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THE CRISES OF CONTEMPORARY PHYSICS

When we speak of a crisis in some domain, we usually think of an unfathomable situation which can only be resolved by a general upheaval. We can, however, assign another, more etymological meaning to the word: that of a critical evaluation. While admitting that the crises in contemporary physics have a good deal to do with the first meaning, I believe that their essential impact, on culture and human thought in general, issues from the second interpretation which allows us to envision these crises as a growing consciousness in physics of the range of its domain and the scope of its methods. These crises greatly contributed, on the one hand, to giving physics a new dimension in its field of action, and, on the other hand, they were brought about by a certain number of ideas which belonged to the general cultural heritage at the time they occured. From this point of view we may conceive of these crises as a cause, and conversely as an effect, of the penetration by wider intellectual horizons of an original structure which was somewhat artificially limited, by the selection of its constituent elements, to representing a sort of mental abstraction, justifiable in terms of the successes it

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achieved, but hardly representative of its human dimension as a whole.

In earlier times, a reciprocal influence between general culture and scientific research was, perhaps essentially, effected through those great personalities whose specific accomplishments partook of both domains; in this way, a certain metaphysical picture of the whole sometimes produced a particular conception of nature. Today, the situation is radically different: given the enormous breadth of knowledge, it is rare, even exceptional, for a single individual to be able to consolidate knowledge from various cultural domains. This means that the reciprocal influences which used to exist through personalities must now be conceived of anonymously, as currents of thought independent of and transcending the individuals who contributed to their formulation.

Under the impetus of certain conceptions, indispensable for a number of recently discovered phenomena, the general crises which have erupted in physics at the same time constitute the main factor which thrust this discipline into its generally recognized place at the avant-garde of scientific progress. I would like to emphasize that it is this conceptual self-criticism which, I believe, placed physics in the role of avant-garde, and gave it the unique capacity among the sciences of being able to delimit the frontiers of its domain and its scope. By "de-absolutizing" its results, it was to assert itself in a much wider perspective than before.

To explain more fully what I have in mind, I would like to begin by recalling that at the end of the last century, the great development of the experimental and theoretical aspects of physics had established a conceptual framework of the physical world, based on a vision of the cosmos that was completely governed by a group of mathematical and deterministic laws. This perspective was essentially non-human, not so much because it was experimental and rationalistic, but because these two qualities were considered to be the only ones capable of exhaustively studying the reality of the world; it therefore put nature over man, non-life over life, the inorganic over the organic, the elementary over the integrated. It gradually replaced and eventually supplanted the traditional religious framework which, beyond the particularities inherited from various peoples and centuries of history, based itself on the exact opposite order of

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the pairs of antinomies mentioned above, and founded the assumption that man held a central place in the Creation, and everything else was ordered in relation to him.

We cannot question the fact that the great accomplishments of classical physics constituted the primary reason for the widespread diffusion of this conceptual system which served as the basis for its theories, extended to almost every other science, and eventually influenced a large fraction of modern thought. It is therefore all the more interesting to note that the most acute symptoms of crisis, in the double meaning of the term, occured in this pilot science, and that physics, in which determinism first appeared and flourished, is at least partially removed from its domination today, whereas other disciplines, which acquired determinism second-hand, are still strongly attached to it.

The goal of this study is to present the various stages of these crises. In this respect, we can afford to differentiate the crises into three phases relating to the recent past, the present, and the indefinite future. From another point of view, we could characterize these three principal subdivisions by the different functions they were in the past, are now, and probably will in the future be expected to fulfill. The first, which relates to the past, can be considered as a crisis of interpretation, questioning not only the universality of the mechanistic vision, but also the access of physics to a wider range of ideas; this allowed physics to delimit the permissible scope of its vision. The second phase, dealing with the present situation, is, in my opinion, especially noticeable as a crisis of expansion, in the sense that we can question the degree to which the interpretative framework of physics as a whole, whether in its classical form or in the enlarged form which issued from the first phase of crises, can effectively extend its applications; this poses, in other terms, the problem of the capacity of our sense and faculties for penetrating the realm of physics itself. Concomitantly, the question of whether or not new ideas will contribute to removing, or at least minimizing these limitations, constitutes what I shall call the third phase, necessarily relating to the future since it is only just beginning to appear in a very few examples which may be viewed as heralding symptoms.

It is hoped that my attempt to study what has been happening in the science of physics for nearly three quarters of a century

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on these three levels will help to establish the outline of a fairly broad overview, and will allow us to evaluate the extent to which the crises themselves are due to elements taken from various areas of human culture.

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In order to understand how the deterministic interpretation of physics came to dominate the entire classical perspective, it would perhaps be useful to try to formulate the basic structure of modern science, and, in this respect, demonstrate how all its constructions stem from two roots which are different both in the domains of their action and scope.

On the one hand, the experimental method, introduced as early as Galileo, consists essentially in the observation of facts and their correlations, each of which, when verified, constitutes an empirical law. The numerical expression of these laws was, in turn, introduced through the quantitative definition of physical dimensions that could be reproduced at will; the relative simplicity of these relations permitted their mathematical expression. Taken as a whole, they constituted experimental science.

On the other hand, human intelligence is not content with simply observing; it has to link various observations together. Thus, theory appeared, consisting in attempts to derive logically all empirical laws from a certain number of postulates; the fewer the number of postulates with the greatest number of consequences, the better the theory. No one theory, however, could be considered as definitive: it was always possible for a new empirical law to appear which contradicted previous results; the theory then had to be modified, or enlarged to include the new fact. This situation imposed the necessity of continually renewing science, and its history consists of a series of constant readaptations. We conclude, then, that although there is nothing wrong with empirical laws, since they translate the evidence given to our senses, this is not at all the case with theory which, as a conceptual framework superimposed on the phenomena, is in a way essentially subjective, and thus likely to force certain points of view onto the physical world which it interprets.

Yet it is fairly easy to recognize that the very structure of the mathematical formulation of classical physics very naturally lent

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itself to a mechanistic type of philosophy. This is a consequence of the fact that most of the fundamental laws of this kind of physics express relations between infinitely small values by means of what are called differential equations. The temptation of imposing a philosophical system onto a scientific structure resides in the procedure by which we, so to speak, integrate these equations. On the one hand, the differential equation is such that its integration allows us to deduce, for example, the characteristics of a moving body, its position and velocity at any given time, from the initial values of these two dimensions. It follows that by simply knowing the initial state of a system, and armed with the laws of motion, its future behavior can accurately be predicted. The philosophical extrapolation of this observation leads us to accept a determinism, implying the absolute dependence of all consequences on some preceding situation. On the other hand, the classification of fundamental laws in the differential, that is, the microcosm, and the deduction of macroscopic properties by integration, implies, on the philosophical level, the dependence of the complex on the elementary. From here, we proceed to the inverted pyramid conception which derives the origins of all things from the atom, and naturally reduces the properties of bodies to those of their smallest constituents, and, by extension, the organic to the inorganic, biology to chemistry, thought to life.

In my opinion, however, this microscopic determinism, whose double roots I have just presented, acquired its complete philosophical elaboration only when it accepted, more or less explicitly, the full reality of the micro-causality of the physical world, assigning its intrinsic source to matter. And this entirely gratuitous materialistic hypothesis, turning against itself, conditioned the vision of classical physics on which it exerted its greatest influence: masses or electrical charges, for example, seem to attract and repel one another by means of some "thing" which allowed them to act on each other at a distance. Physical objectivity would have us say, "everything takes place *as if* bodies attracted each other in direct proportion to their masses and inversely to the square of their distance. The effect of the materialist influence consists in our having to suppress the expression "everything takes place as if...," and simply asserting, absolutely, "two bodies (in fact) attract each other in direct pro-

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portion to... etc." Thus, instead of being a conventional representation of what we can observe, the law of forces becomes a part of matter itself, deified as being the cause of its own actions. This is equivalent to attributing a metaphysical function to the concept of force, which, we know, can only be measured by the effects it produces. But by providing it with an intrinsic attribution, the philosophical superposition makes it into a sort of *deus ex machina* which is able to predict the entire future of the sensible world. We can say that the burden of this conceptual framework on science was and remains very heavy: for in selecting it as the standard for scientific constructions, materialistic determinism seriously compromised science in the eyes of most people who, lacking any detailed knowledge of the relationship between materialism and science, were naturally led to confuse the two domains and to consider completely gratuitous postulates as having been proven by scientific experimentation.

The crises of physics, in the various aspects and phases which I mentioned above, all lead to a loosening and, to a certain extent, a break with this narrow correspondence; not so much as the result of any definite ideological scheme, but under the influence of intellectual tendencies of the times which were not, however, specifically scientific. These crises liberated physics from the shackles which impeded its progress, and gave it access to a wider and more varied selection of human culture, allowing it to differentiate and define its various fields of activity.

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The first phase of the crisis essentially concerns what is commonly called a physical model. In general, any conceptual elaboration which seeks to go beyond the mere facts contained in empirical laws, relies on a sort of image that is adopted as an interpretative hypothesis, whose concreteness provides an easily visualized basis for reasoning.

Some well-known examples of these conceptual images, or models, are, among others in the classical definition, the notion of force at a distance which I described above, the corpuscular vision of matter consisting of a group of independent points of matter, and the notion of radiation as waves moving through space. An even more elaborate model is that of the atom, pictured as a miniaturized solar system, in which the role of the sun is played by the nucleus, composed of heavy particles such as protons and neutrons, and the planets by electrons, capable of jumping from one orbit to the next; by these jumps, a number of phenomena of the macroscopic world can be interpreted with such a success that accuracy seems to be guaranteed. Finally, an even more general, although more abstract, model is that of an absolute time and space, measurable by means of definite rules and ideal clockwork mechanisms, which no one ever actually bothered to construct.

From what we have said about materialistic positivism, it is fairly obvious that its basic postulates necessarily imply the perfect realism of its models. In this sense, to use a medieval terminology, the classical vision considered itself to be a philosophy based on "realistic" models; the first wave of crises which it encountered, like a "nominalist" reaction, entailed considering the models as purely conventional representations.

The first example of such a change of perspectives originated in an idea which seems completely trivial today, so deeply has it become a part of our common mentality. I am referring to the notion of relativity, the equivalence of several points of view through adaptive transpositions, and, correlatively, the gradual and increasing disappearance of the notion of the absolute. At the beginning of the century, under the pressure of the theory of relativity, the impact of this general way of feeling shattered one of the central pillars of the classical vision, namely, the conception of the existence of an absolute system of reference. Until Einstein, it was accepted that there was only one system of reference in the cosmos in relation to which certain physical properties, such as the regularity and isotropy of the speed of light, could in fact be verified. The theory of relativity demonstrated the impossibility of such a system and proved the equivalence, in terms of the validity of the properties it defined, of all systems of reference. If Einstein had not been entirely convinced, as a man and as a thinker in general, of the relative nature of all things, would he have ever been led to discover the solution to the problem of reference systems in the concept of relativity, and would he have replaced the absolute model of space and time with relative space-time?

Another example, closely linked to the first, considering that

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relativity tends toward an anti-metaphysical position, appears in the proscription from the domain of science of what, in the materialist perspective, constitutes a dogmatic aphorism, namely, the conception of force at a distance. In fact, the coherent development of electromagnetism, which was made possible through the formalism derived from the theory of relativity, demonstrated that all particles which have an electrical charge emit and receive waves propagated at the speed of light; and this exchange of information gives rise to the forces of attraction and repulsion, previously interpreted as force at a distance. By means of this, the ever so slightly transcendental model was advantageously replaced by a group of signals which is fairly clearly inspired by a similar practice in human activity.

But the ideational element which exercised the most disconcerting influence on the classical mechanistic conception was the whole trend of doubt, skepticism, and awareness of the difficulty of reaching the bottom of things, which we no longer notice in modern man for whom it has become second nature. Originally, it must have seemed to be antagonistic to the perfect clockwork mechanism of physical determinism. And it is precisely on the masterpiece of this conception, the semi-classical model of the atom, that, in the third decade of our century, the tidal wave broke, shattering our conception of the microcosm, as well as our capacity of interpreting it.

As I recalled earlier, the model of the atom in classical physics represented its constituent elements as being literally analogous to microscopic iron balls, governed by the well-known laws of mechanics and electromagnetism. However, as a consequence of the discovery and interpretation of a certain number of phenomena which we can group under the heading "quanta," physicists were obliged to modify not only the model of the atom, but also the body of laws that pertained to it; they went so far as to construct a new body of doctrine, known as quantum mechanics, which was radically different from the laws of classical physics, and which alone had any validity on the level of the microcosm.

To give a very brief idea of what it is, we can say that, first of all, it is a rejection of the atomic model as an assemblage of iron balls. The empirical evidence which supports it shows that while the initial model was adequate for interpreting a certain number of phenomena, others proved to be in flagrant contradiction with it. More explicitly, any fundamental physical entity, be it light, electrons, or protons, is, on the one hand, experimentally identifiable by means of certain properties such as its mass or its specific quantity of movement; this naturally leads to a corpuscular image. On the other hand, this same physical entity, light, electrons, or protons, gives rise to phenomena of interference, typically found in optics, which can only be interpreted in terms of a wave model; this is absolutely incompatible with the corpuscular model, at least for the human imagination. This fact, inconceivable in terms of a model, by which the very same physical entity gives rise to corpuscular as well as wave phenomena, obliged physicists to create a dualist and apparently contradictory vision, combining the two conceptions. Inconceivable on an intuitive level, it nevertheless explains the various characteristics of the particle. In other words, the dualist theory is a sort of model that provokes a crisis in all intuitive models and demonstrates their inability to account for the reality of the atomic world. Henceforth, the physicist must realize that in speaking, for instance, about a particle, he is using a practical image to visualize certain phenomena which is entirely false with regard to other phenomena. He can no longer ignore the fact that he is using a fiction which only very imperfectly translates an undescribable reality. Thus, he becomes used to assigning a conventional meaning to the models in question, since the facts he observes force him to deny their reality.

The state of the atomic world might also be characterized by saying that the different dimensions which we use to describe a physical entity are not all observable simultaneously. Whereas in classical physics the movement of a particle was completely determined by its position and velocity at any given moment, this double determination appears, in reality, to be inapplicable to atomic physics. For example, if we are able to identify the position of a particle, this very measurement makes it impossible to determine its speed. This is not due to any imperfection in the instruments of measurement, but to the fact that the measurement itself can only take place by means of a physical agent, such as light, which, when diffused by the particle, reveals the actual state of the particle; this agent, which is not a spirit but a physical entity, interacts with the particle, modifies its situation,

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and therefore alters its velocity in unpredictable ways. Thus, while the particle can be represented as a localized body at a given moment, after a certain time it will inevitably have lost that definition, and can then be better described as a wave moving over a vast portion of space; but in that case, the initial corpuscular description will have been abandoned.

These considerations, brief though they are, make it clear that while the old conception of matter, with all its heavy literal realism, naturally tended toward a mechanistic vision of the world, the new "model" of the quantum domain, which is not really a model, tends, on the contrary, toward a sort of agnosticism. The new rules of the atomic world show us, in fact, that our information can only attain a certain level of determination; there is a whole realm beyond identifiable causality which we cannot attain by our present means of information and which we call the inherent indetermination of atomic magnitudes of the physical world. This should be understood not as an affirmation of the non-existence of determinism in this domain, but simply as our inability presently to deal with the problem. We can only measure the probability that some phenomenon will occur, but we cannot predict whether in a particular case it will actually occur. Certainty is only statistical and the individual phenomenon escapes all possibility of exact prediction.

In summary, during the course of several decades, the evolution of the concept of model has permitted physicists to modify radically their mental attitudes. From blind faith in the realism of the mechanistic model, they were led to a sort of critical skepticism. Furthermore, whereas faith in the positivist model, as all faith, was oriented toward conquering new domains, entering into conflict with all conceptions that contested its basic postulates, the agnostic and possibility-oriented attitude places no *a priori* burden on that which may exist beyond the limits of experimental research, and consequently leaves the field open for all arguments relating to the contents of this prospective knowledge. The incredible elasticity of mind acquired through the emergence of quantum physics reflects the growing intellectual freedom in science, and the higher incidence of such an attitude in the common culture of the twentieth century; it is certainly one of the factors which instead of naturally repressing the wave of criticism which invaded physics, allowed it to develop and increase during the later phases of the crises with which I shall now try to deal.

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We might have imagined that after the first crisis, with the necessity of having to elaborate and master such a vast domain of knowledge, governed by the classical laws and the theory of relativity on the level of the macrocosm, and by quantum mechanics on the microcosmic level, rising to astronomical dimensions and descending to the atom, physics would have been left to a phase of respite and calm development. But in fact, today's research must face a second period of tension due to the encroachment of its most active parts beyond established frontiers in hopes of invading still unknown regions. This effort puts physics in contact with what I would call, in a general way of speaking, the mysterious, a term which refers not only to what we do not presently know, but also to that which belongs to the physical world but which, for one reason or another, might never be apprehended by scientific methodology.

Such circumstances give rise, today, to a situation that is quite different from the previous one. The state of crisis issuing from contact with the mysterious has not yet produced its solutions. Objectively, we can only indicate the difficulties and hope that in the future, that temporal region of the foreseeable third phase of the crisis, we will find the germs of new ideas that will lead us out of the maze.

The orientation of the most active research is, at the present moment, divided along not two, but three principal fronts of contact with the unknown, all of which diverge from anything on the human scale. Besides the orientation toward the infinitely small and the infinitely large, we must include the line of research on the infinitely complex.

The main questions which emerge from these different orientations can be essentially formulated as follows: on the one hand, is it possible to exhaust the content of the physical world, in all dimensions and on every level of complexity, by means of the known laws of classical physics and quantum mechanics? Can we consider that discoveries on other dimensions will simply reproduce, on a larger, smaller, or more complex

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scale, what we already know? On the other hand, from another but only apparently different point of view, as we gradually change our conception of dimensions, should we suppose that the gravitational and electromagnetic forces which govern on astronomical and atomic scales, will always and forever be the same? Or should we foresee that new domains will contain qualitatively different physical situations and new types of interactions which will have no resemblance to the existing ones?

The most accurate indications we have at the present time can be found along the line of research concerned with the elementary structures of matter. Some thirty years ago, the nucleus of the atom was supposed to consist of a very limited number of particles, protons and neutrons, whose behaviour, it was hoped, could be interpreted in the conceptual context of quantum mechanics. Research, however, completely transformed this situation: it was discovered that the nucleus was held together by a series of new types of forces, termed strong and weak, for which no simple mathematical formulation has yet been found. The strong interactions, responsible for the principal phenomena of the nucleus, act through the intermediary of unstable particles called mesons. In high energy reactions, the nucleus disintegrates, giving rise to large quantities of new particles, of which we can now identify about one hundred, grouped in three large families, baryons, mesons, and leptons, according to their modes of interaction which are more and more complex as their number increases. To try to interpret this discouraging multiplication of physical entities, which are now far from being elementary, it is hoped that sub-particles will be discovered, acting as building blocks for the known particles.

The general picture which emerges from this research on the ever more minute can be compared to a kaleidoscopic image that we are increasingly incapable of analyzing. The idea that the macroscopic world can be explained as the result of the interplay of these smaller and smaller mechanisms, which seemed to work fairly well down to the level of the atom, seems to lose all validity as we delve further into the qualitatively different world of nuclear and subnuclear structures.

Examining the opposite direction of research, toward the increasingly large cosmological context, we find, perhaps with surprise, a totally different picture. Beyond the microastrono-

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mical scale (which includes the stars constituting our galaxy, as well as nearby galaxies, in the tens of millions of light years away), optical and radio-telescope research permits us to see several billion light years away. Several new and unknown structures have been discovered, radiogalaxies and quasars which, in all probability, are the result of colossal explosions, involving the most enormous amounts of energy we know of. Since the speed of light is finite, and therefore a distance in space is equivalent to distance in time, these far away objects appear to us as they were millions of years ago, constituting historical links which allow us to retrace the history of our universe backwards, as it were. We can thus observe that all the galaxies are moving away from us at a speed that increases with its distance, which seems to indicate that the universe is expanding. The most coherent explanation for such a situation consists in postulating the existence of an initial universe contained within a small but extremely dense volume which, as the result of an unimaginable explosion that occured about ten billion years ago, projected the galaxies like bits of torn matter in all directions of space; since then the universe has been continually expanding. The study of the laws of this expansion constitutes the domain of modern cosmology. But as soon as we enter it, we are surrounded with difficulties that prevent us from determining its exact geometrical structure: we would have to use the galaxies as reference points of light in order to evaluate it, but since we do not know whether the luminosity of galaxies remains constant over such a large scale of time, we may wonder if they actually provide a reliable standard of measurement. This is equivalent to not being able to dissociate two unknowns, in this case, the structure of the universe and the evolution of the galaxies. Should we wish to pursue our inquiry and ask about the causes and forces involved in the above-mentioned explosions, and ultimately about the initial and supreme explosion, we would discover that physics leads us to the brink of the very same mysteries, such as the question of the creation, which are at the root of all philosophies and all religions.

Thus the perspective which was naturally opened up by the study of the heavens, at the same time encouraged science to reflect the substantive foundation of the important mysteries which lie before man and his origins. For since physical evidence

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seems to show that space and time had an origin, it seems fairly plausible to think that, even if cosmology as a physical science has nothing to do with it, such a beginning, whatever it turns out to be, necessarily evokes a metaphysical base in the human mind which, as such, is outside of time, and for which the adventure of the corporeal world as a whole constitutes but a limited episode.

I shall be less explicit with regard to the third line of research, toward increasingly differentiated multicorpuscular systems. The effects of this tendency manifest themselves in a series of always more complicated aggregative states, as, for example, conductors and semi-conductors among the solids. But the most specific environment for complexity to develop in is a liquid one, where we find solutions, colloids, in which giant molecules are polymerized, forming associations such as amino acids and proteins. There is a point at which we are no longer certain when or how we leave the domain of chemistry to enter the domain of biology, with its viruses and cells, the various organized tissues, and ultimately, the vegetables, animals, and man.

Sensational discoveries in chemistry and molecular biology have made it possible to describe certain structures and to establish the effects and rules governing certain phenomena, such that a good number of biologists continue to believe in the somewhat anachronistic illusion that everything in biology can be explained in terms of mechanistic patterns. Personally, I am a little skeptical, and tend to believe that this illusion could perhaps be dispelled if we sought to distinguish clearly the pure facts, which remain undisputed, from the interpretative theories with which they are presented, and which are fairly gratuitous. Given the accumulation of the degrees of complication and the increasing number of unknowns which physicists have had to acknowledge in this domain as advances were made in the other two lines of research, we should expect, *a priori*, to find situations in the domain of complexity which cannot be reduced to simple initial givens.

In the most general sense, the first conclusion we can draw from this commentary is that the three directions indicate various degrees of expanding horizons, on different levels, riddled with stretches of fog which prevent us from grasping the real relationships and reciprocal ties. These blind spots are due

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to the fact that on certain scales, new types of forces appear, as with the nucleus of the atom; that modifications of the fundamental concepts, such as space and time, enter into play; or finally, that certain aggregations of molecules reach such a degree of complexity that interpretations in terms of two-body interactions, according to the rules of atomic physics, no longer make any sense at all.

Whatever the context in which these difficulties arise, we can perhaps identify a common denominator which, for a good part, if not entirely, constitutes the stumbling block: our lack of means for effectively dealing with the behaviour and interactions of a large number of bodies, be they elementary particles, gigantic molecules, stars, or galaxies. A certain number of problems concerning the properties of groups of elements have been brilliantly solved by mechanical statistics; but these solutions are applicable only when the number of objects in question is really enormous, when they are identical, or when they are in a state of equilibrium. Inevitably, one or the other of these restrictive conditions is missing from the problems we are concerned with here: the constituent elements of nuclear particles or organic macromolecules are not generally identical, and their number, while large, is not enormous; stars and galaxies are not generally in a state of equilibrium.

It seems probable, then, that whatever methodology is used in the future to deal with these types of problems, it will have nothing in common with the basic conception of current physics which is founded on elementary laws rooted in the microcosm and from which the macroscopic properties of bodies can be deduced by integration. This would imply the necessity of abandoning the usual forms of mathematical processing which are conveniently constructed to screen the substance of the sensible world through forms of reasoning derived from this very conception. Thus, we can justifiably ask ourselves the extent to which everything can be expressed in the available mathematical terms; if it is really worth the effort of trying to do so; and if the cases in which it is actually possible, far from being the established rule, are not to be considered as fortunate exceptions. After so many years of positivism, we can almost ask ourselves whether the substance of the physical world might not oblige us to forfeit a certain amount of the unknowable that is inherent

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in all things: God sometimes uses mathematics to show certain regularities; but he undoubtedly possesses other ways which we cannot easily grasp with our elementary patterns of logic.

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We have now to consider what I called the third phase of the crisis, which relates to the future since we may plausibly suppose that its role will be to discover methods capable of dealing with the problems created by the preceding phases. And, in spite of the danger involved in guessing about the future, basing ourselves on existing evidence, it is perhaps not too unreasonable to focus our attention on a few of the conceptions that may help us to indicate some guidelines for research, which have only recently emerged, in exceptional circumstances or on the margin of thought in physics.

We can say, first of all, that the main question regarding all dimensions, that is, concerned with treating the properties of a collection constituted by groups of dissimilar elements which are generally not in equilibrium, can be considered as a reflection in the physical world of one of the main problems facing human thought at the present time on all levels, social, political, moral, as well as religious: this is the relation of the individual to the collectivity, the integration of people with different intellectual and moral characteristics into a whole, which, rather than suffocating the individuals, reflects their traits, and imposes itself by means of a higher unifying principle whose specific features are not shared by any of its constituent parts; a whole which, as such, ignores and supercedes the competitiveness and contrasts, in a word, the micro-interactions between its elements which occur from one instant to the next, and allows only a stable, constant, communitarian, and thus, in a way, extratemporal state to emerge through its unity.

This brief statement on the human collectivity allows us to envisage two conceptions which may assume, by analogy, a guiding role in the new ways of dealing with the groups that appear in the context of physics: that of extratemporality, on the one hand, which dissociates the behaviour of the system as a whole from the temporal micro-causality of its constituent fragments; that of totality, on the other hand, in the sense that the whole possesses properties which are not equal to the sum of the properties of its parts. It is evident, however, that if these modes of thought are to provide acceptable alternatives to the current procedures of physics, they will have to fulfill the requirements contained in the following questions:

— are these new modalities capable of giving alternative interpretations to the current explanations formulated in deterministic terms?

— will they be able to surpass certain limits of our capacity for knowing things which emerged during the preceding phases of crisis?

Of course, since we are involved in making predictions here, I can only try to point out some examples of these types of interpretation which, taken from the field of physics, indicate that these ideas, alien to the principal deterministic line of thought, have occasionally been produced, some time ago, if only marginally. And we may suppose that the first of these enclaves constitute bridgeheads for the extension of these modalities into other portions of physical knowledge. For the sake of brevity, I shall give but one example in reference to each of the above-mentioned requirements these modalities must fulfill.

In regard to the first, I shall use as an example a principle whose results, in various domains of physics, are identical with those obtained through differential analysis, but which replaces the vision in which each stage is directly determined by the preceding one with a group of general conditions which act in a global and extratemporal way. I am refering to the variational principle which, formulated synthetically, states: "the true path of a moving body is characterized by the fact that its variational integral is a maximum or a minimum in relation to all other possible trajectories." This may seem to be a finalist, or at least totalist type of statement. The best known axiom of this type is the principle of Fermat in geometrical optics, which states that the path that light follows from one point to another is such that the time it takes to cross that distance is maximal or minimal. But we can show that any law of movement of a physical entity, while it is generally expressed in differential terms, can always be written in a form derived from the variational principle; such that it is permissible to conclude that physical laws as a whole can be expressed in two different equivalent modalities, differential and total. But while the law is stated in a deterministic and causal language in the first case, the same law is expressed globally in the second case, for the variational integral holds for the whole length of the trajectory, representing a sort of extratemporal image which identifies, at first glance and before it occurs, the real trajectory from all the other possible but false ones. Thus, no longer does each stage appear to be conditioned by the stage that immediately preceded it, but it is predicted in a global way outside the flow of time. This shows that, since the two procedures are mathematically equivalent, temporal determinism and the integral glance, far from contradicting one another, are simply alternative ways of understanding the same phenomenon. The reason we generally use the differential version is merely a practical one, since we know how to solve the equations involving motion and can therefore calculate the trajectories in simple cases. But when it is affirmed that physical reality is conditioned by temporal succession, a practical procedure is made into a philosophical axiom, and the reality of the global aspect is ignored simply because, until now, we did not know how to use it.

The second example is intended to demonstrate how new conceptions which have imposed themselves over the last few decades in the domain of physics, have a strength of interpretation which far exceeds that of the differential deterministic vision. The power of these conceptions is derived from the notion of totality, as previously defined, which is the key to explaining certain facts that we would be incapable of translating into the language of differential conditioning of successive stages. Specifically, these are the principles of symmetry and asymmetry, basic to the physics of particles, according to which a group of photons, electrons, or protons, behave according to unpredictable laws which are different from those that govern these particles taken individually; the totality of electrons, for example, has properties that are not understood and are unpredictable in terms of the mechanics of single electrons, but depend on the properties of wave phenomena which represent them as a whole. The best known example of this type is given by the electrons on the various energy levels of the atom, according to Pauli's principle of exclusion. Each electron, by itself, would sponta-

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neously tend to find the deepest level of energy, and we would expect all the electrons to place themselves on this fundamental level. But it is precisely at this point that the constraints of the totality appear, limiting to two the number of electrons, with opposite spins, that can occupy the same energy level. This requirement makes it so many energy levels are filled, independently of their depths. Of course, the atom which is thus constituted is qualitatively different from what would have happened if all the electrons had sought the deepest level. Thus, the whole has properties which are independent from those of its parts.

The requirements of symmetry and asymmetry, responsible for these effects, are considered today as a general property of all fundamental and composite physical entities, and we would be hard pressed to cite laws which have a wider scope. This is perhaps sufficient to measure the breadth of vision these laws entail. Hence, far from appearing to be the result of competition in a disorganized mob, whose temporal evolution would reside in the momentary and unpredictable products of reciprocal interactions between participants, the dynamics of identical particles as a whole presents itself as being activated by a general principle which constitutes a sort of organizational factor, imposed from without, a fixed motor that orders and harmonizes the whole according to some higher idea.

These examples, borrowed from already well-established domains of physics, are cited as illustrations that are likely to evoke analogies by which we may be able to apprehend virtual possibilites for the enhancement and elaboration of the conceptual framework of scientific interpretation. But up to what point, and by what means? It is obviously impossible to say precisely today. To get some idea, we can only speculate on the indications which have perhaps emerged from the ideas presented herein, and which I shall try to synthesize in conclusion.

The most striking element in the panorama I have attempted to sketch in this article is, perhaps, the mental variability of the interpretative framework of science. The facts and observations accumulate and overlap as science progresses; but not the theories they lead to. We must not, therefore—and this is the first and most important lesson to be drawn from the successive crises in physics—presume too much from science, or imagine that it will inform us about things outside its domain, or especially that it can prove the truth of one philosophical system or another.

A second point which I would like to stress can be summarized in the observation that, as new domains of physics are opened to research, there is an increasing complexity demanded of our abilities for understanding. In complete opposition to the optimism of positivism, according to which the fundamental ought to be simple, we observed that the more we discover about the infinitely small, the infinitely large, and the infinitely complex, the greater the necessity of relying on abstract concepts that are far removed from a purely mechanistic rationality, and similar to those which emerged through the notion of relativity, indeterminism, and which seem to emerge from the situations which constitute the actual crisis of physics. We should not be surprised by such a state of affairs: whatever is simple lends itself easily to the usual categories of human thought. And given the adaptability of our faculties to the circumstances and the environment, what is strange about our intelligence being modelled on that which is within our reach, and consequently drawn to our scale? If this is true, should we not logically expect that the discoveries in domains that are far removed from what was providentially assigned to us will inevitably stumble on what I called the mysterious, and that our attempts to interpret it will necessarily have to rely on increasingly profound faculties and intuitions which will probably only appear as we delve further into the unknown that constitutes the very foundation of human nature and which, like a fourth infinity, would allow us to apprehend the reflections of the other mysteries of things?

The third general observation we can make about the past and present crises indicates that every time a scientific progress is made, two factors, in one sense contradictory, but also complementary ones, are always involved. On the one hand, there are the facts: the experiments which produce situations which the concepts in use are no longer able to explain. The facts pertaining to this new reality become the source which stimulates and provokes a new wave of ideas. But, on the other hand, once these new ideas have come to terms with the difficulties, we realize that they are nothing more than a particular reflection,

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oriented toward a specific goal, of an intellectual trend which pre-exists and determines, in a way, the intellectual character of the era during which the new discovery develops and matures. What are we to conclude? Is it that the crucial fact suddenly appears at the same time as the trend of thought that contains its solution? Or, on the contrary, is it that the crucial fact possesses, virtually, several possible interpretations, and the one that comes to prevail is simply a better reflection of the mentality of the times than the others? Or, finally, is it that the fact itself contributes to the domination of the trend of thought which was called on to provide the solution? I should be wary of answering such a dilemma, which is perhaps not really a dilemma if we realize, as the ultimate conclusion of any slightly elaborated effort of reflection, that our logic fails to exhaust all the roots of things, and that the correspondences between the various facets of the material, the vital, psychological, intellectual, and spiritual universe, which we often observe without being able to explain, could lead science along lines that we do not even suspect, pertaining to a domain that man, by his only intelligence, must admit not being able to master, but of which, from the source of his being, he has a profound intuition.

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