PHILOSOPHY AND 20^TH CENTURY PHYSICS

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INTRODUCTION

The celebration in 2005 of the centennial of the "miraculous year" during which Einstein produced his articles on the energy quanta, on the Brownian motion and on restricted relativity has provided an opportunity to draw up a comprehensive assessment of the contribution of 20th century physics to human knowledge. One must recognize that this contribution is impressive. Contemporary physics has made available what is known as the *standard model,* namely, a set of *effective theories* that, with the help of a finite set of adjustable parameters, lead to an acceptable agreement with all experimental or observational data on the microscopic structure of matter and on the evolution of the universe.

The study of the microscopic structure of matter is the objective of the physics of elementary particles and fundamental interactions. This part of physics is the heir of the atomistic conception of ancient Greek philosophers, according to which all the various forms of matter are determined by the combinatorial arrangements of huge numbers of infinitesimal, irreducible constituents that exist in a small number of different species, and, as such, it has far reaching philosophical implications. In this domain, the standard model consists, on the one hand, of quantum Chromo Dynamics (QCD), the theory of the strong interactions of *quarks* and *gluons*, and, on the other hand, of the *electroweak* *theory* of the electromagnetic and weak interactions of quarks, *leptons*, *intermediate* and *Higgs bosons*. The theoretical framework of this part of the standard model is the *quantum theory of fields*[1] that realizes the merging of quantum physics and restricted relativity.

The study of the universe as a whole is the objective of cosmology, a domain that, until recently, belonged rather to philosophy than to science. It is not the least merit of 20th century physics to have provided this domain with a scientific basis through Einstein's theory of general relativity[2]. This theoretical framework has made it possible to put together the observational data in a cosmological standard model, the so-called *big bang* model.

The standard models of particle physics and of cosmology both involve a time-energy relation: in particle physics that belongs to quantum physics, this relation is a consequence of the Heisenberg inequalities stating that the product of indeterminacies on the measurement of time and space variables and those on the measurement of energy and momentum variables is bound to be larger than the quantum of action equal to Planck's constant $\hbar$; in cosmology, according to the big bang model, the universe is expanding, diluting and cooling after an initial singularity, the big bang, when it was infinitely dense and hot; in its primordial state, the universe is modeled as a homogeneous fluid the temperature of which, namely the average kinetic energy of its constituents, decreases as the inverse of the square root of the time elapsed since the big bang. Due to this circumstance, particle physics and cosmology acquire, through their convergence, a fascinating temporal dimension: exploring the world of the infinitely small with a high energy probe amounts to simulate, in the laboratory, the conditions prevailing in the primordial universe, at a time after the big bang when the temperature corresponded to the energy of the probe. The representation of the universe that the standard models of particle physics and of cosmology are offering us is one of a universe in evolution, in becoming, from a primordial phase when all interactions and particles were unified to the state in which it can now be observed through a long sequence of phase transitions in which interactions differentiate, particles acquire their

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[1] For a text-book intended for physicist, see Weinberg, 1995 (foundations) and Weinberg, 1996 (modern applications); an interpretive introduction to quantum field theory is given in Teller, 1997

masses, symmetries are broken, new structures form, new states of matter emerge. In this exploration one has to rely on the methods of statistical physics, a domain in which important philosophical questions arise. In any case, again, physics is getting a foothold in a domain that *par excellence* belongs to philosophy, namely *cosmogony*[3].

The objective of the present chapter is to present to a public of philosophers of science the philosophical implications of 20th century physics as a physicist understands them. We shall have to discuss the fundamentals of the theoretical framework of the standard model in connexion with some philosophical issues concerning reality, objectivity, causality, and completeness, arrow of time, reductionism, and determinism. For this discussion we shall rely heavily on the contribution of Einstein not only because he has initiated almost all the developments of 20th century's physics, but also because his epistemological[4] writings, including his acute criticism of quantum physics provide very useful guiding lines for those who want to understand the philosophy of contemporary physics. We shall first recall the program of *rational mechanics* whose aim was to comprehend the whole of physical reality in terms of the motion of material objects in space and time, and that developed from the works of Newton to the apogee of the end of the 19th century. We shall then describe the *deep conceptual crisis* this program went through at the beginning of the 20th century, and then explain the very profound *transformations of the conceptual basis* of physics called for by this crisis and validated by the successes of the standard models. It is this validation by the confrontation of theory and experiment that enables us to reach a reliable understanding of the philosophical implications of modern physics. At the beginning of this chapter I wish to apologize for some technicalities in the following developments that may seem hard to follow for a non-specialist: indeed I believe that the price to pay for this reliable understanding is to be at least aware of the real stakes of the conceptual developments that led to the current achievements.

The problems encountered by the founders of contemporary physics were extremely difficult because of their far-reaching philosophical implications. To solve these

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[2] Einstein, 1916
[3] Lemaître, 1946
[4] Paty, 1993

problems, physicists could not and did not want to rely on any philosophical system, because the very adherence to a system would have restricted the field of possibilities in the search for a way out of the conceptual crisis they were confronting. This attitude toward philosophical systems, which I shall adopt in the present chapter, is very well-expressed by Einstein in his “Reply to Criticisms”, included in *Albert Einstein: Philosopher-Scientist*:

> The reciprocal relationship of epistemology and science is of noteworthy kind. They are dependent upon each other. Epistemology without contact with science becomes an empty scheme. Science without epistemology is — insofar as it is thinkable at all — primitive and muddled. However, no sooner has the epistemologist, who is seeking a clear system, fought his way through to such a system, than he is inclined to interpret the thought-content of science in the sense of his system and to reject whatever does not fit into his system. The scientist, however, cannot afford to carry his striving for epistemological systematic that far. He accepts gratefully the epistemological conceptual analysis; but the external conditions, which are set for him by the facts of experience, do not permit him to let himself be too much restricted in the construction of his conceptual world by the adherence to an epistemological system. He therefore must appear to the systematic epistemologist as a type of unscrupulous opportunist: he appears as realist insofar as he seeks to describe a world independent of the acts of perception; as idealist insofar as he looks upon the concepts and theories as the free inventions of the human spirit (not logically derivable from what is empirically given); as positivist insofar as he considers his concepts and theories justified only to the extent to which they furnish a logical representation of relations among sensory experiences. He may even appear as Platonist or Pythagorean insofar as he considers the viewpoint of logical simplicity as an indispensable and effective tool of his research[5].

THE PROGRAM OF RATIONAL MECHANICS

The general program of mechanics known as *rational*, initiated by the works of Galileo and Newton, marks, in the aftermath of the Renaissance, what one can call the birth of modern science. This program consists in trying to reduce the whole of physics to mechanics, i.e. to the study of the motion of material objects in space and time. The two basic concepts of the program of mechanics are the *material point* and the *force*, starting points of the two roads that lead to the current physical concepts of *elementary particle* and *fundamental interaction*. The concept of material point is a sort of asymptotic concept: it corresponds to the simplest material object the motion of which in space and time can be determined according to the program of mechanics. It obviously corresponds to the atomistic intuition of elementary, point-like, structure-less

[5] Einstein, 1949, in Schilpp 1949, p. 683-684

constituents of matter, which implies that eventually the program of mechanics will converge with the atomistic conception of the world. The concept of force, on the other hand, is somehow the blind spot of the program. In fact, in rational mechanics, forces are supposed to be given, they are not the object of any theoretical derivation, to use a common terminology, "they are put by hands" (*"hypotheses non fingo"* says Newton), they can act instantaneously at a distance. In mathematized mechanics, forces are often taken as deriving from a *potential*. The program of mechanics can then be reduced to the two following reciprocal questions:

- Given a system of material points, and some forces, what motion do these forces induce for the system of material points (provided that the initial conditions are fixed)?
- Given the motion of some material points, what are the forces that have given rise to this motion?

The immense success of the program of mechanics, in particular when it was applied to the motion of planets, is incontestably due to the effectiveness of its mathematical method. Newton is indeed the founder, at the same time as and independently of Leibniz, of what one now calls the differential and integral calculus, which enabled him to develop the mathematical formalism of mechanics. Under the action of the continuators of Newton, like Euler, Lagrange, Hamilton and Jacobi, rational mechanics, developed considerably, and reached, at the end of the 19^{th} century a true apogee. It is interesting to note that in spite of the crisis it went through at the beginning of the 20^{th} century, the ambition of mechanics remains a true guiding principle of research in contemporary theoretical physics.

Intended at the beginning to account for the motion of simple material points, mechanics immediately tackled the description of the most general motions affecting material objects of any kind. After the material point, the simplest object that one can consider is the rigid solid body, the motion of which is split into the translation motion of its centre of mass, and a rotational motion around this centre of mass. Mechanics extends then to the dynamics of fluids, which one decomposes by thought into infinitesimal cells comparable to material points. It thus appears that with the concepts of material point and force, mechanics has vocation to extend to the description of the sum total of all physical phenomena, provided that one carries out the extension of its applicability to phenomena like light, electricity, magnetism or heat.

Such an extension of mechanics obviously required empirical or experimental explorations but also the significant improvements of the formalism of mechanics that one owes to the above-mentioned continuators of the work of Newton. Lagrange thus revolutionizes mechanics by axiomatizing it in what he calls *analytical mechanics.* He unifies mechanics mathematically, by establishing a formal framework making it possible to solve all the problems of mechanics, including statics and dynamics, for solids or fluids. This reformulation of mechanics ascribes a central role to the concept of energy, which one splits up into kinetic energy and potential energy; the equations of motion are derived from the *principle of least action* that had been postulated in a heuristic way by Maupertuis, and was formalized in a rigorous way by Euler, Lagrange and Hamilton. The interest of this formulation of mechanics is due to its systematic nature: it provides a genuine methodology, comprising strict rules, which it is enough to observe rigorously to derive the equations of motion for any material system. As this methodology remains, in spite of certain adaptations and generalizations, at the heart of contemporary physics, it is worth taking some time to discuss its mains concepts and moments.

A degree of freedom is a parameter, depending on time, that enters the definition of the position of a material object in space. A material point, for example, depends on three degrees of freedom, its three co-ordinates in a certain reference frame, and thus a system of N independent material points depends on 3N degrees of freedom. A fluid (liquid or gas) is a system depending on an infinite number of degrees of freedom, co-ordinates of the infinitesimal cells of which it is made up and that are comparable to material points. The state of a fluid can then be defined using one or several functions of these co-ordinates, which is called a *field*. As systems depending on an infinite number of degrees of freedom, fields can thus in principle be integrated into the program of mechanics. Let us note however that, at this stage, the concept of field is not a primitive concept: it is a secondary concept making it possible to account for the state of a given complex material system.

The state of a system depending on N degrees of freedom is represented by a single point, the coordinates of which, in an abstract space with N dimensions called the *configuration space*, are the N degrees of freedom. For such a system, the program of rational mechanics consists in determining, using the equations of motion and the initial conditions, the trajectory of the point representing the system in the configuration space.

The Lagrangian formulation of mechanics consists in making the equations of motion derive from a *variational* principle, known as the *principle of least action*. In mathematical terms, this principle stipulates that the trajectory followed in the configuration space by the point representative of a system is the one that minimizes a certain integral, called the *integral of action*, the integral over time of a function called the Lagrangian. This Lagrangian, which has dimensions of energy, is, for the simplest mechanical systems, equal to the difference between the kinetic energy and the potential energy.

The Lagrangian formulation of mechanics relies on the powerful variational method that consists in elucidating the dynamics of a physical process, in considering the whole set of ways the process can *virtually* follow and in establishing a criterion making it possible to determine the one *actually* followed.

Another advantage of the Lagrangian formulation is that it highlights particularly well the coordination between *relativity*, properties of *symmetry*[6] and *conservation laws*. The Galilean principle of relativity is the true foundational principle of all mechanics, because it plays an essential role in allowing an objective approach of physical reality: are objective those aspects of reality that are maintained when one changes the reference frame, i.e. when one changes the point of view from which this reality is observed. Still it is necessary to define what "is maintained" when the change of reference frame takes place. One then has recourse to two narrowly connected concepts: on the one hand *invariance* (or *symmetry*), i.e. the fact that the equations of motion do not change when one carries out certain transformations and on the other hand the *conservation* in the course of time of certain quantities. The Lagrangian formulation of mechanics makes it possible to establish a fundamental theorem, due to

[6] The basic reference about symmetry is Weyl, 1952; a pedagogical presentation of symmetry is given in Rosen, 1995

Emmy Noether, that mathematically gives an account of this coordination: with any property of relativity is associated a certain symmetry of the Lagrangian, i.e. a certain invariance of the Lagrangian with respect to certain transformations, and the law of conservation in the course of time of certain quantities. In mechanics, the theorem of Noether applies

- to the relativity of time, coordinated with the invariance with respect to time translations and the conservation of energy,
- to the relativity of space, coordinated with the invariance with respect to space translations and the conservation of momentum
- And to the isotropy of space, coordinated with the invariance with respect to rotations and the conservation of angular momentum.

THE CRISIS OF MECHANICS

Thanks to the improvement of its formalism, analytical mechanics reinforced the hope that one can base on it a scientific conception able to account for the whole realm of observable physical phenomena. But in order for this prospect to take shape it was necessary to widen its field of application to phenomena that hitherto seemed to be foreign to it. The extensions of mechanics fall into two main categories with regard to its two basic concepts, the material point and the force. In connection with the concept of material point are the phenomena that could be integrated into mechanics thanks to the atomistic assumption, like heat phenomena, thermodynamics, and even chemistry. In connection with the concept of force are the electric and magnetic phenomena that the electromagnetic theory of light developed by Maxwell made it possible to associate with optical phenomena. Essentially, these extensions of mechanics were achieved by 20th-century physics, but only at the price of completely restructuring its foundations.

At the beginning the crisis was signaled by a few very specific and academic problems, namely some phenomena that one was unable to quantitatively explain by means of the available mechanistic or mechanistically inspired models. To these puzzles belong the photoelectric effect that did not fit in the framework of Maxwell's theory of electromagnetism; the advance of the perihelion of Mercury, an effect disagreeing with the predictions of Newton's theory of gravitation; the specific heat of poly-atomic substances that challenged Maxwell's kinetic theory of matter, which aimed at unifying mechanics with the atomistic conception; the spectrum of black body radiation, which could not be described with the tools of thermodynamics and electromagnetism. The crisis was also fuelled by some unexpected experimental discoveries like those of X-rays by Roentgen in 1895, of the electron by Thomson in 1897, and of radioactivity by Becquerel in 1896 and Pierre and Marie Curie in 1898. The discovery of radioactivity was the most intriguing one, since, although it suggested that atoms actually exist, it also suggested that they are not eternal and that they can undergo a change of species through a transmutation process.

In addition to the above-mentioned puzzles and discoveries, the program of rational mechanics was confronted with some conceptual questions that led it to a state of crisis. This crisis concerned the three domains of statistical, relativistic and quantum physics that we are going to review in the following sections.

STATISTICAL PHYSICS AND THE PROBLEM OF THE REALITY OF ATOMS

One can attribute to Carnot the foundation of theoretical thermodynamics: in an almost unnoticed work of 1824, *Reflexions on the Motive Power of Fire*[7], he makes the assumption that heat is a fluid, and starting from an analogy between the power of heat and that of a waterfall, he establishes what one can regard as the origin of the second principle of thermodynamics. To give rise to the power of heat, one needs a difference in temperature between a hot body and a cold body, and the output of any heat engine is necessarily lower than 1 (the maximum output is equal to the ratio of the difference in temperature to the highest temperature). But, in 1831, he questions the assumption of the heat fluid and a little further he states what is nothing but the first principle of thermodynamics (stated after the second one!), the principle of conservation of energy.

[7] *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*

The complete formalization of thermodynamics is the work of Clausius who states in a clear way the two principles of thermodynamics: the first expresses the conservation of energy and the second one expresses, in terms of the increase of *entropy*, the impossibility of perpetual motion of the second kind (which would consist in producing work starting from only one heat source). The tendency of heat to pass in an irreversible way from hot bodies to cold bodies is explained by this second principle. After the work of Clausius, thermodynamics seemed a well-established theory, but its relations with mechanics were not clear. If energy seemed to lend itself to a mechanistic interpretation, other concepts of thermodynamics like pressure, temperature, or entropy did not seem to be easy to integrate into the framework of mechanics. It is thanks to the atomistic conception of matter and with the recourse to *statistical methods* that the synthesis of thermodynamics and mechanics took place through the *kinetic theory of matter* and *statistical thermodynamics* developed by Maxwell and Boltzmann.

The kinetic theory of matter made it possible, thanks to statistical methods, to determine some characteristics of the hypothetical constituents of matter called atoms or molecules, and to begin connecting the physical quantities of thermodynamics to the concepts of mechanics. A link is thus established between the microscopic laws of the elastic collisions of molecules and the first principle of thermodynamics, established at the macroscopic level, that of the conservation of energy. Temperature is interpreted in terms of molecular agitation: it is proportional to the average kinetic energy of the molecules, namely half the product of their mass by the average value of the square of their velocity. The proportionality factor is Boltzmann's constant k. It is Boltzmann who completes the synthesis of thermodynamics and mechanics by establishing a mechanistic interpretation of entropy at the basis of the second principle: Boltzmann's constant acts as a proportionality factor between the entropy S and the logarithm of the number W of microscopic configurations, called *complexions*, giving rise to a given macroscopic state, $S = k \mathrm{Ln} W$. Entropy thus gives a measure of the disorder that tends to increase with time for an isolated system, and the second principle of thermodynamics accounts for the fact that, insofar as randomness is at work, it is likely that a closed system presenting a certain order will go towards disorder, which offers so many more possibilities[8].

In a conference intended for a wide audience, under the title "Molecules", Maxwell presented the recourse to the statistical methods as a makeshift to which we are constrained due to the imperfection of our means of knowledge and observation: "Thus molecular science teaches us that our experiments can never give us anything more than statistical information, and that no law deduced from them can pretend to absolute precision[9]." To reach a world "where everything is certain and immutable", Maxwell said it is needed to pass "from the contemplation of our experiments to that of the molecules themselves, to leave the world of chance and change." This marks a severe conceptual difficulty: if molecules do exist, they are so small that they will never be observable and our knowledge about them will always be based on statistical assumptions, i.e. incomplete. This difficulty led some philosophers or physicists like Mach and Oswald to adopt a positivistic stance and to reject the atomistic conception. The way out of this difficulty required, on one hand, providing statistical methods with a more solid theoretical ground and, on the other hand, discovering ways of making atoms or molecules experimentally observable.

At the very beginning of the 20th century, in 1902 precisely, it appeared, through the work of Gibbs and once again of the very young Einstein[10], that statistical methodology is not necessarily a makeshift but that its range is perhaps fundamental and universal. In the foreword of his *Elementary Principles of Statistical Mechanics*, Gibbs explains the major shift of point of view he proposes for the recourse to statistical methods:

> We may imagine a great number of systems of the same nature, but differing in the configuration and velocities which they have at a given instant, and differing not merely infinitesimally, but it may be so as to embrace every conceivable combination of configuration and velocities; And here we may set the problem, not to follow a particular system through its succession of configurations, but to determine how the number of systems will be distributed among the various conceivable configurations and velocities at any required time, when the distribution has been given for some one time[11].

[8] For a pedagogical discussion see Gell-Mann, 1994
[9] Maxwell, 1873
[10] For a discussion of the contributions of Gibbs and Einstein to the foundations of statistical physics, see Barberousse, 2002
[11] Gibbs, 1902, p. xii -ix

The advantage of so proceeding is that, as Gibbs says a little further:

> The laws of statistical mechanics apply to conservative systems of any number of degrees of freedom, and are exact. This does not make them more difficult to establish than the approximate laws for systems of a great many degrees of freedom, or for limited classes of such systems. The reverse is rather the case, for our attention is not diverted from what is essential by the peculiarities of the system considered, and we are not obliged to satisfy ourselves that the effect of the quantities and circumstances neglected will be negligible in the result.

The articles published by Einstein in 1902, without being acquainted by Gibbs' book proceed from his constant endeavor to work out the fundamental principles at work in a physical theory, specifically in statistical physics, the main object of his concerns at that time, while keeping as close a contact as possible with experiment. For Einstein, as for Gibbs, the concepts of statistical physics apply to ensembles of systems. Einstein considers ensembles that one calls today, following Gibbs, *canonical*, i.e. ensembles with a fixed temperature. Einstein also endeavors to transcend mechanics and to discover the most general statistical laws that do not depend on mechanistic modeling.

From the same thought process proceeds Einstein's endeavor to show that *fluctuations*, i.e. departures from the laws of thermodynamic equilibrium, able to affect "small systems" visible with the microscope, are accessible to experimental observation, which neither Boltzmann nor Gibbs believed. He presumes that the order of magnitude of these disturbances is related to Boltzmann's constant k and, since 1900, contemplates means of determining the characteristics of the atoms (their numbers, their sizes) using the observation of these fluctuations. In 1905 he succeeds in elaborating a theory of Brownian motion that could, in principle, be tested experimentally. When the existence of atoms was clearly established, after the experiments were carried out in accordance with this theory by Jean Perrin in 1908, this achievement was considered as a genuine triumph of rational mechanics, providing the scientific basis of the atomistic conception.

Restricted Relativity, Relativistic Particles and Fields

Another conceptual difficulty of rational mechanics is related to the controversy concerning the nature of light: is light made of waves or of corpuscles? This controversy was one of the subjects of concern to theorists at the end of the 19th century. True, Newton had proposed a corpuscular model for light, but the discovery of the phenomena of interferences and diffraction had tipped the scales on the side of an undulatory interpretation of light. The theory of the electromagnetic field developed by Faraday, Maxwell and Heaviside, strongly reinforced this interpretation when Hertz highlighted the fact that the waves of the electromagnetic field propagate precisely at the same speed as light: the propagation of light was then comparable with the propagation of waves of the electromagnetic field. But this conception raised difficult questions of a theoretical nature: one hitherto had never met waves which were not carried by a certain medium, or a certain fluid (it was known that there are no sound waves in the vacuum); what then was the medium "carrying the light waves"? One had thus postulated the existence of a mysterious fluid, called *ether*, which was supposed to carry the light waves. But then, such a medium was to be describable by means of rational mechanics, it was to induce observable effects, like "an ether wind" due to the Earth moving in it. However all the theoretical and experimental efforts to establish the existence of this mysterious fluid appeared vain.

One can say that in 1905 the physics of electromagnetic interactions was in full crisis. The failure of the experiments of Michelson and Michelson and Morley, aimed at testing the existence of an ether wind, was the subject of various interpretations. Independently of the model of ether, it came to be recognized that Maxwell's equations are not invariant under the transformations known as Galilean, supposed to translate mathematically the principle of relativity, fundamental in mechanics: the laws of physics are expressed in the same way in two reference frames of inertia (i.e. in the absence of any external force) in relative rectilinear and uniform motion. It is Lorentz who discovered the transformations, called by Poincaré *Lorentz transformations*, and shown by him to form, together with spatial rotations, a *group*, which leave invariant Maxwell's equations. However the significance of this invariance was not understood and its implications such as the contraction of length and the dilatation of time appeared very mysterious.

In 1905 Poincaré and Einstein produced almost simultaneously and independently their works on relativity. The work of Poincaré, founded on the Lorentz invariance of Maxwell's equations, modeled the electron like an extended object, undergoing the "pressure of ether" in the form of a contraction in the direction of its motion. Einstein's theory of relativity, which eliminates the very idea of ether, is very different: it affects the most fundamental part of mechanics, namely kinematics, the very doctrine of space and time. Einstein first shows that, because of the finite time that light (or any other signal possibly carrying information) puts to be propagated, it is impossible to decide in an absolute way of the simultaneity of two instantaneous events spatially separated. He thus reinterprets the speed of light in the vacuum c as a universal constant translating the absence of instantaneous interaction, and he redesigns mechanics by adding to the principle of relativity the principle of the *invariance of the speed of light*. This refondation implies that one abandon the absolute character of time (two clocks in relative motion do not mark the same time) and the absolute character of spatial metric (two identical rulers in relative motion do not measure the same length). According to the expression suggested some time afterwards by Minkowski, time in this new kinematics must be regarded as the fourth dimension of *space-time*, a continuum whose other three dimensions are those of space. In this new kinematics, the Lorentz transformations express the way in which space-time co-ordinates change in a uniform rectilinear motion with a speed necessarily lower than or equal to the speed of light. A little time after this historic article, again in 1905, Einstein established the principle of the inertia of energy, which is translated in his most famous formula $E=mc^2$. A material point of mass m, moving in a rectilinear uniform motion has an energy E and a momentum $\boldsymbol{p}$ that form a 4-vector of space-time, called the four-momentum (the analogue of a 3-vector in the three-dimensional space of classical mechanics). Einstein's famous formula is a particular case of a relation between the mass, the energy and the momentum, known as the *mass shell or dispersion relation* which expresses the fact that the norm of the 4-momentum (the analogue of the length of a 3-vector), equal to mc^2, is invariant under the Lorentz transformations (in the same way as the length of a 3-vector is invariant under space rotations). In a space-time reference frame where the material point is at rest, namely where its momentum vanishes, the norm of the

4-momentum reduces to the rest energy or proper energy, which thus equals mc^2. This relation between mass and energy is a true novelty of relativity: in classical mechanics a particle at rest has no energy since the only energy that a material point may have is its kinetic energy which vanishes when the velocity vanishes, whereas, in relativity, even at rest, a particle has a proper energy, that, in units in which the speed of light is a large number, is enormous. It is interesting to note that the mass shell relation allows the value zero for the mass, which is also a novelty with respect to classical mechanics, for what could a material point of zero mass mean? In relativity a mass-less particle is never at rest, it moves, just as light, at the speed of light in any reference frame; it has an energy and a momentum equal to the energy divided by *c*. In a sense one could say that, whereas in classical mechanics mass precedes energy (there is no energy without mass), in relativity energy precedes mass (there is no mass without energy).

With this relativistic kinematics, implying the Lorentz invariance for all phenomena, it becomes possible to integrate the electromagnetic theory within the renewed framework of mechanics. In this framework the new fundamental concept is the concept of *field*, of which the electromagnetic field is an archetype. A field is a physical object, with an infinite number of degrees of freedom, extended to the whole of space-time: it corresponds to the definition, at each point of space and at any instant of time, of a function or a set of a few functions. So conceived, the electromagnetic field does not need unspecified ether or any carrying medium; it is itself the seat of the oscillatory phenomena associated with the propagation of light. The electromagnetic field carries energy and a momentum equal to the energy divided by *c*, so one can say that it is a *mass-less field*. A particle like the electron has a specific property, called its electric charge, which makes it able to produce an electromagnetic field and to react to the action of such a field. The electromagnetic interaction is not propagated instantaneously at a distance: a moving charged particle produces a variable electromagnetic field, the variations of which can subsequently put in motion another particle spatially separated from it.

GENERAL RELATIVITY, GRAVITATION AND COSMOLOGY

Einstein then seized this concept of field and tried to make it into the most fundamental concept of the whole of physics. His research then went on to generalize the theory of relativity. Not seeing any reason that the principle of relativity should be restricted to the changes of inertial reference frames, he sought to extend this principle to the most general changes of reference frames. He succeeded in reaching that aim thanks to a detour through the theory of gravitation: by noting that the acceleration produced by gravitation on a material body does not depend on the mass of this body, he showed that a change of reference frame comprising acceleration is equivalent to a gravitational field of opposite acceleration. More generally, he established that any change of reference frame can, locally, be replaced by a certain gravitational field, and that, reciprocally, any gravitational field can, locally, be replaced by a certain change of reference frame. In this sentence, the adverb *locally* means that the equivalence between the gravitational field and the change of frame is only possible in an infinitesimal region of space-time. Applied to the propagation of light, this reasoning implies that light undergoes the action of gravitation, which, we recall, is acceleration. To safeguard the invariance of the speed of light, Einstein was led to postulate that the effect of gravitation is a modification of the metric of space-time: gravitation influences the length of the measuring-rods and the running of the clocks, in such a way that the speed of light remains constant! Thus the generalization of the theory of relativity leads to a new theory of universal gravitation, geometrical in nature: *matter and the gravitational field that it induces are replaced by a space-time the metric of which is a universal field*. In 1915, Einstein put into equation this masterpiece, in terms of a theory of universal gravitation, which encompasses that of Newton, reduces to it at the approximation of weak fields, makes it possible to solve the puzzle of the motion of Mercury's perihelion, and finally, predicts new effects, such as the deflection of light by heavy stars, which was observed during the solar eclipse of 1919.

Immediately after having elaborated the theory of universal gravitation based on general relativity, Einstein tried to apply it to cosmology. He first noticed that Newton's theory of universal gravitation is not in harmony with the observation that the density of matter in the universe is in average approximately uniform, whereas it predicts rather a maximum density of stars at a sort of a center and decreasing to zero far away from this center, "a stellar universe [that] ought to be a finite island in the infinite ocean of space[12]." He then showed that thanks to the non-Euclidean character of the geometry implied by general relativity, one can conceive a universe that is finite and yet without boundary.

RELATIVITY AND THE PROBLEM OF SPACE

The title of this section is taken from the fifth appendix added by Einstein in 1952 to the fifteenth edition of his book *Relativity*, in which he had explained, as early as 1917, restricted and general relativity for a wide audience. In this appendix he expresses the wish "to show that space-time is not necessarily something to which one can ascribe a separate existence, independently of the actual objects of physical reality,[13]" and that finally "the concept of 'empty space' loses its meaning". In this very dense text, Einstein exposes his epistemological views about space and time. To conceive physical reality one needs the concept of *event* and the concept of *material object*. He first notes that "it is just the sum total of all events that we mean when we speak of the 'real external world'" and then that "it appears to [him], therefore that the formation of the concept of the material object must precede our concepts of time and space." He goes on to discuss the evolution of the conception of matter, space and time from classical Newtonian mechanics to restricted and general relativity. In Newtonian mechanics physical reality:

> thought of as being independent of the subject experiencing it, was conceived as consisting, at least in principle, of space and time on one hand, and of permanently existing material points, moving with respect to space and time, on the other; The idea of the independent existence of space and time can be expressed drastically in this way: If matter were to disappear, space and time would remain behind (as a kind of stage for physical happening)[14].

12 Einstein, 1961, p. 106
13 Einstein, 1961, p. vi
14 Einstein, 1961 p. 144

The passage from classical mechanics to restricted relativity is characterized by the promotion of the concept of field that "becomes an irreducible element of physical description, irreducible in the same sense as the concept of matter in the theory of Newton." However this evolution in the physical description does not affect the idea of the existence of space (more precisely this space together with the associated time) as an independent component of the representation. Also, even when they have been made compatible with restricted relativity, the electromagnetic theory and the rest of mechanics still need the concept of material points, possibly carrying electric charges. In the general theory of relativity, the concept of field acquires a more important status, because, on the basis of this theory:

> Space, as opposed to 'what fills space', which is dependent of the co-ordinates, has no separate existence. […] If we imagine the gravitational field […] to be removed, there remains absolutely nothing. […] there exists no space 'empty of field'[15].

QUANTUM PHYSICS: FROM THE DISCOVERY OF THE QUANTUM OF ACTION TO QUANTUM MECHANICS

The introduction of the elementary quantum of action by Planck in 1900 in his formula accounting for the spectrum of black body radiation initiated a long period of research and strong controversies that led to the current universal agreement about the fundamental status of quantum physics. True, the implications of the quantum of action were very intriguing: as soon as agreement was reached concerning the undulatory interpretation of light, one discovered, through Planck's formula and its interpretation by Einstein in terms of energy quanta, that it has also a possible corpuscular interpretation; as soon as it was possible to clearly reject the positivistic objections against the atomistic conception, one discovered that, because of their quantum properties, atoms cannot be thought of as material points. More fundamentally, as an element of discontinuity in action, Planck's constant and the physics in which it enters put the crisis of mechanics at a genuine climax, because it questions the two pillars of the whole scientific enterprise, namely, *causality* and *objectivity*. Causality is

[15] Einstein, 1961 p. 156

questioned because, in classical mechanics, as we said above, the causal laws of motion are derived from a principle of least action, which imperatively requires the continuity of action, and one does not know how to apply it if there is an elementary quantum of action. Objectivity is also questioned since, at the quantum level, the object to be observed is modified, transformed by the observation. If one wants to observe a microscopic structure with a high spatial and temporal degree of accuracy (i.e. with a small spatial and temporal margin of error), it is necessary to transfer to it, for a certain length of time a certain quantity of energy. The product of this duration by this energy has to be at least equal to Planck's constant. But since the duration of the measurement must not exceed the tolerated temporal margin of error, the energy necessary for obtaining a result of measurement will be at least inversely proportional to this temporal margin of error. True, this circumstance does not bear any consequence as long as one remains in the field of classical physics, i.e. when the actions brought into play are very large with respect to the elementary quantum of action, but as soon as one wants to explore with sufficient precision the atomic or subatomic world, it obliges us to give up the implicit prejudice according to which it is always possible, at least in principle, to disregard the condition of observation: in its preparation, as well as in its results, any experiment in the microscopic world depends in such an essential way on these conditions that they must be taken into account down to the very formalism itself. Such a constraint seems to question the possibility of an objective description of the microscopic world.

The resolution of such a crisis took about thirty years of trials and errors, controversies, new experimental discoveries and conceptual innovations to lead to what came to be called *quantum mechanics*, comprising a rigorous mathematical formalism and a physical interpretation. Although the discovery of the quantum of action took place in the field of electromagnetic radiation, a field not directly related to mechanics, and although the contributions of Einstein, till the mid 20's mainly concerned the quantum theory of radiation, the founders of quantum physics concentrated on "quantizing" non-relativistic mechanics of point particles, postponing for a further stage the quantization of (relativistic) field theory.

The formalization of quantum mechanics was carried out at a frantic rhythm in 1925 and 1926. It is initially Heisenberg who, in 1925 and in collaboration with Born and Jordan, developed a completely new approach that was called the *mechanics of matrices*, which associates with the observable physical quantities matrices obeying relations of commutation. On his side, P. Dirac arrived by a different way of thinking to a formalization of what he called *quantum mechanics*, (the title of the thesis he defended in 1926). It is likewise in 1926 that Schrödinger developed, with the aim of making comprehensible the wave-corpuscle duality of de Broglie, a third approach, called *wave mechanics*, based on the *wave function* that obeys the now celebrated *Schrödinger's equation*. Some time later, again in 1926, Schrödinger showed the equivalence of his approach with that of Heisenberg, as well as that of Dirac. A coherent formalism, primarily founded on Schrödinger's equation, thus began to emerge, which made it possible to account in a precise way for the experimental observations like, for example, the Stark and Zeeman effects.

To these advances in the formalization, it is worth adding two major contributions pertaining to interpretation: the probabilistic interpretation of the wave function suggested by Max Born in June 1926, and the principle of indeterminacy stated by Heisenberg in 1927. Thus, at the end of the 20's, a consensus was reached on a formalism and an interpretation, known as the *Copenhagen interpretation*, which made it possible to elucidate the problems left open by classical physics and to undertake the systematic exploration of the quantum universe.

Although it is called mechanics, the physics that quantum mechanics is supposed to describe has several features that seem completely foreign to rational mechanics. A first such feature is the *particle-wave duality*. Whereas the observation of the Compton Effect confirmed the existence of a corpuscular structure in the electromagnetic field that hitherto was conceived only in an undulatory way, Louis de Broglie, proposed, in his PhD thesis in 1924, that corpuscles of matter, like electrons, can show undulatory aspects. These ideas were confirmed by the observation of the phenomenon of interferences and diffraction induced by electrons. "The work of de Broglie made me a great impression. It lifted a corner of the great veil[16]" said Einstein, impressed by this

[16] de Broglie, 1956

vision. Gradually, it indeed appeared that in the quantum world (i.e. when the actions involved are of the order of magnitude of the elementary quantum of action) both in the realm of the structure of matter, and in the one of the interactions, phenomena are suitable for two descriptions, which would be completely contradictory in the framework of classical physics, one in terms of waves and another in terms of particles. The frequency and the wave vector that characterize the propagation of the wave are proportional to the energy and the momentum that characterize the motion of the particle with a proportionality factor equal to Planck's constant.

Another very intriguing feature of quantum mechanics is the *superposition principle*. Whereas, in classical mechanics, the states of a system are represented by points of the space of configuration, they are represented, in quantum mechanics, by vectors of a *Hilbert space*, a linear vector space of complex functions on which are defined a norm and a scalar product. One also uses the term of *wave function* to indicate a vector of the Hilbert space representing a quantum state. The linearity of the Hilbert space corresponds to the superposition principle according to which quantum states can combine, superimpose, i.e. can be added like complex numbers, as do, in classical physics, waves or fields. This property of *coherence* is one of the essential characteristics of the entire quantum universe. But it is also this property which is at the origin of the most disconcerting and paradoxical aspects of this new physics: one could thus imagine thought experiments in which a physical system could be in a state of superposition of two contradictory states (as the poor cat which Schrödinger had imagined, at the same time dead and alive).

EINSTEIN'S CRITICISM OF QUANTUM MECHANICS

Another essential characteristic of quantum mechanics that is revealed by radioactivity is that its predictability is *probabilistic*. One is obliged to resort to probabilities, on the one hand because there are processes, bringing into play an action of the order of the elementary quantum of action, like a radioactive decay or a nuclear or particle reaction, which it is impossible to describe in a deterministic way using differential equations, and on the other hand because it is necessary to include in the formalism the conditions of observation and that these conditions cannot in general be better determined than in a statistical way. This feature was Einstein's main concern in his criticism of quantum physics. His attitude towards quantum physics varied with time. Till the mid 20's, not only did Einstein not criticized quantum physics but, as one of its founders he very warmly praised the advances it made possible. A careful reading of his articles shows that what he tries to establish is a quantum theory of fields rather than a quantum mechanics: this appears in his 1905 article on the photoelectric effect and in his famous article in 1917, "Quantum Theory of Radiation", in which he provides a demonstration of the Planck formula for the black body radiation; even in his articles in 1924 and 1925 on the quantum theory of the mono-atomic ideal gas, in which he integrates the Bose statistics (now known as the Bose-Einstein statistics) in the framework of quantum physics, he notes that "it is possible to associate a field of scalar waves with a gas." In any case, the feature that he never accepted is the recourse to probabilities at the fundamental level, because this recourse would imply that the *theory is incomplete*. In his "Reply to Criticisms", quoted above, he considers a radioactive decay described in quantum mechanics by means of a "Psi-function" (i.e. a wave function):

> This Psi-function yields the probability that the particle, at some chosen instant, is actually in a chosen part of space (i.e., is actually found there by a measurement of position). On the other hand, the Psi-function does not imply any assertion concerning the time instant of the disintegration of the radioactive atom. Now we raise the question: Can this theoretical description be taken as the complete description of the disintegration of a single individual atom? The immediately plausible answer is: No. For one is, first of all, inclined to assume that the individual atom decays at a definite time; however, such a definite time-value is not implied in the description by the Psi-function. If, therefore, the individual atom has a definite disintegration time, then as regards the individual atom its description by means of the Psi-function must be interpreted as an incomplete description. In this case the Psi-function is to be taken as the description, not of a singular system, but of an ideal ensemble of systems. In this case one is driven to the conviction that a complete description of a single system should, after all, be possible, but for such complete description there is no room in the conceptual world of statistical quantum theory[17].

In the celebrated "EPR" *Physical Review* paper, written in 1935 in collaboration with Boris Podolsky and Nathan Rosen, "Can Quantum-Mechanical Description of Physical Reality be Considered Complete[18]?", Einstein proposes a thought experiment

[17] Einstein, 1949
[18] Einstein, 1935

that could lead to a paradox possibly ruining the whole consistency of quantum physics. In this paper, the paradox was formulated by means of a pure thought experiment concerning the determination of the positions and momenta of a pair of particles produced in a well-defined quantum state. Although, for each particle of the pair, the position and the momentum obey the law of non-commutation and can thus be determined only with uncertainties constrained by the inequalities of Heisenberg, the difference of the positions commutes with the sum of the momenta. It would thus seem that one could measure with an arbitrarily high precision this difference and this sum and that consequently one could predict with precision either the value of the position or that of the momentum of the first particle of the pair, if, respectively, the value of position or that of momentum of the second particle of the pair is measured. Since, at the time of measurement, the direct interaction between the particles of the pair has ceased, the position and the momentum of the first particle can be regarded as physical attributes of an isolated object, which would mean that one could "beat the inequalities of Heisenberg", and thus that quantum mechanics does not provide a complete description of reality.

In a letter to Schrödinger of June 19th 1935, Einstein reconsiders the EPR thought experiment of which he presents the implications in the form of a true antinomy: either quantum theory is incomplete or it violates what he calls a *separation principle* according to which if one considers a system whose real state is composed of the real states of two subsystems A and B, then the real state of subsystem B cannot depend in any way on the experiment one performs on subsystem A.

The complete elucidation of the EPR paradox took several years. It required several advances on the experimental and theoretical grounds. A first advance was made by David Bohm, who imagined possible experiments, more realistic than that evoked in the EPR article, in which the position and the momentum are replaced as non-commutative observables by components of spins on different axes, which, in quantum mechanics, are represented by operators which do not commute. On a theoretical grounds, it is John Bell who, in 1964, established some inequalities that should satisfy the results of the experiments imagined by Bohm, on the first assumption that quantum mechanics would be incomplete and would thus have to be supplemented with some *hidden* *variables* and on the second assumption of *locality* i.e. the assumption of absence, in accordance with Einstein's principle of separation, of an instantaneous connection between spatially separated systems. These inequalities thus made it possible to put Einstein's argument to a precise quantitative test: either they would be satisfied, and then Einstein would be right, or they would be violated, and then at least one of the two assumptions made by Bell (hidden variable or locality) would be at fault. In the 70's, some experiments aiming to test the Bell's inequalities were carried out in atomic physics and nuclear physics, but it is in 1982 that the decisive experimental advance occurred: Alain Aspect and his collaborators succeeded in carrying out a genuine EPR experiment (in the version of a Bohm experiment); they found, and this was confirmed by many other experiments carried out since, a clear violation of Bell's inequalities, thus confirming the predictions of quantum theory.

MATURE QUANTUM PHYSICS, THE QUANTUM THEORY OF FIELDS

With the failure of the lawsuit in incompleteness brought by Einstein against quantum physics, the verdict of the experiment is without appeal: quantum physics is discharged. Therefore, in at least one of his criticisms, Einstein was wrong. With the encompassing view that more than seventy years of implementation of quantum physics give, it is advisable to reassess the objections he made to this physics, to locate in what respect he was right and in what respect he was wrong, and also to evaluate, in a critical way, the Copenhagen interpretation to correct its possible defects.

We believe that it is the passage from quantum mechanics to the quantum theory of fields that enables us to answer the epistemological objections raised by Einstein with respect to locality, reality and completeness, and thus to solve the crisis of physics initiated by the discovery of the elementary quantum of action.

Not only was Einstein entirely right to require what he called the principle of separation, but one can blame the Copenhagen interpretation for not having sufficiently stated it. Expressed bluntly by Steven Weinberg, who calls it the *cluster decomposition principle*, in his textbook on the quantum theory of fields, it affirms that

> Experiments that are sufficiently separated in space have unrelated results. The probabilities for various collisions measured at Fermilab should not depend on what sort of experiments are being done at CERN. If this principle were not valid then we could never make any predictions about any experiment without knowing everything about the universe[19].

This principle, also called the *principle of locality*, indeed seems to be one of those with which it is really impossible to compromise.

Several of the Einstein's queries about quantum physics are related to the question of reality: the belief in the existence of a material reality, independent of any observation, and describable in space and time; the difficulty in defining what is "reality" since it is known to us only by the description that physics gives it; the dualism of the field and the material point, two descriptions that are possible but contradictory. This dualism, which Einstein always rejected and he was unable to get rid of, is indeed overcome by the quantum theory of fields, as Weinberg says in an article, under the title "What is Quantum Field Theory and What did We Believe It Is?" in which he highlights some topics of his textbook:

> In its mature form, the idea of quantum field theory is that quantum fields are the basic ingredients of the universe, and particles are just bundles of energy and momentum of the fields. In a relativistic theory the wave function is a functional of these fields, not a function of particle coordinates. Quantum field theory hence led to a more unified view of nature than the old dualistic interpretation in terms of both fields and particles[20].

To address the question of completeness, we need to go back to the above-mentioned articulation of the two basic concepts necessary to conceive reality, the concept of *object* and the concept of *event*. The concept of object belongs to the realm of theory, whereas the concept of event belongs to the realm of experiment: the aim of theory is to constitute a scientific object, an element of reality independent of the way it is observed; events on the other hand are the modalities through which reality is empirically or experimentally known to us. Completeness is a *theoretical* requirement, not an experimental requirement that thus concerns the object not the event. On the one hand, Einstein was right when he blamed quantum mechanics to keep the particle as a representative of the primitive concept of object while giving the wave function a

[19] Weinberg, 1995 p. 177

probabilistic (i.e. incomplete) interpretation; but, on the other hand he was wrong in his hope that quantum events be individually predictable in a deterministic way. The finiteness of the elementary quantum of action forbids any subdivision of individual quantum processes. These processes must be considered as irreducible events that are neither individually predictable nor reproducible. In the framework of relativity, general covariance requires events to be strictly localized in space-time. In the quantum framework, even in absence of relativistic effects, it is the principle of locality that requires quantum events to be strictly localized in space and time. The only possible predictability concerning quantum processes is probabilistic by means of statistical averages over ensembles of strictly localized events occurring in some region of space-time.

A quantum field is a physical entity defined at each position in space and instant in time. Whereas a classical field entity is a real or a complex function of the space-time coordinates, a quantum field entity is an operator that produces or destroys a particle in a quantum event strictly localized at the space-time coordinates. According to the quantum theory of fields the particle-wave duality is interpreted in a non dualistic way: quantum fields are *objects* that behave, either as particles or as waves according to their being involved or not involved in actual *quantum events*. As Feynman says in the article in which he introduced the *path integral* reformulation of quantum physics,

> The electron acts as a wave, so to speak, as long as no attempt is made to verify that it is a particle; yet one can determine, if one wishes, by what route it travels just as though it were a particle; but when one does that [the classical way to combine probabilities] applies and it does act like a particle[21].

Quantization of field theory is often named “second quantization”. According to this terminology, the first quantization is the association with a system of particles of a wave function that is considered as a classical field, the quantization of which is the second quantization. Actually, it appears that the quantum theory of fields is rather a complete change of perspective. In quantum mechanics, the *states of the system* are represented by *vectors* of the Hilbert space, and the *observable physical quantities* are represented by *operators* acting on these vectors. In quantum field theory there is a

[20] Weinberg, 1997

complete change of point of view: operators are associated with the object, the quantum field, whereas vectors are associated with the states, not of the system, but rather of the experimental apparatus. A quantum field operator that produces or destroys a particle acts on the state of the particle detector. In quantum mechanics, the wave function of a particle is a complex function of the space and time coordinates, or of the energy and momentum, the squared modulus of which is the probability that *the* particle has these coordinates or these energy and momentum. On the other hand, according to the quantum field theoretical point of view, the wave function is a field amplitude, a complex function, the modulus squared of which is the probability of counting at the corresponding position or with the corresponding energy and momentum *a* particle produced by the quantum field. Actually, it turns out that in quantum physics, all experiments are more naturally interpreted according to this quantum field theoretical point of view than according to the quantum mechanical point of view, for all the detectors that enable us to experimentally observe the atomic or subatomic world are nothing but *event counters*, possibly including some filters that make it possible, say, to select particles with a given spin component, but never apparatuses that would enable us to determine the wave function of an isolated particle. Having this in mind, one understands why the passage from the quantum mechanical point of view to the quantum field theoretical point of view provides a solution to the EPR paradox: as Einstein himself noticed, there is no paradox if experiments are interpreted in terms of statistics of ensembles. The only mistake Einstein made was to consider such ensembles as ensembles of systems and not as ensembles of events.

QUANTUM FIELD THEORY AND THE PHYSICS OF FUNDAMENTAL INTERACTIONS

Historically, quantum field theory was applied for the first time in Quantum Electrodynamics (QED) that is the quantum field theory of the electromagnetic interactions of electrons and positrons. It is in order to work out a tractable scheme

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[21] Feynman, 1948 p. 370

suited for this purpose that Feynman was led to elaborate his above-mentioned *Path Integral Quantization* as an alternative to the standard methods of quantization that were available at that time. Starting from the simplest example, i.e. the quantum mechanics of a one-particle system, he rewrites the Schrödinger's equation as a functional integral equation, the solution of which, the wave function of the particle at a given space-time position, is a functional integral (that is an infinite dimensional integral) over all the "paths" or trajectories that could possibly bring the particle from an arbitrary position in the infinitely remote past to its actual position. Such a reformulation looks very complicated in the very simple case considered, but it can be applied to very general situations, including the treatment of fundamental interactions with quantum field theory. The integrand of the path integral, namely the weight given to the contribution of each path (in the case of a field theory, one should rather speak of each "field history") involves the Lagrangian of the theory in which is encoded all the information concerning the considered interaction (the fields involved, the masses, spins and other quantum numbers of their quanta, the symmetries of the interaction, the *coupling constants* that characterize the intensity of the interaction at the elementary level, etc.) The Lagrangian is the sum of the kinetic energy terms corresponding to the free propagation of the fields involved and of the interaction terms corresponding to the interactions or couplings of the fields. The locality principle constrains all the terms in the Lagrangian to be of the form of products of fields, or field derivatives *evaluated at the same space-time point.*

The quantization of field theory confronted two major difficulties, negative energies and infinities, the overcoming of which is one of the keys of the success of the standard model.

The first difficulty arose as soon as one tried to work out a relativistic generalization of the Schrödinger's equation. Even for free particles, in which case standard and path integral quantization can be worked out explicitly and lead to the same results, such a generalization leads to negative energy solutions that would imply that no quantum state could be stable since the energy would not be bounded from below. The physical interpretation of these negative energy solutions is impossible in the framework of quantum mechanics where the number of particles is fixed and conserved. It is precisely the passage from quantum mechanics to the quantum field theory that makes it possible to overcome this difficulty: in quantum field theory the number of particles is not conserved; particles can be produced or destroyed, and the problem of negative energies is solved by constraining negative energy, i.e. unphysical particles to *go backward in time* and replacing such a negative energy particle with a given charge by a positive energy, i.e. a physical *antiparticle* with the opposite charge *going forward in time*. With this scheme time is axiomatically given an arrow: *only physical particles or antiparticles go forward in time*. The experimental discovery of the *positron*, the antiparticle of the electron, and then of the antiparticles of all the known particles has clearly demonstrated the adequateness of this scheme.

When interactions are taken into account, the standard quantization methods lead to very cumbersome, almost intractable calculations, whereas path integral quantization leads to a very powerful scheme known as the *perturbative expansion* in terms of *Feynman's diagrams and amplitudes*. For any process relying on a given fundamental interaction, the amplitude the modulus squared of which is the probability of its occurrence, can be expanded in powers of the coupling constant, the coefficients of which are a sum of Feynman's amplitudes associated with Feynman's diagrams. These Feynman's diagrams make it possible to picture in a very suggestive way the basic idea of the path integral of decomposing an *actual* process in terms of a sum of terms associated with *virtual* processes. The higher the power of the coupling constant in the power expansion is, the more complex are the Feynman diagrams, so, if the coupling constant is a small number (as it is the case in QED) one can hope to get with the contributions of a few simple virtual processes a good approximation of the full amplitude.

The amplitude associated with a Feynman diagram is always written in terms of multiple integrals over a finite number of variables. At this point one has to confront the difficulty of infinities: in general the integrals necessary to compute Feynman's amplitude *diverge*, namely are equal to infinity. Actually, this difficulty, which seems to possibly ruin the entire quantum field theoretical program, is deeply rooted in the conflict, already raised by Einstein, between locality and completeness: locality requires considering point-like couplings of fields, which in turn requires taking into account virtual processes involving arbitrary large energies responsible for the divergent integrals; if, in order to get finite amplitudes one would simply ignore the virtual processes involving energies higher than some arbitrary *cut-off*, then the theory might be blamed for incompleteness. The idea of a way out of this difficulty is to split the values of the parameters of the theory into their *bare values*, i.e. the values they would have in absence of interaction, and their *physical values*, i.e. the values they acquire due to the interactions. In QED, where the parameters are the electron mass and the electron charge, it turns out that infinities arise when one tries to express the physical amplitudes in terms of the bare values of the parameters whereas no infinity occurs in the expression of the amplitudes in terms of the physical values of the parameters. Of a theory, like QED, in which such a "miracle" occurs for all amplitudes and at all orders of the perturbative expansion, one says that it is *renormalizable*. Since the physical values of the parameters can be experimentally determined, it is possible to compare with experiment the predictions of a renormalizable theory. In the case of QED, for some physical quantities that are theoretically calculable and experimentally measurable, the agreement between theory and experiment is amazingly good.

TOWARDS A PHILOSOPHICAL CATEGORY OF *REALITY HORIZON*

From the rational explanation of this "miracle" can be drawn the main philosophical lesson of the present chapter. Actually, the physical values of the parameters implicitly depend on an energy associated with the *coarse graining* with which the interaction is experimentally observed. The realization of this coarse graining dependence is an asset of what is known as the *modern interpretation* of quantum physics that, in turn, is an asset of the path integral quantization method. In order to be able to attribute probabilities to actual events produced by interacting quantum fields one has to perform the path integral with a graining that is sufficiently coarse so that interferences that might prevent ascribing additive probabilities to independent events actually cancel[22]. Now, because of that circumstance, a renormalisable theory like QED cannot be

[22] Gell-Mann, Hartle, 2006

considered as a fundamental theory valid at all energies, but rather as an *effective* theory, suited to describe the interaction at a given resolution related to the coarse graining energy. But does that not imply such a theory to be incomplete since it would depend on parameters varying with energy? Actually, this is not the case because the way in which the parameters depend on the coarse graining energy is not arbitrary: it has to be such that the measured and calculated physical quantities *do not depend on it*. The equations that translate this physical independence on the coarse graining are called the *renormalization group equations.* According to the QED renormalization group equations, the fine structure "constant", equal to the square of the electron charge divided by the product of Planck's constant by the speed of light is not constant: it is *predicted* to vary from 1/137 at an energy of a MeV (a million electron-Volt) to 1/128 an energy of a hundred GeV (a hundred billion electron-Volt), and this prediction has been confirmed by experiment. On the physical ground, the great achievement of the standard model is that one has embedded QED in a set of renormalizable theories (the electroweak theory and Quantum Chromodynamics, QCD) leading to predictions that have been experimentally confirmed with an excellent accuracy.

On an epistemological ground these achievements have put in the foreground a concept that currently plays a growing role in the context of quantum cosmology, the concept of *horizon*. In contemporary physics this concept is relevant in the interpretation of the fundamental limitations of human knowledge implied by some universal constants[23] like Planck's constant or the velocity of light: these limitations are not to be considered as insuperable obstacles but rather as *informational horizons*, namely some boundaries beyond which lie some inaccessible information. The fact of assuming the existence of an informational horizon does not mean that one neglects or forgets the information lying beyond it. The methodology that allows keeping track of this missing information is based on functional integration: to evaluate the probabilities of the values of the dynamical variables bearing the accessible information (the followed variables) one *integrates out* the dynamical variables bearing the inaccessible information (the non-followed variables). Such a methodology is used in classical

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[23] G. Cohen-Tannoudji, 1991 Lehoucq and Uzan, 2005

statistical physics where the microscopic configurations leading to the same macroscopic state (what one calls the *complexions*) are treated as non-followed variables that are integrated out through the statistical averages leading to the definition of the Boltzmann-Gibbs probability distribution of the followed variables. Basically, the path integral quantization relies on the same methodology: the summation, with a certain coarse graining, over all possible paths or field histories exactly corresponds to integrating out non-followed variables. Actually, it can be shown that the similarity between the Boltzmann-Gibbs probability distribution in statistical classical physics and the path integral in quantum physics is not a simple analogy, but rather a rigorous mathematical correspondence, with a strict "dictionary" translating Boltzmann's constant into Planck's constant, entropy (or information) into action, inverse temperature into imaginary time, critical phenomena occurring at a second order phase transition into the results of a renormalisable quantum field theory. The last item of this dictionary led in the 70's to a remarkable interdisciplinary synthesis, since one was able to use, with great success, the same theoretical tools in two domains of physics which hitherto seemed completely disconnected, the physics of critical phenomena on one hand and Quantum Chromodynamics, the physics of strong interactions of quarks and gluons on the other. In this respect it is interesting to note that the same correspondence allowed designing some computer simulations of QCD, the so called "lattice QCD" providing some insight on the non-perturbative regime of this quantum field theory.

A last comment is in order about the correspondence between classical statistical physics and quantum physics. Since an imaginary time can be considered as a fourth Euclidean dimension of space, one can say that somehow quantization adds an extra space dimension to classical physics: quantum physics in a three-dimensional space is equivalent to classical statistical physics in a four-dimensional space. Such a feature is analogous to what occurs in the reconstruction of a three-dimensional scene by means of a two-dimensional *hologram*. Following this line of thought, some very important developments currently occur in cosmology. Gravitation is the only interaction capable of so much curving space-time that it leads to the formation of a spatial horizon, namely a "one-way membrane", a two-dimensional informational horizon hiding information lying beyond it. Because of the expansion of universe, there exists in cosmology a horizon, called the *particle horizon* that is defined by the distance beyond which lie galaxies whose light had not the time to reach us. Beyond that horizon one suspects the existence of another horizon, called the *event horizon* that would be defined by the distance beyond which no information can *ever* reach us. This event horizon is usually assumed to rely on *quantum cosmology*, i.e. the domain of cosmology in which gravity has to be quantized. A theoretical laboratory to explore the physics of such event horizons is the physics of *black holes.* The event horizon of a black hole is the surface surrounding it beyond which any matter (and thus any information), trapped by the black hole escapes from perception. Although black hole physics is classical as far as gravitation is concerned, at the horizon, the classical gravitational field is so intense that it may induce in matter certain quantum effects such as the production of particle-antiparticle pairs, which have to be dealt with. Since, in quantum statistics, missing information is equivalent to entropy, it is natural, in this framework, to attribute entropy to such a horizon. Bekenstein and Hawking have shown that the entropy corresponding to the information trapped inside a black hole is proportional to the area of the event horizon rather than to the volume embedded inside it. It seems possible to generalize this result to space-time metrics involving a horizon which leads to conjecture that cosmology associated with such metrics is completely determined by the quantum properties of the horizon[24]. According to such a *holographic principle*[25], the total information contained in a universe involving a horizon would not be proportional to the volume embedded by the horizon but only to the area of the horizon.

On a philosophical ground, I would like to conclude this chapter by emphasizing the relevance to philosophy of science of a concept that could act as a genuine philosophical category, the concept of *reality horizon*. The reality horizon is one of the key concepts of the philosophy of Ferdinand Gonseth (1890-1975), a Swiss mathematician-philosopher who was familiar with theoretical physics (he was a close friend of Michele Besso[26], the closest friend of Einstein; he was asked by Georges Lemaître, one of the founders of modern cosmology, to write a foreword for his book

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[24] Smolin, 2001, Padmanabhan 2006
[25] Susskind, 2005
[26] Gonseth, 1967

The Hypothesis of the Primitive Atom[27]) and who designed what I think is the philosophy that 20th-century science deserve. In a development in his major book *Geometry and the Problem of Space*, devoted to the articulation of the three essential aspects of geometry, namely intuition, axioms and experiment, he notes that

> The previous results have a value that goes beyond the framework of geometry. They concern the entirety of knowledge, we mean the state in which knowledge comes to us, at a given instant: Nothing authorizes us to think that our knowledge, even at its last frontiers, is more than a knowledge horizon; that the last 'realities' that we have conceived are more than a reality horizon[28].

It seems to me that all the developments of 20th-century physics, from the resolution of the crisis of rational mechanics to the promising speculations about quantum cosmology through the successes of the standard model, confirm the validity of this ambitious and yet humble philosophy: we are such, and the world is such that it is never given to us in its full reality but as a reality horizon.

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[27] Lemaître, 1946

[28] Gonseth, 1949, p. IV-46 (310).

BIBLIOGRAPHY

Barberousse, Anouk (2002), *La mécanique statistique – De Clausius à Gibbs –,* Paris, Belin, 2002.

Broglie, Louis de (1956), *Le dualisme des ondes et des corpuscules dans l'oeuvre d'Albert Einstein, discours à l'Académie des Sciences, Paris, 5 décembre 1955,* in *Nouvelles perspectives en microphysique,* Paris, Albin Michel, 1956.

Cohen-Tannoudji, Gilles (1991), *Les Constantes Universelles,* Paris, Hachette, 1991.

Einstein, Albert (1916) "The foundation of the generalized theory of relativity" (*Die Grunlage der allgemeinen Relativitätstheorie*), *Annalen der Physik,* ser. 4, XLIX, 1916, 769-822.

Einstein, Albert (1935), *Physical Review,* vol.XLVII, 1935 p. 777-780.

Einstein, Albert (1949), "Reply to criticism. Remarks concerning the essays brought together in this cooperative volume." In Schilpp, 1949.

Einstein, Albert (1961), *Relativity, The Special and the General Theory – A popular Exposition –* (English translation of *Ueber die spezielle und die allgemeine Relativitätstheorie, Gemeinverständlich,* Braunschveig, Vieweg, 1917), New York, Crown Trade Paperbacks, 1961.

Feynman, Richard P. (1948), "Space-Time Approach to Non-Relativistic Quantum Mechanics", *Review of Modern Physics*, Vol. 20, Number 2, p. 367-387.

Gell-Mann, Murray (1994), *The Quark and the Jaguar – Adventures in the simple and the complex –,* New York, W. H. Freeman and Company, 1994.

Gell-Mann, Murray; Hartle, James B. (2006), "Quasiclassical Coarse Graining and Thermodynamic Entropy", (arXiv:quant-ph/0609190).

Gibbs, J. Willard (1902), *Elementary Principles in Statistical Mechanics – The rational foundation of thermodynamics –,* New York, Charles Scribner's sons, London, Edward Arnold, 1902.

Gonseth, Ferdinand (1949), *La géométrie et le problème de l'espace*, Neuchâtel, Éditions du Griffon, 1949.

Gonseth, Ferdinand (1967), "Connaissance de la nature et connaissance philosophique chez Albert Einstein", in *Science et synthèse*, Paris, Gallimard NFR, 1967, p. 21-28.

Lemaître, Georges (1946), *L'Hypothèse de l'Atome Primitif –Essai de Cosmogonie– (Préface de Ferdinand Gonseth)*, Neuchâtel, Éditions du Griffon, 1946

Maxwell, James Clerk (1873), "Molecules", *Nature*, Sept. 1873, pp. 437-441.

Padmanabhan, Tanu (2006), "Dark energy: Mystery of the Millenium", Talk presented at the Albert Einstein century International Conference at Palais de l'Unesco, Paris, July 2005 (arXiv:astro-ph/0603114), 2006.

Paty, Michel (1993), *Einstein Philosophe,* Paris, Presse Universitaire de France, 1993

Rosen, Joe (1995), *Symmetry in Science – An introduction to the general theory* – New York, Berlin, Heidelberg, Barcelona, Budapest, Hong Kong, London, Milan, Paris, Santa Clara, Singapore, Tokyo, Springer, 1995.

Schilpp, Paul Arthur (1949) *Albert Einstein:philosopher-scientist,* The library of living philosophers, Lasalle (Ill), Open Court, 1949.

Smolin, Lee (2001), *Three roads to Quantum Gravity,* New York, Basic Books, 2001.

Susskind, Leonard and Lindesay, James (2005), *Black Holes, Information and the String Theory revolution – The Holographic Universe –,* New Jersay, London, Singapore, Beijing, Shanghai, Hong Kong, Taipei, Chennai, World Scientific, (006).

Teller, Paul (1997) *An Interpretive introduction to Quantum Field Theory,* Princeton (NJ), Chichester (UK), Princeton University Press, 1997.

Uzan, Jean-Philippe and Lehoucq, Roland (2005), *Les Constantes Fondamentales,* Paris, Belin, 2005.

Weinberg, Steven (1995), *The Quantum Theory of Fields (Volume I Foundations),* Cambridge, New York, Melbourne, Cambridge University Press, 1995.

Weinberg, Steven (1996), *The Quantum Theory of Fields (Volume II Modern Applications)*, Cambridge, New York, Oakleigh, Madrid, Cape Town, Cambridge University Press, 1996.

Weinberg, Steven (1997), "What is Quantum Field Theory, and What did We Think It Is", Talk presented at the conference "Historical and Philosophical Reflections on the Foundations of Quantum Field Theory," at Boston University, March 1996 (arXiv:hep-th/9702027).

Weyl, Herman (1952), *Symmetry,* Princeton, Princeton University Press, 1952.

Notice about Gilles Cohen-Tannoudji

Born in Constantine (Algeria) in 1938, Gilles Cohen-Tannoudji is graduate from Ecole Polytechnique (1958-1960). He has done his whole career in the French Atomic Energy Commission (CEA) at Saclay, from which he retired in 1998. He is currently emeritus researcher in the Laboratoire de Recherche sur les Sciences de la Matière (LARSIM, CEA-Saclay) directed by Etienne Klein. He has worked as a theorist in the domain of particle physics (PhD in 1967, about sixty publications in international reviews) in the theory department (Service de Physique Théorique) and then in the experimental department (Service de Physique des Particules). At the level of the Master degree, he has taught theoretical physics at Orsay from 1979 to 1983, history of theoretical physics, also at Orsay from 2000 to 2004 and now, philosophy of physics at Paris. He is the author, or co-author of some books of reflection on physics intended to a wide audience: La Matière-Espace-Temps, with Michel Spiro in 1986, L'Horizon des Particules, with Jean Pierre Baton in 1989, Les Constantes Universelles in 1991, a book that has been translated in English (Mac Graw Hill). He is currently preparing a thesis in philosophy of science on the work of the Swiss philosopher Ferdinand Gonseth, under the direction of Dominique Lecourt.