# The unity of physics

## With the trend toward increasing generality during the development of physics, will we one day be able to represent all our physical knowledge by a single deductive logical system?

Edoardo Amaldi

What is the "unity of physics" and how far can it be accomplished? Before considering these questions let us look at a wider problem—the unification of all the sciences. This is itself a special case of an even wider question, the unification of all human knowledge, which I cannot dwell on here. The term "unification of the sciences" usually refers to a unification of the *results* obtained in the sciences; the problem of coordinating the scattered and immense body of specialized findings into a systematic whole is a real one and cannot be neglected. It includes a comparison of the methods and results of cosmology, geology, physics, biology, behavioral science, history and the social sciences in different ages. But first of all it implies a unification of scientific *language*. Some difficulties in science, even within a specialized discipline, arise because one cannot be sure whether two scientists speak about the same or different problems or whether they state the same or different opinions in their different scientific languages.

But there is always the question of unifying the efforts of all those who apply the scientific method to collective and social problems, so that these efforts may gain the force that comes from united effort.[1] Very often attempts to apply the scientific approach to certain problems are hampered (and sometimes defeated) by obstruction due not merely to ignorance but also to active opposition to the scientific attitude on the part of those influenced by prejudices, dogma, class interest, external authority and nationalistic and social sentiments. From this point of view the problem of the unity of science constitutes a fundamentally important social problem.

Having thus established that a need for scientific unity exists, let me now turn to my main topic, the problem of the unity of physics.

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### The naive form of unity

I will try first to introduce a historical perspective by recalling two lectures given by Max Planck in Leiden. The first of these took place on 9 December 1908 at a time when Antoon Lorentz and Kamerlingh Onnes were still active, and its title was "The unity of the physical picture of the world" [*Die Einheit des Physikalischen Weltbildes*].[2] The second lecture, delivered twenty years later on 18 February 1929, was called "Twenty years' work on the physical world picture" [*Zwanzig Jahre Arbeit am Physikalischen Weltbild*].[3]

The first lecture begins with the remark that, from the beginning, the science of nature had as its greatest goal a summary of the extreme variety of physical phenomena in a unitary system, possibly in a single formula. Thus the water of Thales, the energy of Wilhelm Ostwald and the principle of least curvature of Heinrich Hertz were considered, in turn, as the center and the essence of the physical image of the world, in which all physical processes should be framed and should find their explanation.

Planck argues that, in order to understand the direction of development of physics, one should compare the present situation with that prevailing in a previous epoch. But, he continues, the best indication of the stage reached by the development of a science is provided by the way in which its fundamental concepts are defined and its main parts delimited. The point made by Planck is that the subdivision of the matter of study and the definitions, when rigorous and appropriate, very often contain implicitly the latest and most mature results of the scientific investigation. He notes that the edifice of physics in 1908 was completely different from the primordial one, when the various parts of physics originated from immediate practical necessities and from particularly conspicuous phenomena.

In 1908 physics appears—again according to Planck—with a much more unitary character; the number of its "chapters" is considerably diminished because some of them have amalgamated. Thus acoustics had become a part of mechanics; magnetism and optics had become parts of electrodynamics.

This simplification is accompanied by an impressive disappearance of historical and human elements from all definitions. For example, in the study of electricity no one thinks any longer about rubbing amber with silk, and in the study of acoustics, optics and heat the physicist no longer takes account of the corresponding sense perceptions, but refers instead to frequencies or wavelengths and to the absolute thermodynamical scale.

The general trend of the development of physics appears to be towards a unitary system, independent from anthropomorphic elements—especially sensory judgments. The principal parts of physics by 1908 were reduced to two, mechanics and electrodynamics, or, in Planck's words, the physics of *matter* and the physics of *ether*. Moreover, the limits between these two fields were not completely clear since, for example, it was difficult to state to which of these two parts of physics the emission of light by atoms belongs.

After these considerations, Planck moved on to discuss the general principles that would certainly play an essential role in the process of further unification. He concentrated his attention on the first and second laws of thermodynamics, dwelling upon the relation between probability and entropy and the conceptual difference between these two fundamental laws, the first of which absolutely forbids perpetual motion of the first kind whereas the second shows only that a perpetual-motion machine of the second kind has an exceedingly small probability.

The same general subject was again discussed by Planck in his lecture of 1929; he notices, of course, that in the meantime the situation has changed completely—mainly because of the advent of quantum mechanics. His attention is now concentrated mainly on the probabilistic description of the atomic phenomena, and on the meaning of the expression "sensory world" and its distinction from the "real world" that—in Planck's opinion—should exist in itself independently of Man. Planck recognizes that the existence of a "real world" is certainly not imposed by logical, "intellectual," considerations, but he claims that it is imposed by the reason [*Vernunft*], which, together with the intellect, governs physics as it governs all the other sciences.

He notes that with the passing of time the image of the "sensory world" becomes more and more abstract, and he interprets this tendency as due to the progressive approach to the "real world" (which however remains unknowable, in principle). Then he argues that, in this process of approach, the image of the world should become increasingly free of all anthropomorphic elements. Therefore, any concept connected with the human technique of measurement cannot be accepted as part of the physical "image of the world." For this reason, Planck concludes, the probabilistic interpretation of quantum mechanics, and in particular the uncertainty principle, cannot be accepted as definitive parts of the edifice of physics.

I have dwelled at length on these two Planck lectures, not in order to take a critical attitude with respect to some of his views, but because of the lessons that we can learn from them. It is very instructive to consider, about half a century later, how the problem of the unity of physics was set up and dealt with by the scientist who introduced the quantum of action to physics and thus opened the door to one of the most important upheavals of modern scientific thought.

I will not enter the discussion of the Copenhagen interpretation of quantum mechanics, which was clearly unacceptable to Planck. He insisted on the existence of an unknowable real world separated from the world of our sensory perceptions, which, as he recognized explicitly, is the only one knowable to Man.

The same problem is still under discussion today. Attempts have been made to change the language used for interpreting quantum mechanics to give it a closer resemblance to classical physics; other attempts are based on the use of "hidden parameters" that escape detection but determine the outcome of experiments in the causal way typical of classical physics.[4] However, I cannot here embark on a review or summary of this work—it would take me too far away from my main subject. But I will point out just one fact, a platitude perhaps but in my opinion far stronger than any argument of principle: Today every physicist (or, more generally, any pure or applied scientist) uses the formalism of quantum mechanics in his daily work and discusses his problems and expresses his results in a language typical of the probabilistic interpretation of this theory, irrespective of his political or religious opinion and of the society in which he lives. This widespread consensus provides a kind of measure of the objectivity of the quantum-mechanical description of phenomena. Of course quantum mechanics will also, most probably, be eventually overcome, but we do not yet have any idea of when, how and in which direction this change will take place. What appears today to be improbable is that such a step forward will provide a description of the observed phenomena closer to the classical conception than that suggested by quantum mechanics.

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On reading Planck's lectures, one should recognize that the fact that his arguments (and, here and there, even his language) appear so naive and old-fashioned reminds us how ephemeral are all considerations of general nature, especially when compared with new basic physical concepts and formal procedures such as the concept of the quantum of action and the quantization of the harmonic oscillator.

### Partial unification processes

Looking back, one has the impression that the historical development of the physical description of the world consists of a succession of layers of knowledge of increasing generality and greater depth. Each layer has a well defined field of validity; one has to pass beyond the limits of each to get to the next one, which will be characterized by more general and more encompassing laws and by discoveries constituting a deeper penetration into the structure of the Universe than the layers recognized before.[5]

In this descriptive frame a number of partial unification processes do take place, some of which have a vertical, others a horizontal, nature. I use the adjective "horizontal" to specify the unification of different chapters or parts of physics, as in the cases mentioned by Planck in his 1908 lecture. The vertical unification refers to relationships between the descriptions of the same phenomena provided by theories belonging to layers of knowledge of different depth. In many cases a horizontal unification carries with it, or derives from, a vertical one and vice versa.

Processes of partial unification of both types have been going on at an extraordinary pace during the last fifty years. The most important steps in this direction are connected with the advent of quantum mechanics and its successive applications.

Among these one should recall the study of the structure of matter in general, including an adequate description of vast categories of atomic and molecular, liquid and solid-state phenomena. These developments, begun in 1926–27, are still going on and have opened the door to a large number of applications, many of which are of paramount importance.

The same should be said about the application of quantum mechanics to nuclear processes and nuclear structure, where often the same basic concepts are used as in the study of liquid and solid states.

Other important processes of unification took place during the 1950's. One is a kind of vertical unification resulting from the recognition that the macroscopic parameters, describing the observed properties of matter, can be expressed in terms of spatial and temporal correlation functions. They are embedded in the quantum-statistical description of the system, without any recourse to specific models.[6]

Whereas space correlation functions were used since 1927 by Frits Zernike and J. Prins[7] and by Peter Debye and H. Menke,[8] the first example of space- and time-correlation functions was given by Léon van Hove in the problem of the scattering of slow neutrons by matter.[9] Subsequently various macroscopic parameters, such as the dielectric constant, the magnetic permeability, the electric and thermal conductivity, and so on, were all obtained by the same two-stage procedure:[10] the first stage consists of expressing these parameters in terms of two-particle time-correlation functions, the second of a Fourier transformation of these correlation functions and of taking its limit at infinite wave length.

An interesting example of horizontal unification is provided by the recognition that different phenomena occurring very near the critical points show quite marked similarities. The molecular-field approach brings in the concept of an "order parameter" and suggests that there are close relations among different phase-transition problems. A different theoretical approach, known as the "scaling law," predicts relations among the critical indices used to describe singularities in the various correlation functions and thermodynamical derivatives.[11]

The field theory, created and developed as a unifying thinking frame, attempts to describe all known types of interactions between subnuclear particles by analogy with the electromagnetic field. In the electromagnetic case the interaction between two charged particles is mediated by photons, and the use of perturbative methods is fully justified by the smallness of the coupling constant. These methods have allowed the computation of all observed purely electromagnetic phenomena with very high accuracy. But the theory of the electromagnetic field is affected by a few constitutional faults: Their influence on the results to be compared with experiments is eliminated by means of mathematical devices such as renormalization. These procedures cannot be considered as fully satisfactory, in view of the absence of a proof of the convergence of the perturbative expansions.

When one passes from the theory of the electromagnetic field to the theory of other interactions, the situation becomes much worse. It is true that in the case of the strong interactions, for example, the first steps in this direction were marked by a few fundamental discoveries, such as the existence of mesons as suggested by Hideki Yukawa. But successive developments have met unsurpassable obstacles that arise because the use of perturbative methods cannot be justified, on account of the very large value of the coupling constant. Thus, in this case, one no longer has a computational procedure capable of providing numerical results sufficiently accurate to allow a significant comparison with the experiments.

In the case of the weak interactions the coupling constant is much smaller than that of the electromagnetic interaction, so that, at first sight, one would expect the application of perturbative methods to be fully justified. This is true, but as a consequence of the fact that the weak interaction involves the product of the amplitudes of four particles, the coupling constant has the dimension of an energy raised to the power minus 2, ($M^{-2}$), and the theory is not renormalizable.

Furthermore the W meson, which has been hypothesized as the mediator of the weak interactions (in analogy to mediators of the electromagnetic and strong interactions, the photon and the $\pi, \rho, \ldots$ and K-mesons), has not yet been observed despite various experimental efforts toward its discovery. There are arguments suggesting that its mass should be so large (not less than 37 GeV)[12] that it cannot be produced by existing accelerators or by those now under construction. It could be observed in cosmic rays as a secondary product of very high energy muons. But for the moment it remains a purely mathematical device for describing the weak interaction in the language of field theory.

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We cannot assert today with any certainty that field theory provides a satisfactory unification of the description of the different interactions. It is based on analogies and extensions that appear very reasonable, but which, after all, derive from the presupposition of a uniformity of structure of the observed world, which *a priori* is not justified.

An interesting historical precedent of such a search for a similar uniformity of structure that went on unsuccessfully for many years is provided by Einstein's theory of gravitation.[13] At its appearance in 1919 this theory conquered the scientific world with its elegance, simplicity and amplitude of conception. Consequently for about ten years many of the greatest theoreticians of the epoch considered that this theory constituted the model to which the future developments of physics had to conform. Many physicists were convinced that a further extension of the two Einstein principles (the representation of physical reality as geometrical, and the invariance with respect to general coordinates) would have led to the understanding of the chief phenomena that remained outside the original theory of Einstein; that is, the electromagnetic field and matter. These attempts, however, were unsuccessful, and the theories of matter and electromagnetic field were developed along a completely different line with the advent, in 1925, of quantum mechanics.

The possibility that a similar situation may emerge in the case of quantum electrodynamics should be kept in mind. After the first steps, made in the period 1928–30 mainly by Werner Heisenberg, Wolfgang Pauli, Paul Dirac and Enrico Fermi, and the great successes, obtained in 1946–48 by Sin-itiro Tomonaga, Julian Schwinger, Richard Feynmann, Freeman Dyson and others, the majority of physicists arrived at the conviction that quantum electrodynamics had to represent the model for the construction of the field theory, in particular for the case of the mesonic field. But today there are indications that some experimental observations of subnuclear particles may require theoretical concepts that fall outside the framework of field theory.

One should recognize, however, that the formalism developed for field theory, in its nonrelativistic approximation, has found wide and important applications in nuclear physics, and in solid- and liquid-state studies. The concepts of quasi-particles, of phonons, rotons and magnons, represent constituent elements of these constructions, which are essential parts of what we call the "observable world," or "reality," no less than the concepts of electrons, neutrons and neutrinos.

Among the adaptations of the methods of quantum field theory to quantum many-body systems, one should recall the theory of nuclear matter and nuclei initiated by Keith Brueckner and collaborators[14] and developed by Hans Bethe, J. Goldstone, N. M. Hugenholtz and others.[15] Although not yet satisfactory from the point of view of providing the observed values of binding energies and density distributions, this approach is of considerable methodological interest as one of the few aiming to derive the properties of many-nucleon systems from those observed for the two-nucleon system.

Also the statistical mechanics of irreversibility and the development of the mathematical technique for treating dynamical problems known as the Liouville representation of quantum mechanics[6,16] originates from the reformulation, made by Ilya Prigogine and collaborators,[17] of results obtained by adapting the methods of quantum field theory to quantum many-body systems with irreversible behavior such as solids.[18]

In the domain of elementary particles there are other attempts at unification, formulated once again in the language of the field theory, which, although in their infancy, should be mentioned here.

The first attempt looks at the unification of the strong interaction and the gravitational field.[19] Its basic assumption is similar to the mixing of the photon with the $\rho$-$\omega$-$\phi$ complex ($\equiv\rho^0$); which had been previously postulated[20] in an attempt to stress that hadronic electrodynamics can, to a good approximation, be separated from lepton electrodynamics, with the result that photons interact directly with leptons but only indirectly with hadrons via $\rho^0$-$\gamma$ mixing.

By analogy, the attempt to unify strong interactions and gravitation is based on the assumption that mixing takes place between the graviton—the quantum of the Einstein field—on the one hand and some mixture of known, massive, strongly interacting, spin-2 particles on the other. In such a theory a graviton would interact directly with leptons, but only indirectly with hadronic matter.

The second recent attempt mentioned above refers to the unification of the electromagnetic and weak interactions. (The idea of combining electromagnetism and weak interactions is very old.[21] The first successful attempt is that direction is due to Steven Weinberg, who has been followed by others.[22] The postulated Lagrangian is invariant with respect to a non-Abelian group, a condition that may make it possible to explain the universality of the charge and, at the same time, achieve the renormalizability of the theory.)

### An overall unification of physics?

These examples, as well as many others that can be taken from different chapters of physics as well as from many interdisciplinary subjects, obviously illustrate one of the most important aspects of the theoretical development inherent to the various fields of research. They do not, however, refer to the unification of physics at the largest scale, by which I mean the organization of all our present knowledge of the observable world in a single deductive logical system. The existence of such a logical structure was a basic assumption of the Laplace description of the world, and was clearly accepted by Planck, at least in 1908.

The problem of such a unification has been reexamined in recent years by Carl F. Von Weizsäcker[23,24] who organizes our present knowledge of the physical world in five interlinked fundamental theories:

1. A theory of space-time structure (special or perhaps general relativity)
2. A general mechanics (quantum theory)
3. A theory of the possible species of objects (elementary-particle theory)
4. A theory of irreversibility (statistical thermodynamics)

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5. A theory of the totality of physical objects (cosmology)

Theories of special objects such as nuclei, atoms, molecules, wave fields and stars do not appear in Weizsäcker's list, since they can in principle be derived from fundamental theories. Weizsäcker notices that we are today inclined to consider the theories 1, 2 and 4 as more or less final, whereas much work is being done in order to find 3 and perhaps 5.

He notes that these five theories appear to arrange themselves like parts of a systematic unity of physics that is yet seen rather confusedly. The principle of this unity can be expressed, by saying: There are objects in space-time. Hence an account of space and time must be given (1). Being in space and time means for an object that it can move. Hence there is a set of general laws that govern the motion of all possible objects (2). All objects can be classified in more or less distinct species. Hence there must be a theory telling what species of objects are possible (3). This theory describes objects as composites of more elementary objects. The composition can be described in detail, leading to the higher species (atoms, molecules, and so on). It can also be described in a statistical manner (4). All known objects somehow interact, or else we would not know about them. Hence some theory about all existing objects may be needed (5).

This preliminary account of a possible unity of physics shows, however, a number of shortcomings when the interlinkage of the theories and the problems connected with the concepts used in their description are analyzed more closely. Thus, for example, the interlinkage between the two theories 1 and 2 was discussed, years ago, by Eugene Wigner and H. Salecker.[25] From an analysis of their basic concepts Wigner concluded that "there is hardly any common ground between these two theories."

The concepts used in quantum mechanics, for example measurement of positions and momenta, do not appear to be significant if the postulates of the theory of general relativity are adopted. Among these there is the premise that coordinates are only auxiliary quantities, which can be given arbitrary values for every event.

Many other shortcomings are listed in Weizsäcker's 1971 paper.[24] Just to give an idea of the nature of his considerations I will recall his discussion of the interlinkage of theories 1 and 3, where the problem is faced that according to general relativity the space-time structure is described by gravitation, which on the other hand seems to be a field that one would like to deduce from elementary-particle theory.

Regarding the theories 2 and 3, Weizsäcker notes that quantum theory is described as stating the general laws of motion of all possible objects, while elementary-particle theory tries to describe all possible species of objects. It is not clear what this distinction means. Either these two theories will "in the end turn out to be coextensive and then, probably, identical, or objects will be thought of which would be possible according to general quantum theory, but which are excluded by the additional information of elementary-particle physics. The second alternative expresses the conventional view. But then the quantum theory of rejected objects turns out to be physically meaningless: should we therefore reject it?"

Weizsäcker recognizes that the search for the unification of physics is a project far transcending the work of any one individual or even of any one generation. He considers however, that such a search can get support from what he calls "philosophical guidelines" and that the detailing of these is his own main task.

He notes that certain basic concepts are common to the five theories listed above, such as object, space, interaction, time and probability, and he believes that their thorough analysis helps in preparing the tools for the construction of unified physics.

Concerning "time and probability" Weizsäcker argues that all science is based on experience, and experience means that we learn from the past for the future: physical laws set up on the basis of past experience are used to predict future experiments, which are verified in the present. Thus "time" is a presupposition of "experience," and a new logic of temporal propositions must be developed.

The term "object" presupposes "time": an object is something that remains identical with itself in time, though its contingent properties may change. In Weizsäcker's view the simplest and most general object is one characterized by a single twofold "alternative." The term "alternative" is introduced by him to indicate the possible outcomes of an experiment.

The concept of "object" is closely linked to the concept of "interaction," and interaction in turn is closely linked to "space."

Thus one of the philosophical guidelines of Weizsäcker for the construction of unified physics is that the mathematical structures of "space" and "interaction" should be developed jointly. In present-day physics the mathematical description of space, provided by the Lorentz group, is disconnected from interactions, and we do not have a general theory of "interactions" but only a promise of a beginning.

In Weizsäcker's scheme the analysis of "time" and "probability" (and of the two related terms "reversibility" and "indeterminism") leads to a theory of the probabilities with which changes in the observable state of any object can be predicted; that is, it leads to quantum mechanics, although not necessarily in its present form.

Finally, in collaboration with M. Drieschner, Weizsäcker tries to set down the foundations of a new form of quantum theory, conceived to provide a possible core to unified physics. This construction, however, appears (at least to me) rather arbitrary; so I will not try to summarize it, nor to present its main implications. I will only say that Weizsäcker's conclusions unavoidably remind one of those reached about 40 years ago by Eddington and by Milne, both of whom formulated general theories constructed to embrace all physical phenomena.

### Closed and open theories

The scheme for a unified physics sketched by Weizsäcker has clearly been conceived as an attempt to set down the foundations of a new "closed theory." This term was introduced by Heisenberg, who describes the past progress of theoretical physics as a series of distinct closed theories [*abgeschlossene Theorien*]. While the piling up of empirical data, and of their explanation by existing well established theories, appears to take place smoothly, the basic theories advance in infrequent great steps or jumps.

These jumps are certainly historically prepared for, but in many cases there is no accompanying feeling of growing clarity but rather increasing awareness of unresolved problems. This historical phenomenon is most clearly seen in the years preceding the formulation of special relativity and quantum mechanics, which represent the latest examples of closed theories. These are generally characterized by an intrinsic simplicity, although we are not able to define what the word "simplicity" means in such a context. In any case closed theories show a remarkable ability to answer those questions that can be clearly formulated within their own framework, and to give their followers the feeling that questions that cannot be so formulated may be altogether meaningless. In the historical sequence of closed theories each new one usually reduces its predecessors to some "limited" or "relative truth" assigning them the role of approximations or limiting cases. Thus we have learned to speak of the field of applicability of a theory, the limits of which are not known in the beginning and are clearly defined only by later theories.[24]

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The role and scope of theories is, however, not seen by all physicists with the same perspective. Many are of the opinion that a theory that pretends to comprehend everything is doomed to break down on this point. A closed theory in particular is often unnecessarily rigid, because it cannot incorporate new discoveries or concepts. Of course new discoveries may always upset some theory and wreck it completely, but in the opinion of Hermann Bondi,[26] for example, physicists should aim to shape theories in such a form that new discoveries won't upset every theory, and for that purpose plenty of open theories should be at our disposal. He attacks what he calls the type of heresy very popular about forty years ago, when Eddington and Milne put forward their overall theories. Today, says Bondi, there are attempts to find "the world equation" capable of telling us everything. One of the many objections that can be raised against this tendency is that an equation that says everything says nothing, because if the enormous variety of things that we see in this remarkably variegated world all spring from one equation, then the way from the equation to the observed things must be awfully long and difficult to deal with.

Bondi, of course, is aware that this remark could be interpreted as a criticism of all fundamental works. But such an interpretation would be wrong; what he tries to stress is that fundamental work is not only fully justified, but is also very important, provided it is maintained within reasonable limits. One should try in particular not to eliminate entirely the openness of the theory, so that its capacity to be adapted to new discoveries can be preserved. His view is that a theory is scientific only if it can be disproved, but the moment one tries to cover absolutely everything, the chances are that nothing is covered.

A number of remarks and questions appear to be in order at this point. First of all there is a certain confusion resulting from the fact that the expression "scientific construct" is currently used in the literature to denote two different things.

It is used in a restricted sense to indicate the idealized description of reality that becomes concrete through observations and experiments. The word "reality" refers to the ensemble of our (present and possible) observations, and the word "experiment" is intended in the Galilean sense as a reproduction of natural phenomena under conveniently selected, artificial, conditions. Such a construction refers to a well determined piece of the observed reality. It is *a priori* an unhistorical construction; it can be built (though not necessarily) as a unique logical deductive system. It helps us to construct even more general models.

The other meaning of "scientific construction" refers to a general image of the world; it is typically historical, because it involves the evolution of the universe (and of life) that is unique and unrepeatable. This construction should be unique and should have an ontological significance, but it is highly metaphysical and arbitrary.

A complete unification of science in

general, and of physics in particular, would involve the organization of theoretical constructions of the first restricted type, within a unique scientific general construction of the second kind. Such a unification certainly was impossible in the frame of the classical point of view, because of the absence of any element of freedom. A way out from such a difficulty may be provided by quantum mechanics, which preserves the most powerful methods of classical physics, such as the use of differential equations, and, at the same time, liberates single events from the determinism of classical type.

It should also be pointed out that such a unification, important for the physicist, is *necessary for the biologist*, because the various forms of life now

> *"There should be a unity of goals of experimental and theoretical physics, which sometimes seems to be forgotten."*

present can hardly be imagined independently of their evolution through the past.[27]

The unity of physics intended as the construction of a unique deductive logical system providing a satisfactory description of all observations and experiments has too many facets to allow a simple clear answer. Certainly present theories do not constitute such a system since they clearly have many points of mismatch or points of discordance.

A few scientists and philosophers have tackled the problem of constructing a deductive logical system of this type, convinced that the problem should have a solution as a consequence of what may be briefly called the "unity of nature."[23] But the meaning of such an expression is not clear if it refers to something different from the totality of our possible observations.

My remarks should not be taken as criticism of those that have made or are making these attempts, which are certainly very interesting, and in any case can be useful for clarifying and widening some deep aspect of the scientific construction. They help us underline a few problems to which we are not yet able to give an answer.

If one accepts, however, the schematic distinction between closed and open theories it is rather natural to ask oneself to which of these two categories would the unitary physical theory belong?

If it should be a closed theory, then one can consider two alternatives. Perhaps the theory is a final theory, which represents the final stage of our physical knowledge beyond which there is no further possible development. Alternatively, it may represent one further layer of the physical knowledge, which will be overcome, in a more or less distant future, by the construction of a deeper one. The first alternative appears very unlikely on the ground of our past experience, while the second would imply the construction—not impossible but certainly not easily conceivable—of a deductive logical system that can be extended, without changing its basic postulates, to layers of the observable reality that originally were foreign to the theory. (In this connection van Hove pointed out to me that mathematics itself can no longer be regarded as a closed theory. Indeed, as shown by Godel's undecidability theorems, there are always propositions that can be rightfully formulated but can be *neither* proved *nor* disproved on the basis of the axioms. On such propositions "progress" means extension of the system of axioms, which is openness of the theory. This, for van Hove, is a strong reason for believing that a full mathematization of physics in the sense of one closed theory is unlikely to be achieved and unreasonable to ask for. Thus, in the light of Godel's results, the problem of constructing a physical open theory becomes that of choosing such an initial system of axioms that the "endless mathematical openness" covers the "physical openness" that may be required at some later time for accomodating new experimental discoveries.)

The last remark prior to my digression on van Hove's comment would obviously hold, with only minor changes, if the unique deductive logical system were an open theory, that is, a theory capable of incorporating new discoveries.

One should, however, recognize that the very distinction between closed and open theories does not appear to be very clear. If one examines all past and present theories from this point of view, only a few of them appear to conform to one or the other of these two extreme conceptions. Thus, for example, classical electrodynamics—summarized by the Maxwell equations—provides the best example of a closed theory. As other examples one could mention classical mechanics, quantum mechanics and special relativity. The basic equations of all these theories require the introduction from the outside of the masses and interactions necessary for specifying the system to which the theory is applied. These data originate either directly from experiments on the system under consideration or from another theory, which very often belongs to a deeper layer of knowledge. On the other hand, the two Einstein principles mentioned above—the geometrization of physical reality and invariance with respect to general coordinates—constitute the basis for an open theory of gravitation. (The best way for appreciating the openness of this frame of thinking is provided by the so-called "Parametrization Post-Newtonian" (PPN) formalism. This frame work takes the slow-motion post-Newtonian limit of all conceivable metric theories and characterizes that limit by a set of nine real-valued pa-

> *"Sooner or later any critical analysis, starting in a particular subfield, is likely to influence all, or almost all, of the other branches of physics."*

rameters: each metric is specified by a set of particular values of these PPN parameters.[27])

In many other cases, however, it is not clear to which of these two categories a theory should be assigned, because by adding convenient terms or introducing other modifications in the corresponding equations at a later time it becomes possible to incorporate new sets of phenomena in frames of thinking that originally would have been considered clear examples of closed theories.

Two examples of these not-completely-closed theories may be mentioned here. The first is Dirac's theory of fermions, which has the typical features of a closed theory. But the addition of the Pauli term to explain the anomalous magnetic moment of the nucleon has shown that in reality it had a certain openness. A second example is provided by Fermi's theory of beta decay, which also, in its original form, appeared as a closed theory. However, when shortly after Fermi's original paper Gamow and Teller proposed a different expression for the weak interaction, the theory acquired some kind of openness; the limits were clarified a few years later by the recognition of the existence of only five Lorentz-invariant interactions, two of which were those proposed by the authors mentioned above. This kind of openness has been fully exploited—following the discovery of nonconservation of parity—by a number of experiments that have allowed the selection, among the various possibilities, of the (V-A) interaction.

### Other forms of unity

Less important philosophically, perhaps, but possibly even more relevant to the development of physics are certain other concepts of "unity." One is the idea of a truly global unity among physicists. This should not be intended as global unity of programs of research. The development of physics proceeds along many different lines, the work of a large number of individuals whose abilities and imagination vary enormously from one person to another and are determined by a few hereditary qualities and a great number of environmental factors. The lack of either general or partial coordination among the world's physicists active in each specific field is of paramount importance. One could even say that it is essential for progress. Plans exist and should exist for the development of the applications of scientific knowledge, to meet the needs of society and for its benefit; but wide plans directing the search for a deeper understanding of the physical reality would unavoidably orient the efforts and therefore limit the freedom of research.

But some forms of unity are necessary, or at least highly desirable. There should be a unity of goals of experimental and theoretical physics, which sometimes seems to be forgotten. The community of experimental techniques and methods, together with the community of the mathematical tools determines the unity of the language used by all physicists and opens the possibility of transferring ideas and procedures from one field of research to another.

Other elements of unity can be found in the critical examination of concepts and the return to the origins in basic physics. Sooner or later any critical analysis, starting in a particular subfield, is likely to influence all, or almost all, of the other branches of physics.

And finally one must consider unity with respect to geographical and political divisions. From time to time the ideologists of some specific school of thought or creed assert that societies based on different principles produce different sciences.

Now, it is true that the surrounding society, with its many characteristic features and in particular its general culture, influences the way of thinking of the local scientists and their program of work. An interesting example was pointed out, some years ago, in the remarkable contributions to field theory made by the Japanese school of theoretical physics; it was said that their work was helped by the fact that their culture had never been under the influence of Aristotelian thought. However, once an idea or procedure has been put forward and its usefulness proved, it is immediately accepted by physicists belonging to all other cultural groups and societies. They immediately develop the new idea, or apply the new procedure, so that it is universally amalgamated into the present description of the physical world as a more or less important part of it, irrespective of its place of origin.

Differences of opinion may remain in the philosophical interpretation, but "physics," the final product, consisting of a certain number of definitions and relationships, is universal.

* * *

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