and the basic laws governing their fundamental interactions seek to understand and explain complicated phenomena from more basic science describing their simpler component parts. It is a matter of our conception of the structure of Nature itself. In fact it is a way as physics progresses. The conciliation of conflicting theories always gets into new and interesting understanding of Nature. Relationship between celestial and terrestrial motion of bodies due to Newton and the synthesis of electricity and magnetism due to Maxwell, are classical examples.

In the framework of this reductionism tendency one would believe that *emergent phenomena* like superconductivity or superfluidity, for example, have to be addressed in their own terms, not by reduction to the laws governing the fundamental interactions. But when we learn to know the solution to this problem, it will have a structure that can be obtained from basic physical theories like electrodynamics and if we try to understand the reason for the structure of the equations governing these phenomena, we will find the answer, through many intermediate steps, in the laws of the fundamental interactions, thus of elementary particles, and/or the theory of gravitation and cosmology or perhaps in theories that could be even more general and fundamental like the theory of superstrings.

It has, however, been argued that there is another philosophical point of view and it is that there is a *principle of emergence* at every level. Emergence is to be understood as the process by which our biological and social world has developed from its physical substrate. Everything we observe emerges from a more primitive substrate; that is, by obeying the laws of the more primitive level, but not conceptually consequent from that level. Nuclear physics, by example, is assumed to be consistent with QCD (Quantum Chromodynamics), yet it has not even been reduced to QCD. A hierarchical structure then exists, and from this philosophical point of view structures, like the standard model or the laws of chemical bounding or molecular biology, break the chain of reductionism and make further investigation into the underlying laws somewhat irrelevant to higher levels of organization.

A profound philosophical debate exists with some arguing that the principle of emergence at every level is more pervasive in our understanding of the Universe than any possible "fundamental brick" representing a hypothetical milestone in the reduction to even simpler and more abstract laws in the dynamics of subatomic particles. Others will say that the phenomena in chemistry are as they are because the quantum properties of the electrons, atoms, electromagnetism and the different types of atomic nuclei; in biology, the mechanism of heredity which drives biological evolution has been understood in molecular terms and no one would believe today in autonomous biological laws. These two philosophical approaches have influenced our way to understand and discover the physical principles underlying our theories. They also have had an important influence on the way physics has been supported. The reductionism point of view is more related with what has been called big science which is related with very large and expensive projects. The principle of emergence is more connected with small science, projects that in general do not require a large investment and are worked out by many research groups.

It is not the central purpose of this chapter to discuss and analyze the mentioned debate among the concepts of reductionism and emergence. However, it seems to be useful to have them in mind when analyzing the concepts, principles and laws in the different theoretical structures in physics. Essentially, concepts in the first three chapters under this topic have more to do with the principles and laws that govern the most elementary components of our Universe and therefore they are in the realm of the philosophical concept of reductionism. Some of these laws and principles are used in the next three chapters to construct new structures and laws. But also concepts and laws at a different hierarchical level are an essential element of these theories. So, the principle of emergence seems to be more related with the theoretical framework of these second three chapters.

The six chapters that integrate this topic cover the fundamental concepts, the theoretical framework and experiments in each of these fields and also deal with current research in diverse interesting topics. In the following we will divide this presentation in two parts, including the first three articles and the second three articles respectively. As we have mentioned these two groups of articles seem to be related to different conceptions of our understanding of physics.

On the other hand, we will first present some general aspects that have to do with each one of the related chapters. In particular, with respect to the first group of chapters, at the end, we will emphasize how Quantum Mechanics and General Relativity are incompatible and the efforts to understand them in a coherent way; we will mention the two main ideas to deal with this problem namely: Loop Quantum Gravity and String Theory. In these theoretical proposals, in particular in String Theory new and interesting symmetries emerge, the theme of the first chapter in the first group.

In the following we will proceed with the mentioned first part dealing with the concepts, theory and experiments already described in the first group of articles. We will pay attention to the ideas mentioned above that intend to relate and make compatible the fundamental theories described in these three chapters. The second part will be devoted to emphasize particular aspects and to cover in a broad manner the content of the second three chapters.

2. Concepts, Theory and Experiments

Symmetry is a fundamental notion in physics; this concept was already present in Greek philosophy. Conservation Laws follow from the symmetries in nature. They arise in classical physics, quantum mechanics, Galilean and special relativity and in general, in quantum field theory where the standard model of elementary particles is an example. Symmetries also appear in the general theory of relativity. The physical laws have a structure that must be invariant under symmetry operations. Thus each type generator of a symmetry has an associated conservation law. Symmetries restrain the form the laws of physics can take and are in this sense more fundamental. As explained in the chapter on this theme, there are four main kinds of symmetries (or broken symmetries), namely, space-time symmetries, internal symmetries, discrete symmetries and permutation symmetries. Continuous space-time symmetries are divided into *global* and *local* symmetries. In global symmetries, the transformations are the same at each point of the space-time. For the local symmetries, the transformation depends on the point of space-time and can be different for each point. For local symmetries of space-time, for instance the conservation of linear momentum is a consequence of space translations, angular momentum conservation will be related to the invariance under space rotations. Also the mass-energy conservation, in relativistic physics, follows from the fact that the physical laws are invariant under time translations; they generally depend upon time but not upon a particular time at which we apply them. There are also discrete symmetries such as parity symmetry, conjugation by changing particle with its antiparticle and time reversal. These symmetries are very important when quantum mechanics is taken into account. Unitary symmetries are very important for describing the conservation of baryonic and leptonic charges. Finally, permutation symmetries appear in statistical physics and are relevant in the Bose-Einstein and Fermi-Dirac statistics.

In classical physics as well as in relativistic and quantum physics a Lagrangian functional can be defined. In classical mechanics this functional is the kinetic energy minus the potential energy. As this physical system evolves in time, one can imagine that the system progresses along a particular evolutionary path. This particular path among other possible ones, the so called classical path, will provide the smallest sum of the Lagrangian functional having been measured at each point of the path. The Lagrangian functional is a powerful tool which allows to get the equations of motion governing the phenomena corresponding to a particular physical theory. But also important is to know the dynamical behavior of the theory as well as to get the associated conservation laws. For classical, relativistic and quantum physics, certain symmetries are already present in the way we build this Lagrangian functional, and we learned from Emmy Noether how to obtain from it its associated conserved quantities.

In quantum physics, in the standard model of elementary particles, as well as in theoretical models proposed that include gravity just as in string theory, there are symmetries that are not relevant at the classical level like the discrete symmetries mentioned. These symmetries and their corresponding conservation laws are, in general, in a range of validity of the theories and have associated quantum numbers.

Formally the discrete symmetries are associated with *finite groups* while unitary symmetries are associated mathematically with *Lie groups* and *Lie algebras*. They are part of the structure of the Lagrangian functional under interest and they provide important conserved quantities, as will be seen in *Symmetry Principles and Conservation Laws*.

The standard model possesses all the information of the symmetries associated with the elementary particles and it is up to today the most concise, precise and elegant picture we have got. Nevertheless, we know the forces and particles that produce them (fermions) and carries them (bosons), the underlying reasons for some of our observations have, however, not been found. The fermions that produce the forces, *quarks* and *leptons* appear with increasing mass and are organized in three generations. The mass of the neutrinos is quite negligible compared with that of the other fermions.

Nowadays certain models have been constructed and we have an understanding of how electromagnetic and weak interactions are unified into an electroweak theory (also called Glashow-Weinberg-Salam model). We also have learned how the electroweak (electromagnetic and weak) and strong forces should be unified at high energies. Today it is still not understood how the weakest force of Nature, gravity, should fit into this unification picture, apart, probably from the string theoretical proposal.

Experiments should illuminate the most compelling questions. In the standard model the Higgs boson is a necessary element to have a self-consistent and predictive theory. It is through the Higgs mechanism that the masses of the particles are generated. It is expected that the Higgs boson will be detected in the Large Hadron Collider (LHC) at CERN on the Swiss-French border. These results are expected around the year 2010. If the Higgs boson would fail to appear, we may have an exception that will produce confusion and an effort to understand this unexpected situation should be performed.

In a series of recent experiments we have learned that neutrinos have tiny masses, a new generation of experiments is determining the properties of neutrinos and attempting to understand how they fit into the big picture. Antimatter has very similar properties to those of matter, but matter and antimatter annihilate each other to liberate energy. One would think that the Universe has been created with equal quantities of matter and antimatter, but antimatter exists in our Universe only in very small amounts. Why this remarkable asymmetry exists in our Universe is completely baffling. Clues to an explanation of this asymmetry may come from tiny differences between the properties of matter and antimatter and also might be explained from a fundamental theory beyond the standard model like string theory.

An existing new and very natural proposed symmetry is *supersymmetry*, which implies that each fermionic degree of freedom is associated with a bosonic degree of freedom and vice versa. In general terms this symmetry allows particles with different spin statistics to be related. Some calculations in the so called minimal supersymmetric standard model indicate that there is a chance to detect low energy supersymmetry also in the LHC. Its discovery would be a tremendous experimental result and an indication in favor of the consistency of superstring theories. Also, it might be related to the possibility that our Universe may have spatial dimensions beyond our familiar three may be tested in the short term in collider experiments. Besides, supersymmetry is a natural extension of the Poincaré symmetry group which is the basis of the special theory of relativity and therefore is also space-time symmetry and constitutes a natural extension of the proper space-time to the so called *superspace*. The superspace is an extension of the space-time by considering some new quantum coordinates θ which anticommute. The excitations of the fields in these extra dimensions will provide the superpartners which are expected to be discovered in the forthcoming colliders generation at CERN.

Even though superstring theory is up to today only a consistent and elegant theoretical framework, new and interesting symmetries and dualities emerge in its context and we will mention later some of them. Interesting dualities have been discovered by means of which distinct descriptions of the same physical phenomena provide complementary physical views and mathematical methods to analyze the physical problem. *S*-duality is a symmetry that appears in string and field theories with certain degree of supersymmetry and relates the theory $\mathcal{A}$ "weakly" coupled with the "strong" coupled limit of the same theory $\mathcal{A}$ or another dual theory $\mathcal{B}$. The former case is less usual and it is called, the self-dual case. The latter situation which relates different limits of two different theories is more common. Already in electromagnetism the electric charge appears as a coupling constant multiplying the Lagrangian in terms of the original variables. There are no isolated magnetic charges, monopoles. However, by considering them, P.A.M. Dirac observed that a partner (dual) Lagrange function in terms of the dual variables can be written in electromagnetism where the multiplying charge is that of the monopole and more interestingly, this charge is essentially the inverse of the electric charge. In an elegant way, different proposed string theories can be related among them by a web of dualities. In particular if, in one of them, the coupling constant g_S is lower than unity, we can in principle apply the usual perturbative methods to get physical information and through *S*-duality have also information of the "strong" coupled counterpart of the dual theory. String theory has also another symmetry called *T*-duality. This is a perturbative symmetry of the underlying conformal field theory. For closed strings this symmetry is reflected in the target space where the string is propagating as an identification of a description of large *R* and small 1/*R* typical sizes of the compact dimensions of the target space. On the worldsheet level this symmetry is realized because winding and Kaluza-Klein modes of a string are interchanged. Under this interchange, the observables of the theory and the interactions are unchanged. This is valid at each order in perturbation theory.

Superstring theory is mathematically consistent in 10 dimensions and by making compact the extra six dimensions in the so called Calabi-Yau spaces. These spaces are characterized by their size and shape, which give rise to the moduli space of Kahler and complex structures. They can have different topology, like a multi-handed doughnut; the holes are related with the number of families of leptons and quarks we will get. Mirror symmetry relates two different Calabi-Yau spaces, to give rise to identical physics of the underlying string theories.

On the side of cosmology, as stated in the related chapter, in the last decade more precise observations have been performed as the cosmic microwave radiation, galaxy distributions and distant supernovae. The fluctuations of the cosmic microwave radiation, tiny deviations from the black body radiation temperature in each point of the sky have been detected by the COBE satellite (Cosmic Background Explorer). Anisotropies provide us with information on the very early Universe and they can be understood through linear perturbations of Einstein's equations in general relativity. More recently the observations of the WMAP satellite (Wilkinson Microwave Anisotropy Probe) have improved greatly the resolution of the anisotropies of the background radiation.

The knowledge of the intrinsic luminosity curve of the supernovas type Ia has allowed us to use these luminous objects as standard reference and to follow the expansion of the Universe through ten thousand million of years. By these means Hubble diagrams (those that Hubble himself constructed to discover the expansion of the Universe) have been constructed with an extraordinary precision. These observations seem to indicate, in the framework of general relativity and the simplest cosmological models (those known as Friedman-Robertson-Walker models), that the geometry of our Universe is the corresponding flat Universe. Moreover, baryonic matter (the one described by the standard model) is only about 4% of the material content of the cosmos. The rest 96% is an unknown kind of matter that our present knowledge of physics can not describe. From this about 21% of this matter is generally known as *dark matter*. More surprising is the fact that about 75% of this unknown matter seems to behave as the cosmological constant introduced by Einstein himself in his original equations and is known as *dark energy*. There are other cosmological observations that support the conclusions reached by the cosmic background radiation and the supernovae type Ia observations, clusters of galaxies, gravitational lensing, Lyman-α, etc. Observational cosmology is a very active field that provides us with the possibility to construct more realistic models of the Universe we live in.

The discovery of the anisotropies of the cosmic background radiation suggested the proposal of a highly isotropic but inhomogeneous (the expanding radius of the Universe depends on space and time) Universe as a necessary initial condition for the formation of the cosmological structure. Assuming the philosophical point of view that our Universe was born with highly probable initial conditions and not necessarily particular ones, a period of inflation has been proposed in order to have the seed that produced the structure formation.

In the center of many of the galaxies we observe today, it appears that very massive and compact objects exist and it seems that they can be possibly black holes. The detection of an event horizon is still, however, away from our observational capabilities.

The possible detection of gravitational waves produced by supernovas or collisions of very massive objects like neutron stars or black holes is a very active field. Very precise optical interferometers (LIGO,VIRGO,GEO600, etc.) are being used in various experiments on the Earth; also interferometers in space are going to be used (LISA).

A series of proposals based on different possible theoretical approaches have emerged in the last ten years, they include the possibility of violating the Lorentz symmetry. Thus, the element of distance in space-time that appears in *Special and General Relativity* would be modified. There are various motivations to believe that this could happen, for example loop quantum gravity, one of the main proposals to try to describe quantum gravity, predicts the possibility of Lorentz violations. Also Lorentz violation will happen if the space-time coordinates do not commute — an old proposal in theoretical physics and that arises also from string theory.

It has also been considered that the known physical constants could vary in space-time. These ideas began many years ago by considering the physical constants and by noticing that their combinations result in numbers without units. However, the gravitational constant does not play the same role as the others and it was proposed that it varies with time. Recently, even the fine structure constant that is essential to the spectra we observe and the velocity of light, the same for all initial frames; have been considered in various models as varying functions. All these models are phenomenological proposals and a consistent theoretical picture is still not at hand. Observation and experiments in this respect have been, however, proposed.

Quantum mechanics is one of the most fundamental pillars we have in physics. It is said that more than 25% of the devices we use daily, work utilizing some quantum mechanical principle. Its consequences reach every corner of our understanding and theoretical structures we know today. Most of its richness is discussed in *Quantum Mechanical Laws*.

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