THE 1979 BERNARD GREGORY LECTURES

Given by Victor F. Weisskopf

at CERN, Geneva, Switzerland,
at the Collège de France, Paris, France
and at the Ecole Polytechnique, Palaiseau, France

Autumn 1979

GENEVA
1980
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ABSTRACT

This Volume contains the texts of the lectures given by Professor V.F. Weisskopf at CERN and in Paris in the Autumn of 1979, as the first Gregory lecturer. The titles of the three different texts are "Growth up with Field Theory", "Recent Trends in Particle Physics" and "L'Art et la Science". While the latter lecture was given in French, an English text here follows the French one. The Volume starts with a short biographical note about Bernard Gregory.
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For questions or comments concerning this report, please contact M. Jacob CERN/TH Geneva.
THE BERNARD GREGORY MEMORIAL FUND

Sponsored by

The Institut de Physique Nucléaire et de Physique des Particules (IN2P3, France),
The European Organization for Nuclear Research (CERN),
The French Physical Society.

Bernard Gregory died on 24 December, 1977. Director of the French Délegation Générale à la Recherche Scientifique et Technique (DGIRST) and President-elect of the CERN Council, his already imposing work as a Scientist and as a Scientific Administrator was left unfinished. His untimely death was a shock for all those who had the pleasure to know him and to work with him. In front of such a great and unexpected loss, many of his friends wanted to contribute in one way or another to some endeavour dedicated to his memory. As a modest and first token of gratitude for all that Bernard Gregory did for particle physics in Europe, it was deemed appropriate to organize series of lectures dedicated to his memory. The Gregory lectures have been made possible by a fund raised for this purpose, with contributions from many people. At present it is sufficient to plan two or three more lecture series, similar to the one so brilliantly given by Professor V.F. Weisskopf, who visited CERN and Paris in the Autumn of 1979 as the first Gregory lecturer. Further donations could contribute to the continuation of the series, and should be sent to the "Bernard Gregory Fund" account C7 100-250, Swiss Bank Corporation, CERN Office, Geneva.

Gregory lectures will take place every year as long as the fund permits. Each Gregory lecturer is expected to visit CERN and France. The 1980 series will be organized on the theme "A Physicist's Look at Energy Problems".

Each series of lectures will lead to a publication, similar to the present one, originating either from CERN or from IN2P3, France. It is hoped that these publications will serve as a tangible memory of the Bernard Gregory lecture series.

The Bernard Gregory Memorial Fund Committee

L. Jaumeau
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LE FONDS BERNARD GREGORY

Placé sous le patronage de

L'Institut de Physique Nucléaire et de Physique des Particules (IN2P3, France),
L'Organisation Européenne pour la Recherche Nucléaire (CERN),
La Société Française de Physique.

Bernard Gregory est mort le 24 décembre 1977. Directeur de la DGEST et Président-étou du Conseil du CERN, physicien de grand renom et administrateur scientifique de grand talent, il a laissé une œuvre imposante et inachevée. Sa mort soudaine a été un choc terrible pour tous ceux qui ont eu le plaisir de le connaître et de travailler à ses côtés. Devant une telle perte, aussi brutale qu'inattendue, de très nombreux amis ont voulu contribuer à une œuvre qui puisse être dédiée à sa mémoire. Les Conférences Bernard Gregory ne sont certainement qu'un premier et modeste tribut à la mémoire de quelqu'un à qui l'on doit tant pour le développement de la physique des particules en Europe.

Les Conférences Gregory ont été rendues possibles par la création d'un fonds approprié ayant reçu de nombreuses contributions individuelles. Il est aujourd'hui suffisant pour que l'on puisse envisager deux ou trois autres cycles de Conférences, comparables à celui que le Professeur V. F. Weisskopf vient de brillamment donner, au CERN et à Paris, au cours de l'Automne 1979, comme premier Conférencier Gregory. De nouveaux dons pourront permettre de poursuivre cette série. Ils peuvent être versés soit sur le compte "Fonds Bernard Gregory" C7 100-250, Société de Banque Suisse, Agence du CERN, Genève (en francs suisses) soit sur le Compte de la Société française de physique CCP 227-92 Paris (en francs français) en précisant "Fonds Bernard Gregory".

Un cycle de Conférences Gregory sera organisé chaque année aussi longtemps que le fonds rassemblé le permettra, chaque Conférencier visitant en principe le CERN et des laboratoires français. Le cycle de Conférences de l'Automne 1980 sera organisé sur le thème "Les problèmes de l'énergie vus par un physicien".

Chaque cycle de Conférences donnera lieu à une publication comparable au présent rapport, cette publication étant assurée soit par le CERN soit par l'IN2P3. Ces rapports resteront comme le souvenir tangible de ces cycles de conférences.

Le Comité d'Organisation du Fonds Bernard Gregory

L. Jaumeau
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J. Prentki
Bernard Gregory in 1965 when he was nominated Director General of CERN, thus succeeding V.F. Weisskopf.
Bernard Gregory, 1919-1977*

Bernard Gregory died on 24 December 1977, the victim of a heart attack at the age of 58. His untimely passing is a great loss for the European scientific community. Active in both teaching and research, he mainly became a great scientific administrator, excelling in a role which assumes particular difficulty and importance now that scientific research demands large resources, often concentrated in big laboratories or managed on a national scale.

He was marked out by an intellect of the highest order and a deep sense of justice. His sure judgement, the result of exceptional gifts of analysis and synthesis, coupled with the simplicity and warmth with which he knew how to listen and to persuade, was the key to remarkable accomplishments at European level in the organization of research in high energy physics, the field of his own original work. The European Organization for Nuclear Research (CERN) benefited particularly from his influence: he was its Director-General from 1966 to 1970, and, having been elected President of the Council of the Organization, was to have taken up his duties in January 1978. In France, as Director-General of the Centre National de la Recherche Scientifique from 1973 to 1976 and later as Délégué Général à la Recherche Scientifique et Technique, he had a profound impact on many aspects of the scientific life of his country.

Bernard Paul Gregory was born at Bergerac on 19 January 1919. In 1938 he entered the École Polytechnique in Paris, but his studies were interrupted by the war. He was taken prisoner in 1940 and remained in captivity for the duration of the conflict. After returning to Paris, he graduated top of the École Polytechnique and qualified as an engineer in the Corps des Mines. He was drawn to scientific research and spent three years at the Massachusetts Institute of Technology, working under Professor Bruno Rossi on nuclear reactions caused by cosmic rays. He defended his doctoral thesis in 1950.

Back in Paris, he devoted himself to fundamental research, working at the École Polytechnique laboratory directed by Professor L. Leprince-Ringuet. In this classical period of the study of cosmic rays with Wilson cloud chambers, the team led by Gregory and Charles Peyrou built one of the most powerful detectors then known, with two cloud chambers in tandem, and set it up for operation on the Pic du Midi in the Pyrenees. With it, a large number of results were obtained on the decay of strange particles, notably the demonstration of the muon-neutrino decay mode of the K meson, whose existence played an important part in the understanding of the weak interactions.

This type of research, however, was shortly to undergo a radical change with the advent of the big particle accelerators. Bernard Gregory was the architect of this change in the laboratory of the École Polytechnique. After a year spent at the Brookhaven National Laboratory, in the United States, to master the technique of bubble chambers, he took in 1958 the initiative for the construction of a hydrogen chamber 81 cm in length. This detector, one of the most powerful of its day, was built at Saclay and installed at CERN, in Geneva, where the 28 GeV proton-synchrotron, the PS, had been commissioned in 1959. Between 1961 and 1971, the 81 cm bubble chamber was to provide over 16 million pho-

these new duties on 1 January 1978; but also at the European Science Foundation at Strasbourg and in numerous international negotiations in the scientific field.

Well known also outside Europe, he was Chairman of the Commission for Particles and Fields of the International Union of Pure and Applied Physics and, from August 1977, first Chairman of the International Committee for Future Accelerators (ICFA), a body bringing together for the first time representatives of all the regions of the world active in the field of big particle accelerators - the United States, Western Europe, the Eastern European countries and Japan.

Bernard Gregory's work and influence were of lasting value. His was a personality in which intellectual power and dignity were combined with warmth and simplicity. His passing represents a great loss for France and for Europe.

M. Jacob
L. Van Hove

We are indebted to the Editor of Nature for his kind permission to reproduce this article.
Professor V.E. Reinskoepf during his address at the 25th Anniversary Ceremony held at CERN on 23 June, 1979

"The Significance of CERN"
The first series of Gregory lectures was given by Professor V.F. Weisskopf. Professor Weisskopf spent one week at CERN and then one week in Paris. The lecture series was organized as follows:

The Beginning of Field Theory, A Personal Recollection  
CERN, Tuesday, 30 October, 1979

Perspectives in Particle Physics  
CERN, Thursday, 1 November, 1979

The corresponding texts appear here under the titles "Growing up with Field Theory" and "Recent Trends in Particle Physics", respectively.

Perspectives in Particle Physics  
Ecole Polytechnique, Palaiseau, mardi, 6 novembre 1979

L'Art et la Science  
Collège de France, Paris, jeudi, 8 novembre 1979

Le lundi, 5 novembre le professeur Weisskopf, nouvellement élu Membre Associé Etranger de l'Académie des Sciences, a fait un exposé sur la physique des particules à l'Institut de France.
1. **Introduction**

In 1928 I came to the University of Göttingen as a graduate student in order to work towards a Ph.D. degree in theoretical physics. Before this, I attended some introductory courses in physics and mathematics for two years at the University of Vienna. I remember in particular a course on general classical theoretical physics by Professor Hans Thirring (the father of the presently active theorist in Vienna). His teaching as well as Paul Ehrenfest's, when he was guest professor in Göttingen, had a decisive influence on my attitude towards physics, because of their clear and simple presentations, and their emphasis upon the essential physical insights rather than on mathematical formalisms. I recall Ehrenfest's remark: "Physics is simple but subtle."

When I arrived in Göttingen in 1928, non-relativistic quantum mechanics was in full development. During the few years since its inception, many new ways were opened up for an understanding of the structure of atoms, of the formation of molecules, of the physics of solids, in particular of the electric and magnetic properties of metals. "Never have so few done so much in such a short time."

This report is devoted to the development of quantum-electrodynamics which was born in 1927 when P.A.M. Dirac published his famous paper "The Quantum Theory of the Emission and Absorption of Radiation". Fig. 1 reproduces the first page. Note that it was communicated by Niels Bohr himself. Also note the second and third sentences. The latter is an understatement indeed: Nothing had been done up to this time on quantum electrodynamics.

2. **The Pre-Dirac Time**

Classical electrodynamics started in 1862 when Maxwell created his equations connecting the electric field $\mathbf{E}$ and the magnetic field $\mathbf{B}$ with the charge density $\rho$ and the current density $J$.

\[
\begin{align*}
\text{curl } \mathbf{E} - \frac{1}{c^2} \frac{\partial \mathbf{B}}{\partial t} &= \frac{\rho}{\varepsilon_0} \mathbf{j} \\
\text{curl } \mathbf{B} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} &= \mathbf{0} \\
\text{div } \mathbf{E} &= \frac{4\pi}{\varepsilon_0} \rho \\
\text{div } \mathbf{B} &= \mathbf{0}
\end{align*}
\]  

(1)

This, together with the expression of the Lorentz-force acting on a system carrying charge and current:

\[
\mathbf{F} = \int \mathbf{E} + \mathbf{j} \times \mathbf{B}
\]  

(2)

lead to an understanding of light as an electromagnetic wave, of the radiation emitted by moving charges and of the effects of radiation upon charged bodies. The results were

---

* A variation of a statement by W. Churchill about the Royal Air Force.

** There exist two interesting studies about this subject: A Pais, The Early History of the Electron 1897-1947 in Aspects of Quantum Theory, ed. by A. Salam and E. Wigner, Cambridge University Press, 1972; S. Weinberg, Notes for a History of Quantum Field Theory, P&c, Fall 1977.
The Quantum Theory of the Emission and Absorption of Radiation

By P.A.M. Dirac, St. John's College, Cambridge, and Institute for Theoretical Physics, Copenhagen

(Communicated by N. Bohr, For. Mem. R.S. - Received February 2, 1927)

Introduction and Summary

The new quantum theory, based on the assumption that the dynamical variables do not obey the commutative law of multiplication, has by now been developed sufficiently to form a fairly complete theory of dynamics. One can treat mathematically the problem of any dynamical system composed of a number of particles with instantaneous forces acting between them, provided it is describable by a Hamiltonian function, and one can interpret the mathematics physically by a quite definite general method. On the other hand, hardly anything has been done up to the present on quantum electrodynamics. The questions of the correct treatment of a system in which the forces are propagated with the velocity of light instead of instantaneously, of the production of an electromagnetic field by a moving electron, and of the reaction of this field on the electron have not yet been touched. In addition, there is a serious difficulty in making the theory satisfy all the requirements of the restricted
splendidly verified by Heinrich Hertz in 1885 for radiations emitted and absorbed by antennas.

The physicists tried to apply the equations (1) and (2) to atomic radiation. They were stymied by two facts: First, $v$ and $\mathbf{J}$ in atoms were unknown to them; second, they faced a fundamental difficulty when the statistical theory of heat was applied to the radiation field. The number of degrees of freedom of a radiation field in a volume $V$ per frequency interval $d\nu$ is $\frac{Vdv^2d\nu}{\pi c^3}$, and if each degree is supposed to get an energy $\frac{kT}{2}$ according to the equipartition theorem, the total energy density becomes infinity; the empty space would be an infinite sink of radiation energy. Furthermore, apart from this distressing result, the classical theory of light had no explanation of the daily experience that incandescent matter changes its colour with rising temperature from red to yellow and then to white. The physicists must have felt before 1900 like the neurophysiologists of today feel without any explanation of what is memory.

Then came quantum theory. It developed with increasing speed within a quarter century beginning with Planck's insight into the nature of black-body radiation in 1900, followed by Einstein's revolutionary idea of the existence of a photon in 1905, by Bohr's atomic model in 1913, and by L. DeBroglie's daring hypothesis of the wave-particle duality of particles in 1924. It reached its peak with the formulation of quantum mechanics by Heisenberg, Schrödinger, Dirac, Pauli and Bohr in 1925.*

The difficulties of the classical theory disappeared with one stroke - not without bringing about other difficulties about which much more will be said soon. Of course, the problem of heat radiation was immediately solved and the reasons for the sharp characteristic spectral lines of each atomic species become evident. Atomic stabilities, sizes and excitation energies could be derived from first principles: the chemical forces turned out to be a direct consequence of quantum mechanics; chemistry became part of physics.

We graduate students at Göttingen in 1928 were introduced in a rather unsystematic way to all these new and exciting developments. Regular courses in quantum mechanics were not yet given. Our sources of information were informal discussions, collective readings of the new papers, most of which were rather opaque for beginning graduate students of these days. But two courses remain in my memory, one by Gerhard Herzberg on atomic physics and the other by Walter Heitler on applications of quantum mechanics. The lecturers, hardly much older than the students, gave us exciting accounts of the new physics. The content of G. Herzberg's course is still available in book form and remains - fifty years later - one of the best introductions into atomic physics.

---

* The ideas were so new and unaccustomed that even the most experienced physicists had difficulties accepting them. It was about 1914 when Max von Laue and Otto Stern went for a walk in the neighbourhood of Zurich on a hill called "Uetliberg". This name resembles the name of a hill called Ruettli upon which the representatives of the original cantons of Switzerland came together in 1307, swearing allegiance to their newly won independence from Austria and to defend it with all their power. This event is referred to as "Ruetlischaur". Von Laue and Otto Stern made a vow that they would give up physics if and when those new-fangled ideas by Niels Bohr about the hydrogen atom should turn out to be correct. They dubbed it the "Ruetlischaur". In contrast to the valiant Swiss, they did not keep their vow.
Back to the problem of the radiation of atoms. Did quantum mechanics furnish the expressions for $\rho$ and $J$ within the atoms in order to calculate the interaction of atoms with light? Not really. We were told at that time that the matrix elements $\langle a | \rho | b \rangle$ and $\langle a | J | b \rangle$ between two stationary states, $a$, $b$ of the atom play the role of charge and current responsible for the radiation connected with the quantum transition from $a$ to $b$ or vice versa. The atom was considered as an "orchestra of oscillators" and the matrix elements determined the strengths of those oscillators ascribed to each pair of states.

Actually, the Schrödinger equation allowed the calculation of the absorption of light only, that is, a transition from $a$ to $b$, if $b$ is higher than $a$. The field of an incident light wave could be considered as a perturbation on the atom in the state $a$; it was possible by means of the Schrödinger equation to calculate the probability of a transition from $a$ to $b$, which turned out to be proportional to the intensity of the incident light wave. However, emission from $b$ to $a$ in a field-free vacuum could not be calculated. One had to use either the oscillator model and equate the emission with the classical radiation of these oscillators or one made use of the Einstein relations, from which it follows that the probability of spontaneous emission from $b$ to $a$ is equal to the absorption probability from $a$ to $b$ when the light intensity per frequency interval $d\omega$ is put equal to a certain value $I_0$:

$$I_0 \, d\omega = \frac{\hbar \omega^2}{4\pi^2 c^2} \, d\omega$$

This happens to be the light intensity when each degree of freedom of the radiation field contained one photon. According to this rule the probability of spontaneous emission $b \rightarrow a$ is equal to the probability of a forced emission by a fictitious radiation field (3).

But why? According to the Schrödinger equation, any stationary state should have an infinite lifetime when there is no radiation present.

3. Dirac's Radiation Theory

Dirac's fundamental paper in 1927, entitled "The Quantum Theory of the Emission and Absorption of Radiation", changed all that. He saw that quantum mechanics must be applied not only to the atom via the Schrödinger equation, but also to the radiation field. He made use of an old idea of Ehrenfest (1906) and Debye (1910), to describe the electromagnetic field in empty space as a system of quantized oscillators. In the presence of atoms or of other systems of charged particles the coupling between the charged particles and the field is expressed by an interaction energy

$$H^i = \varepsilon \int J \cdot A \, dx^3$$

where $J$ is the current density of the particles. The value $e$ of the particle charge is inserted here as an explicit factor and $A$ is the vector potential. Both magnitudes are operators in the quantized system of the atom and the field oscillators. Expression (2) is a direct consequence of Maxwell's equations. The Hamiltonian of the combined system then has the form

$$H = H_0 + H^i$$

$$H_0 = H_{\text{Field}} + H_{\text{Atom}}$$
where $H_{\text{Field}}$ is the Hamiltonian of the isolated field oscillators and $H_{\text{Atom}}$ is the Schrödinger-Hamiltonian of the atom isolated from the electromagnetic fields.

The Hamiltonian $H_0$ describes field and atom without interaction. The effects of $H^i$ are treated as a perturbation upon the system $H_0$. The stationary states of $H_0$ are characterized by

$$(\ldots n_i \ldots, a)$$

Here $n_i$ are the occupation numbers of the radiation oscillators (the numbers of photons present in each oscillator $i$), and $a$ indicates the stationary state of the atom.

By applying statistical mechanics to these states as Ehrenfest and Debye have done in 1906 and 1910, the problem of heat radiation is solved; the Planck formula for the black-body radiation results. We know why incandescent matter changes its colour with temperature.

The states (6) are no longer stationary when the perturbation energy $H^i$ is taken into account. The theory yields simply and directly the laws of emission and absorption of light. Indeed the state $(\ldots 0, 0, \ldots, b)$ of an atom is an excited state $b$ without any radiation present, is not stationary according to the Hamiltonian (5). A first order perturbation calculation gives a probability $P_{ab}da$ per unit time for a transition from $b$ to a lower state $a$, accompanied by the emission of a photon of a frequency $\omega = (\epsilon_b - \epsilon_a)/\hbar$ into the solid angle $d\Omega$ and with a polarization vector $\hat{s}$:

$$P_{ab}da = \frac{G^2}{\hbar c} \frac{(2\pi)^2}{\omega^2} I_0 |\hat{s}|_{ab}^2 d\Omega$$

$I_0$ is given by the expression (3). The matrix element is determined by

$$\hat{j}_{ab} = \iint \phi^*_a(x) e^{i \hat{k}_{ab} \cdot \hat{x}} \phi_b(x) \, dx$$

where $\hat{j}$ is the operator of the current, and $\hat{k}_{ab}$ the wave vector of the emitted quantum. The spontaneous emission appears as a forced emission caused by the zero-point oscillations of the electromagnetic field, which are always present, also in a space without any photons.

This is the start of an interesting development in theoretical physics. After Einstein has put an end to the concept of aether the field free and matter free vacuum was considered as a truly "empty space". The introduction of quantum mechanics changed this situation and the vacuum gradually became "populated". In quantum mechanics an oscillator cannot be exactly at its rest position except at the expense of an infinite momentum according to Heisenberg's uncertainty relation. The oscillatory nature of the radiation field therefore requires zero-point oscillations of the electromagnetic fields in the vacuum state which is the state of lowest energy. The spontaneous emission process can be interpreted as a consequence of these oscillations.

An important contribution to the physical understanding of the quantized radiation field was a paper by N. Bohr and L. Rosenfeld (1933) in which a number of "Gedanken-experiments" were described how to measure electromagnetic field strengths. It clearly emerged from these considerations that there exist uncertainty relations like Heisenberg's between different field strengths, in full accord with the quantization of the fields. For example, the $x$-component of the electric field and the $y$- or $z$-component of the magnetic field cannot simultaneously be well defined.
Dirac's theory produced all results regarding the absorption and emission of light by atoms that previously were obtained by unreliable conclusions. The results followed from the Hamiltonian (5) when the interaction energy (4) was treated as a first order perturbation. Not only that, the second order terms of the perturbation treatment described photon scattering processes, such as dispersion, resonance fluorescence and non-relativistic Compton scattering of photons by electrons.

4. The Dirac Equation

In 1928 Dirac published two papers on a new relativistic wave equation of the electron. It was the third great contribution to the foundations of physics; the first was the reformulation of quantum mechanics (Dirac 1926, 1927), the second was the theory of radiation. The Dirac equation was supposed to replace Schrödinger's equation for cases where electron energies and momenta are too high for a non-relativistic treatment. It immediately gave rise to four great triumphs:

1) The spin $\frac{1}{2}$ of the electron appeared to be a natural consequence of the relativistic wave equation.*

2) The $g$-factor of the electron necessarily has the value $g=2$. The value of the magnetic moment of the electron followed directly from the equation.

3) When applied to the hydrogen atom, the equation yields directly the correct Sommerfeld formula for the fine structure of the hydrogen spectrum.

4) The relativistic expression for the photon scattering by free electrons - the Klein-Nishina formula - could be derived.

In spite of these amazing successes a number of serious difficulties turned up immediately and it took a long time to solve them. It is interesting to note that the shake-down of non-relativistic quantum mechanics took only two to three years ('25 - '27) although it was based upon some of the most revolutionary ideas of physics, whereas the understanding of the consequences of the Dirac equation took a much longer time.

All that took place during my graduate studies. For us the Dirac equation was a great mystery and we had difficulties grasping the significance of the four successes mentioned above. Imagine a student who just had gone through the conceptual problems of ordinary quantum mechanics and who begins to feel, not at ease, but barely capable of dealing with Schrödinger wave functions, suddenly facing wave functions with four components and with strange transformation properties of which he has never heard before. It was somewhat discouraging.

A great help to all of us was an article on "the Quantum Theory of Radiation", by E. Fermi, that appeared early in 1932 in Reviews of Modern Physics. It contained a lucid presentation of Dirac's radiation theory, of his relativistic wave equation and of the foundations of quantum electrodynamics. It used what one calls today the "Coulomb Gauge" and thus avoided the difficulties of longitudinal quanta that caused so much trouble to Heisenberg and Pauli (1929) when they tried to develop a consistent theory. Bethe (1955) spoke for many of us when he wrote "Many of you, probably, like myself, have learned their first field theory from Fermi's wonderful article".

* It turned out later that there exist relativistic wave equations for particles with different spin. Dirac's equation for a spin $\frac{1}{2}$ is distinguished by the fact that the energy operator appears linearly.
Now to the serious difficulties of the theory. They came from the existence of states of negative kinetic energy or negative mass. There was no way to get rid of them. If one tried to exclude them from the Hilbert space of the electron, the space becomes incomplete; furthermore, the Klein-Nishina formula could not be derived without them. Taken at face value, the existence of these states would imply that the hydrogen atom is not stable because of radiative transitions from the ordinary states to the states of negative energy.

The properties of those impossible states were constantly in the centre of discussion during those years. George Gamov referred to electrons in these states as "donkey electrons" because they tend to move in the opposite direction of the applied force.

5. The Triumph and Curse of the Filled Vacuum

It was again Dirac who proposed a way out of the difficulty in 1929. As it happens with ideas of great men, it was not only "a way out of a difficulty" but it was a seminal idea that lead to the recognition of the existence of antimatter and ultimately to the development of field theory with all its concomitant insights into the nature of matter. He made use of the Pauli-principle and assumed that, in the vacuum, all states of negative kinetic energy are occupied. This was the second step in the development of "populating" the vacuum. Later on this step was somewhat mitigated by eliminating the notion of an actual presence of those electrons, but the fluctuations of matter density in the vacuum remained as an additional property of the vacuum besides the electromagnetic vacuum fluctuations.

Dirac's daring assumption had most disturbing consequences such as an infinite charge density and infinite (negative) energy density of the vacuum. Some of these impossible consequences were circumvented later as it is reported in the next section. However, the assumption not only solved most of the problems of the negative energy states but led to an impressive and unexpected broadening of our views about matter.

First of all, the transitions from positive to negative energy states were excluded and the stability of the atoms was assured. Furthermore, Dirac's assumption required the existence of processes in which one particle from the "sea" of filled negative states is lifted to a state of positive energy, if the necessary energy is supplied by absorption of photons or by other means. A hole in the sea and a normal particle would be created. The hole would have all the properties of a particle of opposite charge. Moreover, a particle may fall back into a hole with the emission of photons of the right amount of energy and momentum. This, of course, would be a process of particle-antiparticle annihilation. Thus Dirac's assumption led to the recognition of the existence of antiparticles and of the existence of two new fundamental processes: pair creation and annihilation.

In the beginning these ideas seemed incredible and unnatural to everybody. No positive electron was ever seen at that time; the asymmetry of charges, positive for the heavy nuclei, negative for the light electrons, seemed to be a basic property of matter. Even Dirac shrunk away from the concept of antimatter and tried to interpret the positive "holes" in the sea of the vacuum electrons as being protons. It was soon recognized, however, that this interpretation would again lead to an unstable H-atom and that the holes must have the same mass as the particles (Oppenheimer 1930, Dirac 1931). Antimatter ought to exist. Indeed the positron was found by Anderson* in 1932; the antiproton was disco-

* Anderson did not know about Dirac's predictions when he discovered the positron.
vered 25 years later since its production needed energy concentrations several thousand times higher that were unavailable before the invention of the synchro-cyclotron.

We should realize that these theoretical predictions of new fundamental processes and new properties of matter were made before even the slightest experimental evidence was known. On the contrary, all previous evidence contradicted the symmetry between positive and negative charges. These predictions rank among the greatest intellectual achievements in natural science.*

Once the idea of the filled vacuum took hold, it was relatively easy to calculate the cross-section for the annihilation of an electron and a positron into two photons (Dirac 1930) and the cross-section for pair creation by photons in the Coulomb field of atomic nuclei (H. Bethe, W. Heitler and P. Sauter 1933, 1934). The results agreed excellently with the experiments performed after the discovery of the positron. Indeed these mechanisms gave a qualitative account of the development of cosmic ray showers in the atmosphere, once the incoming energy is transformed into electrons and photons.

Positronium is an interesting short-lived object that served as an excellent example for the correctness of the matter - antimatter symmetry. Consisting of an electron and a positron, this bound system is neither matter nor antimatter. It was discovered relatively late by M. Deutsch (1948) and its spectrum and annihilation properties are in excellent agreement with the theoretical expectations.

Today it is hard to realize the excitement, the scepticism and the enthusiasm aroused in the early years by the development of all the new insights that emerged from the Dirac equation. A great deal more was hidden in the Dirac equation than the author had expected when he wrote it down in 1928. Dirac himself remarked in one of his talks that his equation was more intelligent than its author. It should be added, however, that it was Dirac who found most of the additional insights himself.

How unreasonable the idea of antimatter seemed at that time may be illustrated by the fact that many of us did not believe in the existence of an antiparticle to the proton because of its anomalous magnetic moment. The latter was measured by Otto Stern in 1933 and could be interpreted as an indication that the proton does not obey the Dirac equation. The fundamental character of the matter-antimatter symmetry and its independence of the special wave equations was recognized only very slowly by most physicists.

In spite of all these successes, the infinite charge density and the infinite negative energy density of the vacuum made it very difficult to accept the theory at its face value. A war against infinities started at that time. It was waged by the developers of quantum electrodynamics with increasing fervour when more intricate infinities appeared besides those mentioned above, as it will be described in the subsequent sections. Today this war may not yet have been completely won, but we live in a time of "peaceful coexistence" with the remaining infinities.**

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* The possibility of antiparticles was already mentioned by Pauli (1919) and Einstein (1923). More about this can be found in a Review by A. Pais (1979) on p. 909.

** This expression was first used by S. Drell.
The following conclusions must be drawn from the new interpretation of the negative energy states in the Dirac equation. There are no real one-particle systems in nature, not even few-particle systems. Only in non-relativistic quantum mechanics are we justified to consider the hydrogen atom as a two-particle system, but not so in the relativistic case, because we must include the presence of an infinite number of vacuum electrons. Even if we consider the filled vacuum as a clumpy description of reality, the existence of virtual pairs shows that the days of fixed-particle numbers are over.

Particles must be considered as the quanta of a field just as photons are the quanta of the electromagnetic field; such quanta are created or destroyed. The theory of the interaction of charged particles with the radiation field has become a field theory, a theory in which two (or more) quantized fields interact: the matter field and the radiation field.

The quantization of these fields makes use of a method called "second quantization". It is an inappropriate name of a formalism for the treatment of many particle problems that has been devised by P. Jordan and W. Pauli (1928) and W. Heisenberg and W. Pauli (1929). There is no additional quantization involved. It is a formalism appropriate to field theory in which creation and destruction operators are introduced that increase or decrease the number of particles in certain quantum states. The field amplitudes are expressed as linear combinations of these operators. It is a direct generalization of the quantization of the electromagnetic field as decomposed into oscillator amplitudes. The operator of an oscillator amplitude contains matrix elements only between states that differ by one unit of excitation. The corresponding operator either adds (creates) or subtracts (destroys) a quantum of the oscillator.

There are essential differences between the matter field and the radiation field. One describes fermions with half integer spin and the other bosons with integer (mostly unit) spin. In the classical limit, the boson fields are classical fields whose field strength is a well-defined function of space and time (radio wave). The fermion fields cannot have a classical field limit since no more than one fermion can be put into one wave; its classical limit is a particle with the properties of a billiard ball.

Furthermore, the interaction between fermion and boson fields in its simplest form necessarily is bilinear in the fermion fields and linear in the boson fields. This is indicated by the form (4) since the current density is a bilinear expression of the particle wave functions. One cannot construct an invariant against Lorentz transformations that is linear or cubic in the spinor wave functions. Boson fields (vector or scalar), however, may appear linearly in the interaction.

When the fields are expressed in terms of creation and annihilation operators, the form of the interaction can be interpreted in the following way. The basic interaction between fermions and bosons consists of the product of two fermion creation and/or destruction operators $b^*$ and $b$, and one boson operator $a$ or $a^*$: $b^*ba$ or $b^*ba^*$. The character of this interaction is symbolized by the well-known Feynman diagram in Fig. 2. It is interpreted as a change of state of a fermion, destroyed in one state and created in another, accompanied by either an emission or an absorption of a boson.
6. **Fight Against Infinites: The Elimination of the Vacuum Electrons**

There is a rather primitive way to take care of the infinite charge density by a slight change in the definition of charge and current. It amounts to the following argument. Since the theory is completely symmetric in regard to electrons and positrons, it would be equally valid to construct a theory in which the positrons are the particles and the electrons are the holes in a sea of positrons that occupy negative energy states. The actual theory then could be considered to be the combination of these two theories, one with an infinite negative charge density and the other with an infinite positive one. This combination also serves to emphasize the symmetry between matter and antimatter. The vacuum charge densities cancel; the corresponding expressions for charge and current indeed give a more satisfactory description of the phenomena.

It was recognized in 1934 by Oppenheimer and Furry that the creation and destruction operators are most suitable to turn the liability of the negative energy states into an asset, by exchanging the role of creation and destruction for those operators that act upon the negative states. This exchange can be done in a consistent way without any fundamental change of the equations. Obviously the consequences are identical with those of the filled vacuum assumption, but it is not necessary to explicitly introduce that disagreeable assumption. Particles and antiparticles enter symmetrically into the formalism and the infinite charge density of the vacuum disappears. One can even get rid of the infinite negative energy density by a suitable rearrangement of the bilinear terms of the creation and destruction operators in the Hamiltonian.

The fundamental Feynman diagram in Fig. 2 must then be read in three different ways: it symbolizes fermion scattering with the emission or absorption of a photon, a creation or an annihilation of a fermion-antifermion pair with the emission or absorption of a photon. All electrodynamic interaction processes are considered as combinations of these fundamental steps.

Surprisingly enough, it took many years before the physicists realized the great advantages of this formalism. One still reads about the "hole theory" of positrons in papers written in the late 1940's, when renormalization was the topic of the day.

An interesting episode in the fight for the elimination of vacuum electrons was the quantization of the Klein-Gordon relativistic wave equation for scalar particles. I was appointed assistant to W. Pauli in Zurich in 1934; one of those strokes of luck in my life as a physicist. During that time I studied the properties of the Klein-Gordon equation for charged scalar particles. It seemed to be a rather academic activity because no scalar particle was known at that time. In that theory, the charge density \( \langle \psi^* \psi - \psi \psi^* \rangle \) and the wave intensity \( |\psi|^2 \) are not identical. Therefore, it seemed possible that, under the influence of external electromagnetic fields, the total intensity \( \int |\phi|^2 dx^3 \) may increase in time, although the total charge remains conserved. It smelled of a creation process of oppositely charged particles. I was unable to develop the problem further because I was not accustomed to use creation and destruction operators. I went to Pauli for help. It was not too easy to draw his attention to the problem and some of my struggles are described in an essay published in my book "Physics in the Twentieth Century", p. 11 (M.I.T. Press 1972). He finally got caught by the problem. It attracted him because he immediate-
ly saw that the quantized Klein-Gordon equation gives rise to particles and antiparticles and to pair creation and annihilation processes without introducing a vacuum full of particles.* Note that at the time the method of exchanging the creation and destruction operators (or negative energy states) was not yet in fashion; the hole theory of the filled vacuum was still the accepted way of dealing with positrons. Pauli called our work the "anti-Dirac paper"; he considered it as a weapon in the fight against the filled vacuum, that he never liked. We thought that this theory only served the purpose of a non-realistic example of a theory that contained all the advantages of the hole theory without the necessity of filling the vacuum. We had no idea that the world of particles would abound of scalar entities a quarter of a century later. This was the reason why we published it in the venerable but not widely read "Helvetica Physica Acta".

7. Fight Against Infinities II: Infinities on the Attack: The Infinite Self Mass

The infinities of the filled vacuum and of the zero-point energy of the vacuum turned out to be relatively harmless compared to other infinities that appeared in quantum electrodynamics when the coupling between the charged particles and the radiation field was considered in detail. No difficulties appeared as long as only the first terms of the perturbation treatment were taken into account, that is those terms in which the phenomena under consideration appears in the lowest order. It soon turned out that the higher terms always contain infinities as Oppenheimer (1930) has pointed out for the first time.

In some special cases, however, it was possible to calculate higher approximations without getting into trouble with infinities. For example, Wigner and I tried to extract expressions for the natural width of spectral lines from Dirac's theory of radiation (Weisskopf and Wigner 1931). This phenomenon cannot be calculated by the usual perturbation theory. We had to introduce an exponential decay of an excited state ab initio into the equations. It then was possible by judiciously restricting the quantum states under consideration, to solve for the exponential decay constant and for the frequency spread of the emitted light. Today, the obtained results are almost trivial; the width of a line emitted by a transition between atomic states a and b is the sum of the widths (the reciprocal life times) of these states. At that time, the radiation associated with such a transition was still considered to be emitted by one of the oscillators of the "orchestra of oscillators" and, therefore, one expected the width to be that of a classical oscillator.

Another example was a calculation of the scattering of light by light. Such scattering occurs because of the effects of one beam upon the virtual pairs that causes the scattering of the other beam. The straightforward calculation of this effect involves infinities, but Kommer and I (1936) succeeded in calculating this effect without having to eliminate infinities in the limit of long wave lengths. In that case one light beam can be

---

* In the course of this work Pauli asked me to calculate the cross-section for pair creation of scalar particles by photons. It was only a short time after Bethe and Heitler had calculated the same problem for electrons and positrons. I met Bethe in Copenhagen at a conference and asked him to tell me how he made the calculations. I also inquired how long it would take to perform this task; he answered, "It would take me three days, but you will need about three weeks." He was right as usual; furthermore, the cross-sections (not checked by Pauli) were wrong by a factor four.
replaced by a static field; the scattering of light by such fields does not give rise to
infinities in the lowest approximation.

In 1934 Pauli asked me to calculate the self energy of an electron according to
the positron theory. It was a modern repetition of an old problem of electrodynamics. In
classical theory the energy contained in the field of an electron of radius \( a \) (neglecting
the inside) is

\[
e = 4\pi \int_{r_0}^{a} \frac{\varepsilon^2}{r^2} r^2 dr = \frac{4\pi \varepsilon^2}{a}
\]

and would diverge linearly if the radius \( a \) goes to zero. The corresponding calculation in
the positron theory is much more complicated; one had to calculate the difference between
two infinite amounts: the energy of the vacuum and the energy of the vacuum + one electron.
It could be done, and the result was equivalent to the statement that the electric field
inside one Compton wave length \( \lambda_c = h/mc \) from the electron is not \( e/r^2 \) but \( e/(r^{3/2}/\lambda_c^2) \).
The self energy \( \varepsilon \) then becomes (Weisskopf, 1934)

\[
\varepsilon = m_0 c^2 + \frac{3}{\sqrt{\pi}} m_0 c^2 \frac{\varepsilon^2}{nc} \log \frac{\lambda_c}{a}
\]

(7)

where \( m_0 \) is the intrinsic mass of the electron.

It diverges only logarithmically.* A consistent relativistic theory requires a
point-electron, that is \( a = 0 \). It is worth noting, however, that the value of \( a \) for which
the second term of (7) becomes comparable to the first is as small as \( 10^{-5} \) cm! Even the
Schwarzschild radius of the electron is as big as \( 10^{-45} \) cm. It means that the deformation
of the space around the electron is large enough to prevent the electron from interacting
with photons of that wave length. This would provide a natural cut-off long before the
electromagnetic self-energy becomes important. Unfortunately, no consistent calculation of
this effect has ever succeeded.

Another somewhat more benign type of infinities appeared in quantum electrodynamics
when emissions of photons of very low frequencies were considered. Such emissions
take place, for example, when electron beams are scattered by static electric fields.
Classical theory predicts that the emitted energy does not vanish in the limit of zero-
frequencies. The quantum result ought to be identical with the classical one at that
limit; it would indicate that the number of emitted quanta goes to infinity. This trouble,
called "infrared catastrophe", can easily be repaired by describing this limit with the
help of classical fields, as Bloch and Nordsieck have shown in their important paper of
1937. It put an end to any worries about this kind of infinity.

* This brings back one of the dark moments of my professional career. I made a mistake
in the first publication that resulted in a quadratic divergence of the self-energy.
Then I received a letter from N. Furry who kindly pointed out my rather silly mistake
and the fact that actually the divergence is logarithmic. Instead of publishing
the result himself, he allowed me to publish a correction quoting his intervention.
Since then the discovery of the logarithmic divergence of the electron self-energy is
wrongly ascribed to me instead of to Wendell Furry.
Figure 2: Fundamental diagram of QED. The full lines are fermion states; the wave line is a photon.

Figure 3: Running coupling constant in QED. The effective charge $Q_{\text{eff}}$ as a function of the distance $r$. The distance $a$ is very much smaller than indicated in this drawing.
8. Fight Against Infinities: Infinities on the Attack: The Infinite Vacuum Polarization

The virtual pairs endow the vacuum with properties similar to a dielectric medium. The electric force between two charges will be changed. We ascribe a dielectric coefficient $\varepsilon$ to the vacuum. It reduces the true charge $Q_0$ to an effective charge $Q_{\text{eff}} = Q_0 / \varepsilon$. The coefficient $\varepsilon$ of the vacuum turns out to be a function of the distance $r$ of the charges but, unfortunately, it is logarithmically infinite for large distances. $\varepsilon(r)$ decreases with $r$ when $r$ becomes smaller than the Compton wave length $\lambda_C = h/(mc)$. It comes from the fact that, for smaller $r$, only those virtual pairs contribute whose energy is larger than $hc$. Of course, an infinite $\varepsilon$ makes no sense since it would reduce the actually measured charge (that is the charge measured at $r \gg \lambda_C$) to zero. However, one may turn things around and assume that the intrinsic "true" charge $Q_0$ is infinite so that the observed charge $Q_0 / \varepsilon$ becomes finite and equal to $e$ for $r \rightarrow \infty$. The decrease of $\varepsilon$ with decreasing $r$ when $r < \lambda_C$ would then amount to an increase of the effective charge $Q_{\text{eff}}$ at those small distances.

The increase of $Q_{\text{eff}}$ for $r < \lambda_C$ over the value $e$ at large distances is rather small; it is only of the order of $e^2/137$. A strong increase occurs only at very small distances $r = \lambda_C \exp (-hc/e^2)$; these are the same distances as the ones we discussed in connection with the self-energy, at which the theory most likely is inapplicable. We then get a dependence of $Q_{\text{eff}}$ on the distance as shown in Fig. 3. It must be regarded as an interesting result of quantum electrodynamics in spite of the unnatural assumption of an infinite "true" charge $Q_0$.

9. Fight Against Infinities: Counter Attack: Renormalization

The appearance of infinite magnitudes in quantum electrodynamics was noticed since 1930. Since they only occurred when a certain phenomenon was calculated to a higher order of accuracy than the lowest one in which it appeared, it was possible to ignore the infinities and to stick to the lowest order results that were good enough for the experimental accuracy at that period. However, the infinities at higher order indicated that the formalism contained undue contributions from the interaction with high momentum photons.

It was therefore of a certain interest to show (Euler 1936, V.F. Weisskopf 1936) in a more or less convincing way (it was not an exact proof) that the infinite contributions of the high momentum photons are all connected with infinite self mass, the infinite intrinsic charge $Q_0$, and with non-measurable vacuum quantities such as a constant energy density and a constant dielectric coefficient. Thus it seemed that a systematic theory could be developed in which these infinities are circumvented. At that time nobody attempted to formulate such a theory, although it would have been possible then to develop what is now known as the method of renormalization.

A new impetus to such attempts came from an experimental result. Lamb and Rutherford (1947) were able to measure reliably the difference in energy between the $2S_1/2$ and $2P_1/2$ state of hydrogen (Lamb shift). The two states should have been exactly degenerate according to the results of the Dirac equation applied to the hydrogen problem. Already in the 1930's the degeneracy of these two levels was in doubt from spectroscopic measurements (the so-called "Pasternak effect") but Lamb and Rutherford's modern methods using newly developed microwave methods, established the fact and measured the difference with great accuracy.
It was long ago conjectured that this difference came from the coupling of the radiation field with the atom but early attempts to calculate it ran into difficulties because the infinite mass and vacuum polarization appeared in the same approximation. It was H.A. Kramers who pointed out (Kramers 1938) that one ought to be able to calculate that effect by carefully subtracting the infinite energy of the bound electron from the free one and, thus, separating the parts that contribute to the mass and charge from those of real significance. Infinities are always difficult to subtract in an unambiguous way. After the Lamb shift had been measured, and after Bethe (1947) had made a successful attempt to estimate the effect of the radiation coupling, J.B. French and I calculated that difference carefully and got a well-defined result in agreement with the experiment. We believe that we were the first to arrive at that result. Then followed a tragiconal episode. We showed our method and our result to J. Schwinger and to R. Feynman. They independently tried to repeat our calculations but found a result differing by a small numerical additive constant. The trouble was that both of them got the same result that differed from ours. Having Feynman and Schwinger against us shook our confidence and we tried to find a mistake in our calculation without success. Only seven months later, Feynman informed us that he and Schwinger made a mistake. We published our paper (J.B. French and V.F. Weisskopf 1949) but, in the meantime, a similar calculation was made by N.M. Kroll and W.E. Lamb (1949) which appeared a few months earlier than ours. Self-confidence is an important ingredient that makes for a successful physicist.

This episode shows that our primitive methods of subtracting two infinities were clumsy and unreliable. Therefore, a formidable group of physicists took over such as J. Schwinger, R. Feynman, F. Dyson, S. Tomonaga, and developed a reliable way to deal with the infinities (see literature see J. Schwinger 1958). A method of renormalization was introduced in which the initial parameters were eliminated in favour of those with immediate physical significance. In each computation of an electro-dynamical result, the effects of the mass and charge redefinitions had to be incorporated. In order to make this procedure unambiguous it was necessary to keep the expressions in a manifestly relativistic and gauge-invariant form throughout the calculations.

The results were most encouraging. J. Schwinger (1948) found that the magnetic moment of the electron should be slightly larger than the Bohr-magneton, a result that shortly afterwards was confirmed by experiment (Foley and Kusch 1948). The Lamb shift results were recalculated in a much simpler way, radiative corrections of higher order in $e^2/hc$ to scattering processes were unambiguously determined, the vacuum polarization effects were worked out in detail; they found an impressive experimental confirmation in the measurements of the spectrum of muonic atoms (the electron replaced by a muon); the muon moves in the region $r < (h/m_\mu c)$ where the vacuum polarization is a one-per cent effect.

Here are the signs of victory in the war against infinities:

\[
\text{Lamb shift} \quad (\text{about } 10\% \text{ is due to vacuum polarization, most of the rest is the interaction with the zero-point oscillations of the electromagnetic field):}
\]

\[
\Delta \nu (2S_1 - 2P_1) = 1057.862 \quad (20) \quad \text{(experimental)}
\]

\[
\Delta \nu (2S_1 - 2P_1) = 1057.864 \quad (14) \quad \text{(theoretical)}
\]

(The units are Megahertz.)
\[ \mu \text{-factor of the electron } (\mu = \frac{1}{2}(g-2) \times 10^3) \]

\[ a = 1.159652410 \quad (20) \quad \text{(experimental)} \]

\[ a = 1.159652379 \quad (261) \quad \text{(theoretical)} \]

**Vacuum polarization.** 90% of the Lamb shift in muonic helium \((\mu\text{-particle} + \text{muon})\) is caused by vacuum polarization:

\[ \Delta E (2S \rightarrow 2P_{3/2}) = 1.5274 \quad (0.9) \quad \text{eV (experimental)} \]

\[ \Delta E (2S \rightarrow 2P_{3/2}) = 1.5251 \quad (9) \quad \text{eV (theoretical)} \]

The error limits in the theoretical results come from those interactions between the nucleus and the electron or muon that are not completely known yet.

In spite of these victories there remain nagging problems in quantum electrodynamics. The elimination of infinities is not based upon a consistent theory but on a systematic circumvention of the infinities that are still inherent in the theory. Moreover, this circumvention is possible only in a perturbation approach; it is contingent upon the smallness of \(e^2/\hbar c\). But the effective coupling constant at very small (indeed incredibly small) distances becomes larger than unity. Will there be a theory that avoids renormalization by using non-perturbative methods? Or will a future unification of electrodynamics and general relativity heal the disease of divergencies because of the fact that the dangerous distances are smaller than the Schwarzschild radius of the electron? Or will a unification of electrodynamics with strong interactions bring a solution of the problems? The unification with weak interactions by S. Weinberg, A. Salam, G. 't Hooft and G. Ward has not served that purpose.

Moreover, there is no way to understand and derive the mass of the electron within today's electrodynamics. This problem has become even more acute, when heavier electrons such as the muon and the \(\tau\)-electron were discovered. Finally, there is no explanation in sight within present-day electrodynamics for the specific value of the electric charge, that is for the ratio \(e^2/\hbar c = (137)^{-1}.\)

10. **Quantum Electrodynamics as Example**

The tremendous quantitative success of renormalized quantum electrodynamics (QED) has elevated this theory as an (almost) spotless example of a physical theory dealing with the interactions of electrically charged particles with fields. No wonder that the physicists tried to apply similar methods whenever interactions between fermions and bosons occurred. The first well-known use of QED as an example was the attempt of H. Yukawa (1935) to describe the nuclear force between protons and neutrons as an emission and subsequent absorption of a virtual boson. He had to ascribe a mass to that boson, since the nuclear force has a short range \(r_0\) of the order of \(10^{-13}\) cm. Any field theory modelled

---

* Some time ago I was told about the teachings of the Kabbalah by Gershom Scholem, the great scholar of Jewish mysticism. Every Hebrew word is associated with a number that carries some symbolic meaning. He asked me to tell him a few of the unsolved riddles of modern physics. When I told him about \((e^2/\hbar c)\) his eyes lit up in surprise and astonishment: "Do you know that 137 is the number associated with the word Kabbalah?"
after QED would given a exponential force between fermions of the form \((r^{-1}) \exp (\frac{\text{M}}{\hbar})\) if \(\text{M}\) is the mass of the boson. The observed range of nuclear forces leads to \(\text{M} \sim 200\text{ MeV}\). No such bosons were known at that time, but he predicted the existence of them. His prediction was confirmed ten years later; an impressive success of a simple idea. Actually the nuclear force turned out to be the effect of somewhat more complicated processes; it does not detract from the beauty of his prediction.

The exploitation of the full renormalized formalism of QED for other fields began only relatively recently. The next step was the application of field-ideas to the weak interaction. It was J. Schwinger (1957) who first suggested that the weak interactions should be interpreted as transmitted by boson fields. Because of the very short range of these interactions such "intermediate bosons" must have a very high mass. Moreover, since the most common weak interaction processes are accompanied by a charge transfer, some of the intermediate bosons must also carry a positive or negative unit of charge.

Schwinger's original idea initiated an impressive development that culminated in the unification of electromagnetic and weak interactions. A large number of theoretical physicists took part in it, such as S. Weinberg (1967), S. Glashow, G.'t Hooft, J. Ward, A. Salam and many more. Another important and perhaps more fundamental input into that development was a generalization of field theory by C.N. Yang and R. Mills (1954). They introduced so-called "non-abelian" field theories in which the field source can be exchanged between the fermions and bosons. These are theories in which the field may carry the equivalent of charge. When applied to the weak interactions, it is the "weak charge" - the property that flips when an electron becomes a neutrino - that is carried by the intermediate bosons. The fact that this flip is connected with a charge change is an indicator that electromagnetism and weak interactions are bound to be inter-connected.

A detailed description of the unified theory goes beyond the aim of this essay. Suffice it to say that there is only one coupling constant, \(\text{g}^2/\text{hc}\), and that the difference in strength between the weak and electromagnetic interactions comes from the fact that the intermediate bosons are very massive whereas the photon remains massless. In order to get the right strength, the bosons must have a mass of about 100 GeV. Furthermore, the renormalization of the theory is much more complicated since the intermediate bosons carry a mass. It turned out to be necessary to start with a theory in which the boson masses are all zero; then the renormalization can proceed, but that form of the theory is far from the real world. Then a so-called "spontaneous symmetry" breaking is introduced, that is a new field \(\phi\) whose expectation value \(\langle \phi \rangle_0\) in the vacuum is different from zero. This is a most unusual situation: all hitherto known fields are such that their fluctuations average to zero in the vacuum. The coupling of this so-called Higgs-field with the other fields produces three effects: it provides masses to the intermediate bosons, it provides the necessary coupling between electromagnetic and weak phenomena so as to give the correct electric charges to the particles involved in the weak interaction; it produces a special kind of weak interaction without transfer of charges, the so-called neutral currents. The last effect was tested experimentally with an amazing agreement with the theoretical predictions.

* Actually, there is another constant entering into the theory: the Weinberg angle that determines the degree of mixing between the electro-magnetic field and the neutral weak field.
The most important experimental verification is still outstanding: the observation of the intermediate bosons. It is a similar situation as the one of Maxwell's theory of unification of electric and magnetic fields before Heinrich Hertz's experiments. Woe to the theory if the bosons are not seen when the necessary energy and intensity for their production is reached at some of the accelerators under construction!

The second theory which was structured as a parallel to quantum electrodynamics was "quantum chromodynamics (QCD)". It deals with the strong interactions. Since the discovery of the quark structure of hadrons (M. Gell-Mann, 1964; G. Zweig, 1964; H. Kendall, J. Friedman and R. Taylor, 1969) one understands by "strong interaction" the forces between quarks. The nuclear force between nucleons was the previous candidate for that name. Today the nuclear force is considered as a weaker derivative of the quark-quark forces, just like the forces between atoms are weaker derivatives of the Coulomb forces between the atomic constituents.

Considering the successes of field theoretical approaches it is no surprise that present attempts to describe the interquark forces are also structured according to the model of quantum electrodynamics. Here is a dictionary of the analogies:

<table>
<thead>
<tr>
<th>QED</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>quarks</td>
</tr>
<tr>
<td>charge</td>
<td>colour</td>
</tr>
<tr>
<td>photon</td>
<td>gluons [massless]</td>
</tr>
<tr>
<td>positronium</td>
<td>$c^0, \omega, \phi, J/\psi, \rho$</td>
</tr>
</tbody>
</table>

Five analogies exist in QCD to positronium because five different types of quarks have been discovered up to now. Actually QED also predicts the existence of two more "positroniums", made of one of the two heavy electrons and their antiparticles.

There are important differences between these two field theories, which mainly come from the different nature of the charge. In QED the charge is a scalar and remains with the fermions. The field is uncharged. In QCD what acts as the charge is a "trivalent" magnitude referred to as 'colour'. It is trivalent in the same sense in which the spin of the electron is a bivalent magnitude. Furthermore QCD is a 'non-abelian' field theory; this means that the fields (the gluons) also carry charge, that is the emission of a gluon by a quark may change its colour and the gluon carries a corresponding field producing property. Therefore there are two fundamental diagrams (see Fig. 4), one corresponding to the emission or absorption of a gluon by a quark, the other corresponding to the interaction between gluons. All observed hadrons are colourless, that means the colours of the constituent quarks add up to zero. In the spin analogy to colour, it would mean that the spins of the constituents must be opposed to each other and form a state of zero-spin (singlet). In the trivalent case, three quarks are needed so that their colours add up to zero, or a quark-antiquark pair since the antiquark has the "complementary" colour of the quark. Hence hadrons consist of either three quarks or of a quark-antiquark pair."

* This property justifies the use of the term "colour". The three fundamental colours add up to white, and so do a colour and its complementary one.
Figure 4: Fundamental diagrams in QCD. Full lines are fermions; wave lines are gluons. Field carries charge.

Figure 5: Running coupling constant in QCD. The effective charge as a function of the distance. It vanishes as $r \to 0$ (asymptotic freedom); it increases linearly (?) with $r$ for $r > r_0$ (confinement). $r_0$ is the distance for which the coupling constant is unity. $r_0 \approx 10^{-15}$ cm.
The fact that hadrons carry no net colour charge emphasizes the previously mentioned parallel between the nuclear force and the forces between atoms. Atoms are electrically neutral but when they approach each other, their structure is sufficiently altered that attraction occurs through resonance (Van der Waal's forces) or through formation of new quantum states (chemical force). The same would happen when colour-neutral nucleons approach each other.

Again a detailed description of QCD goes beyond the aims of this essay. It may be important, however, to stress two surprising consequences of this theory, of which the second is not yet established with certainty. The first is called "asymptotic freedom". In contrast to electrodynamics, the effective coupling constant decreases when the distance decreases or when the momentum transfer increases. The coupling vanishes at infinitely close distances. This has been shown by Gross and Wilczek (1973) and D. Politzer (1975). For increasingly larger distances, however, the effective coupling constant does not remain finite as in QED, but seems to increase steadily. The potential energy, say, between a quark and an antiquark (the analogue to the Coulomb energy \( -e^2/r \) between two opposite charges) probably increases linearly as \( a \cdot r \) and goes to infinity for \( r \to \infty \). The dependence of the effective charge \( Q_{\text{eff}} \) on \( r \) is very different from the one in QED that was shown in Fig. 3. The situation in QCD is sketched in Fig. 5.

The consequences of these relations are most unusual. It follows that single quarks cannot exist as free particles. Since the effective charge would become infinite at large distances, the energy necessary to isolate a quark from its partners in a hadron would be infinite. An isolated quark would be surrounded by a field that does not decrease with the distance. Obviously no isolated quarks (or gluons) can exist in nature if these conclusions are confirmed.

Here we encounter a new situation: the elementary constituents - quarks and gluons - can only exist in bound states, never as single free particles. It should be noted that this paradoxical situation most probably follows (it has not yet been proved beyond doubt) from a field theory that is a generalization of QED. In the latter, of course, fermions and bosons do exist as free particles; moreover, the system of free particles is the natural limit reached when the coupling constant goes to zero. This limit does not exist in QCD except for very small distances or very large momentum transfer, the opposite situation to that of free particles.

11. Unsolved Problems

The development of quantum field theory since its inception half a century ago is most impressive. Today we have the means to calculate electromagnetic effects with incredible accuracy; new field theories were created that seem reasonably appropriate to deal with the new forces of nature that were discovered during this half century, in spite of the fact that these forces are more complicated than the electromagnetic ones and exhibit different properties, such as charge carrying fields, symmetries broken by vacuum fields and forever confined particles. This is an indication that the mechanisms of field theory play an important rôle in natural phenomena. Certainly the language of field theory is used by nature.
But there are definite indications that we understand only a partial aspect of what is going on. Here is a list of questions that are still unanswered:

i) Is the renormalization procedure sound? So far it can only be carried out in successive perturbation steps. Can it be applied to a theory with an arbitrarily large coupling constant? The answer to this question may save or condemn field theory. A better understanding of the strong coupling limit (small distances in QED, large distances in QCD) may result in a satisfactory solution to the problems of infinities and of confinement or it may reveal fundamental shortcomings.

ii) The large value of the effective coupling constant of quantum chromodynamics at small momentum transfers causes serious problems as to the nature of the vacuum itself. The field fluctuations may turn out to be very large and may require new conceptions of the nature of the vacuum.

iii) Is the present interpretation of the electro-weak interactions correct? Do the intermediate bosons and the Higgs field really exist? These are questions which will soon be answered by experiments.

iv) The present theories contain arbitrary constants. In QED it is the coupling constant $e^2/\hbar c$ at large distances and the masses of the different electrons. Today three are known, but there may be more. There is no way visible at present how their mass values may emerge from the field theories. Moreover, the question remains why there is only one value of the electric charge (the quark charges are simple rational fractions of it) but several mass values seemingly without any simple relations.

In the electro-weak interaction the coupling constant between fermions and intermediate bosons is also $e^2/\hbar c$, but we find arbitrary coupling constants with the Higgs-field that are chosen in order to yield the correct mass for the particles. Furthermore, there is another arbitrary constant, the so-called Weinberg angle, that enters into the coupling of the Higgs field.

In QCD the situation is worse in respect to the mass problem since we deal with many different types of quarks each having its own mass value. The coupling constant problem, however, is less difficult in QCD, if it turns out for sure that we deal with a running constant from 0 to infinity. Such a theory does not require a fixed value such as $e^2/\hbar c$. Moreover, it intrinsically contains a length $r_0$ at which the running coupling constant is near unity. Naturally this length defines a size and a mass of the order of magnitude $\hbar/(r_0c)$. This mass would be the mass of those hadrons that are made of u- and d-quarks, since the masses of those quarks are negligible compared to $\hbar/(r_0c)$. Therefore QCD has the advantage of containing the proton mass as a basic ingredient. But there is no indication whatsoever how the masses of the heavier quarks are determined by field theory. QCD does not even allow us to hope that the mass problem may be answered by strong coupling effects at small distances. Asymptotic freedom excludes any such effects.

* In our description of nature we expect three intrinsic magnitudes to appear that determine the units of our measuring system. Their values do not require any explanation. These units may well be $\hbar$, $c$, and the length $r_0$ as defined above.
The importance of the mass problem may be illustrated as follows. We have no explanation for the mass of the electron, that is for smallness of the ratio \((1836)^{-1}\) between the electron mass and the proton mass. (The latter may be considered as the natural unit defined by QCD.) The small value of this ratio determines the properties of everything we see around us. It is the precondition of molecular architecture, of the fact that the positions of atomic nuclei are well defined within the surrounding electron clouds. Without it there would be no materials and no life. We have no idea about the deeper reasons for the smallness of that important ratio.

v) Our present view of elementary particles is plagued by the following problem. Nature as we know it consists almost exclusively of u- and d-quarks (the constituents of protons and neutrons), and of ordinary electrons; all important processes involve photons, intermediate bosons, gluons and electron-neutrinos. There definitely exist higher families of particles, such as the heavier quarks, the heavier electrons and their neutrinos. These additional particles are very short-lived or give rise to short-lived hadronic entities. They appear only under very exceptional circumstances that are realized during the early instances of the Big Bang, perhaps in the centre of neutron stars, and at the targets of giant accelerators. What is their role in nature, why do they exist? I.I. Rabi exclaimed when he heard of the first of these "unnecessary" particles, the muon: "Who ordered them?"

Again, field theory does not seem to contain the answer to this question. Are they, perhaps, an indication of a deeper internal structure within the quarks and leptons? Are they the excited states of systems made of more elementary units held together by more elementary forces? Will the quantum ladder, the progression from atoms to nuclei, to nucleons and to quarks, ever reach an end?

We will find out sooner or later whether field theory is able to clear up some of these outstanding problems. It may be that a very different approach will be required to solve the questions for which field theory so far has failed to provide answers. Nature's language may be much wider than the language of field theory. We have not yet been able to make sense of much of what nature says to us.

Looking back over a lifetime of field theory, it seems obvious that we have learned much since 1927, but there is a great deal more that is still shrouded in darkness. New ideas and new experimental facts will be needed to shed more light upon the deeper riddles of the material world.
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There are three discoveries made in the last ten years that have deeply influenced our understanding of particle physics.

1) Deep inelastic scattering experiments with electrons and neutrinos as proof for the actual existence of quarks with hadrons.

2) The discovery of two more quark flavours and one more heavy electron.

3) The increasing significance of Yang-Mills field theories.

The first group of discoveries put the quarks definitely on the map. It showed that small ($< 10^{-16}$ cm) charged units indeed exist within the hadrons, with spin 1 and with not too strong interactions at large momentum transfers.

The discoveries of more flavours (c and b quarks) and of the τ electron were to some extent gratifying and to some extent disquieting. The existence of the c quark was a confirmation of theoretical predictions by Bjorken, Glashow and collaborators. The spectrum of the c̅c system, and the transitions between the states of this system was successfully analyzed and corresponds astonishingly well to what one would expect from a two-body system bound by a potential that rises linearly with the distance. The discovery of the b quark opened up the possibility of an unending series of flavours with increasing masses. Certainly, five is not infinity, and six flavours have indeed been proposed in order to explain the violation of CP conservation; but what if there is a seventh flavour? Does the beginning proliferation of flavours indicate an internal structure of the quark, a new spectroscopy, a higher rung of the quantum ladder? Does the third electron (the τ particle) indicate an extended spectrum of electrons coming from some internal structure? Two remarks have to be made here; one is this: a new spectrum of internal excitations would require the appearance of states with $J > 1$. Only the discovery of a particle with $J = 3/2$, 5/2, etc. would be a clear indication of a new spectroscopy. Second: we know from deep inelastic scattering that the size of the quark is less than several $10^{-16}$ cm. Hence, true excitations of an internal dynamics should be expected at energies $> 1/R$ which is $> 200$ GeV, much higher than the masses of the new quarks and electrons. Thus, if the newly discovered particles are part of a spectrum of an internal structure, they can only be the fine structure of the ground state.

It is worth recalling that matter in the whole Universe consists almost exclusively of the u- and d-quark, the ordinary electron and neutrino. There is not enough energy available to excite the higher flavours. Possible exceptions are neutron stars and the earliest stages of the Universe. The question arises what is the rôle of those other short-lived particles. Why are they there? As Rabi has asked "Who ordered them?"

It may be significant, however, that for each quark pair of charge 2/3 and 1/3, there is one electron: the ordinary electron goes with the u-d pair, the muon with the c-s pair and the τ with the t-b pair, of which the τ is not yet discovered. Does this indicate something or is it accidental?

We now come to the Yang-Mills theories. The present views of weak and strong interactions make use of non-Abelian field theories. In a non-Abelian field theory the field itself is a carrier of charge. The charge is not bound to the fermions that are the
sources of the field. The field itself is a source. Therefore, there are direct interactions between the field quanta, such as gluons or intermediate bosons.

Let us first discuss the corresponding theory of strong interactions: Quantum Chromodynamics (QCD). Here the field quanta (gluons) remain massless. The exchange of charge between the quarks and the gluon field produces remarkable features in which QCD differs from Quantum Electrodynamics (QED). One is "asymptotic freedom". The basic reason for this effect lies in the fact that the effective charge is not tied to the quark but spread over the adjacent field. Thus high momentum transfers (small distances) "see" only part of the charge. In addition we believe (no proof yet; see below) that, at large distances, the interaction between quarks becomes infinite so that they cannot exist as free particles. These circumstances lead to the concept of a "running coupling constant", depending on the amount of momentum transfer $Q^2$. It goes to zero for high $Q^2$ and to infinity for low $Q^2$. We are considering here the effective coupling constant $g$, not $g_0$ which appears in the original Lagrangian. The latter one is fixed; the running coupling constant $g$ is the result of taking into account gluon-quark and gluon-gluon interactions plus applying the renormalization methods.

If, for the moment, we consider only $u$ and $d$ quarks which, probably, have no or negligible mass, we face a theory without any length entering the equations, since the coupling constant $g_q$ is dimensionless. Still a length appears in the following way: there must necessarily be a momentum transfer $Q_1$ for which the effective coupling $g$ is of order unity since it runs from zero at large $Q$ to infinity at low $Q$. This value $Q_1$ determines a mass $Q_1^{-1}$ and a length $Q_1^{-1}$. For higher $Q$, one can use perturbation approach, for lower $Q$ one cannot. Since the coupling becomes quite large for $Q < Q_1$, there will be bound states of quarks (hadrons) and they will be of the size $Q_1^{-1}$ and their masses will be $\approx Q_1$. Obviously $Q_1$ must be of the order of one GeV. In other words, we have to choose $g_q$ such that $g(Q^2 - 1 \text{ GeV}) - 1$. (Actually, this is a somewhat simplified description of the situation since the non-renormalized coupling constant goes to zero, but it illustrates the logical connections. One has to choose that solution for which $g - 1$ at $Q - 1 \text{ GeV}$.)

In QED the situation is quite different. There, the effective coupling constant increases with $Q^2$ because, at high $Q$, the vacuum polarization ceases to shield the electric charge. What we understand by "charge $e$" is the fully shielded charge at large distances. That value is finite for $Q = 0$ and equal to $(137)^{-1}$ but it increases as $\log (Q/\alpha)$ for high $Q$.

Let me say a few words on how perhaps one can describe the situation* in QCD for small $Q$. All this is tentative since we do not have a reasonable theoretical approach for the strong coupling situation at $Q < Q_1$. Let us look at the vacuum in QED and in QCD. In the first case it is full of field fluctuations and virtual pairs. The photons and pairs present in the vacuum are virtual because their energy is positive. We call such a vacuum a "simple" vacuum. Let us be sure that the energy of an electron positron pair is positive for all reasonable momentum transfers. For the sake of simplicity, we neglect the masses. Then the energy consists of two parts, a kinetic term $-r^{-1}$, where $r$ is the distance between partners, and an attractive energy $-(e^2/r)$. Clearly $e - r^{-1}(1 - e^2)$ will

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* The following ideas were suggested to me by S. Coleman and K. Johnson. I take the responsibility for the formulation.
always be positive*, since $e^2_{\text{eff}}$ is small and increases only logarithmically with $Q - r^{-1}$. In QCD things are different. The energy $\epsilon$ of a quark pair or of a gluon pair can become negative if $Q - r^{-1} < Q_1$; then $g^2 > 1$ and $\epsilon - r^{-1}(1 - g^2)$ is negative! The true vacuum, therefore, should consist of real (not virtual) gluon and quark pairs or "balls" of a size $\sim Q_1^{-1}$. The very big ones, $r \gg Q_1^{-1}$, seem to have very large negative energy, but their phase space is very small; hence we expect a finite average size of those balls and a finite negative energy density of the true vacuum. The true vacuum is liquid-like, with gluon- and quark-balls of size $\sim Q_1^{-1}$ forming and transforming.

Now we make a daring hypothesis. The true vacuum as just described expels all gluo-electric field lines in a similar way as a superconductor expels magnetic field lines. Then a hadron, which is an assembly of quarks (sources of gluo-electric field lines) would have to form a bubble around itself in the true vacuum. Within that bubble the true vacuum cannot exist (because of the presence of gluo-electric fields) and the bubble will be filled with the "simple" vacuum. After all, in a small region (smaller than $Q_1^{-1}$) the effective coupling constant is smaller than unity and, therefore, it does not pay to form real gluon or quark pairs [$\epsilon = r^{-1}(1 - g^2) > 0$]. Quarks can only exist within a simple vacuum and are caught in the bubble. The energy density of the simple vacuum is zero; it is higher than the true vacuum in which the energy density is depressed by the presence of bound quark and gluon balls. Thus, the forming of a bubble in the true vacuum costs energy proportional to the bubble volume. All this is identical with the assumptions of the bag model. If it is true, we have a QCD argument in support of the bag model. This hypothesis has some support in the mathematical formalism of QCD, as G. Gross, C. Callan, and R. Dashen in Princeton and H. Nielsen and M. Minami in Copenhagen have shown.

The hypothesis of a true vacuum expelling gluo-electric field lines, lends itself also for a simple explanation of quark confinement. Let us consider a quark-antiquark pair (meson). It represents a pair of oppositely (colour -) charged particles, connected by gluo-electric field lines. Since these lines are expelled by the true vacuum and exist only in a simple vacuum the lower energy density of the true vacuum will exert a "pressure" upon the field lines by forcing them to occupy a smaller volume until the counter pressure (due to the higher density of field lines) equalizes the pressure of the true vacuum. This effect will force the field lines into a cylindrical tube ("string") of diameter $\sim Q_1^{-1}$ when the distance between the particles becomes larger than $Q_1^{-1}$. Obviously this gives rise to an attractive force, independent upon the distance, or to a confining potential that increases linearly with distance. In the case of baryons, the intended removal of one quark from the two others will produce a similar effect, since the two others together carry an opposite charge.

T.D. Lee told me about a way that perhaps makes plausible the expulsion of gluo-electric fields from the true vacuum. It goes as follows: A change of the effective coupling constant can also be expressed by a changing dielectric constant $\epsilon(Q^2)$. Let us assume arbitrarily that $\epsilon(Q_1^2) = 1$, and call $g_1$ the coupling constant for $Q = Q_1$ (it is per

* QED tells us that there are values of $Q$ for which $e^2 > 1$. But these values are so incredibly high ($> 10^{40}$ GeV) that we do not need to take them into account.
definition equal or near unity). Then \( g^2(Q^2) = g^2(Q^2) \). Therefore at large distances \( Q^2 \to 0 \), \( \kappa \) must go to zero in order to describe the fact (it may be a fact - we are not sure) that \( g^2(Q^2) \) goes to infinity. So, the true vacuum at large ought to behave as a medium with a gluon-dielectric constant going to zero. In ordinary media made of atoms, the dielectric constant is always \( \kappa > 1 \); that means effective charges are smaller than true charges. This is because the little dipoles in the medium turn their negative ends to the (positive) true charge, thus shielding it. When \( \kappa < 1 \), it is as if the little dipoles would turn their positive ends towards the true charge, thus anti-shielding (increasing) its effectiveness. (Of course, real dipoles would not do that; there must be another yet unclear mechanism. But we know, after all, that gluonic charges indeed are anti-shielded at distances \( > Q^{-1} \).) Now, the electric energy density is \( \mathcal{E} = \beta^2/\kappa \). It becomes infinite for \( \kappa \to 0 \), since \( \beta \) is fixed by the charges. Thus electric fields will not penetrate into this medium, because it costs infinite energy.

The discussion so far applies only to QCD with \( u \) and \( d \) quarks. The appearance of quarks with non-negligible masses, such as the other quarks, represents a further difficulty because neither QCD nor QED contains any mechanism to provide masses to the fermions. However, the masses of the non-strange or non-charmed hadrons (that part which does not come from the intrinsic quark masses) are understandable and can be calculated with reasonable success (MIT bag model). They come from the kinetic energies of the quarks, confined to a volume of the size \( Q^{-1} \), and from contributions of the spin-spin interactions between quarks that are caused by the gluon-magnetic field. The latter raise the masses when the spins are parallel and lower them for anti-parallel spin.

In QED there may be some hope that the strong effective coupling at high \( Q \) gives rise to mechanisms that may explain the masses of the diverse electrons. This hope does not exist in QCD because of asymptotic freedom. The masses of the higher flavours must be produced by another mechanism, such as a coupling to a Higgs-type field.

This brings me to the other Yang-Mills field theory: the Weinberg-Salam theory of electro-weak interactions. I have less to say about this theory, not because I think less of it, but because its triumphs and shortcomings are well known and less controversial. The triumphs consist of a successful unification of weak and electromagnetic forces. This is seen most clearly in the fact that the neutral current effects of the weak interaction are different in character from the charged current effects: they are not purely (V-A) couplings, that is, they do not have maximal parity violations. It comes from the most astonishing, but experimentally well-established, fact that nature chooses to mix the neutral part of the weak interactions (the \( \eta \) component \( W^3 \) of an isotopic triplet of intermediate bosons) with the electromagnetic interactions. The mixing is determined by the so-called Weinberg angle. This shows clearly that there are four "components" of electro-weak field: \( W^+, W^-, Z^0 \) and \( \gamma \), the latter two being the two orthogonal mixtures between \( W^3 \) and an isotopic scalar representing the "U(1)-electromagnetism" (U(1) group) before mixing. What I call "shortcomings" is the necessity of introducing a new field, the Higgs field, which supposedly is responsible for the masses of the participating fermions and bosons, and for the above-mentioned mixing. It is necessary to provide masses by a coupling with a field whose vacuum expectation value does not vanish; with finite masses ab initio, the theory would not be renormalizable. The Higgs coupling contains as many arbitrary coupling constants as there are masses. This is a rather awkward way to "explain" the existence of...
masses and their magnitudes. It is possible, of course, that these Higgs particles really exist. Then the Higgs coupling is Nature's way to make masses. I believe that Nature should be more inventive, but experiments may prove me wrong.

Experiments have verified a great deal of the predictions of the Weinberg-Salam theory, in particular, in respect to the detailed properties of the neutral current events. The deservedly famous SLAC experiment about the parity non-conserving scattering of electrons by nucleons is an outstanding example. The fact that the Weinberg angle comes out to be the same in all experiments, certainly is a strong support of the theory. However, we still have no experimental evidence for the existence of intermediate bosons, to say nothing of Higgs bosons. In a few years, facilities will be available with enough energy to produce them. Woe to the theory if they do not show up!

We have indicated before that a Yang-Mills type of field theory leads to asymptotic freedom and most probably to infinite binding at low momentum transfer. This is the case with QCD. In the Weinberg-Salam theory of electro-weak interactions it is not so. Things do not blow up at low $Q^2$ because the particles get masses from the Higgs field. Thus the "true" vacuum does not form. (In the electromagnetic part, the bosons are still massless, but they do not carry charge.) At high momentum transfer, it is again the Higgs coupling (being not of the Yang-Mills type) which prevents asymptotic freedom.

Although the last decade has given us much more insight into the world of particles, some of the great questions are still open. We do not even know whether QCD makes sense at low momentum transfer. There is the question of the origin of the masses of the higher quarks, the question of the nature of quark flavours and of heavy electrons (is there a limit or is there an internal structure?), the question of the unification of electro-weak and strong forces, and the question of the uniqueness of the electric charge $e$, all of which are still completely unexplained. The fractional charges of the quarks make the last problem even more mysterious.

There are, of course, a number of tentative efforts to get at some of the unsolved questions. The studies of supersymmetries and of grand unification schemes are examples. So far, these studies have not yet yielded solid results. The uncertainty of the number of flavours and heavy electrons makes it hard to invent supersymmetries that contain the right number. The present grand unification schemes are forced to make simplistic assumptions such as that no essentially new phenomena will be found up to the incredibly high energies where supposedly the three interactions merge. Past experience shows that this is not very probable.

Nobody can predict, however, what the experiments will tell us and what new ideas will emerge. There is a Danish proverb: Predicting is difficult, especially if it concerns the future. One thing, however, seems to be sure: Ten years from now, the picture will be very different and much richer, perhaps even more profound.
1. L'espace est bleu

Rien n'est plus différent que la Science et l'Art. La Science est rationnelle, objective, une calme recherche de la nature; l'Art est subjectif, un éclat irrationnel des sentiments émotionnels. Mais on peut aussi regarder les découvertes scientifiques comme des produits de l'imagination, des étincelles ou des aperçus soudains, tandis que l'Art est au contraire parfois le produit d'un travail assidu, où l'on ajoute soigneusement une partie à l'autre par une suite de réflexions rationnelles.

Certainement, l'Art et la Science ont beaucoup en commun; les deux subliment notre expérience et orientent notre esprit, de la vie quotidienne vers des valeurs universelles.

Les rôles qu'ont l'Art et la Science dans notre société sont très différents. La Science, malheureusement, est un livre fermé pour la plupart de ceux qui se situent en dehors de la communauté scientifique. Cependant, son influence sur la société est importante à deux points de vue. D'une part la Science est la base de la technique, et d'autre part les connaissances scientifiques, par les implications philosophiques qu'elles ont, appartiennent une vue matérialiste et rationaliste du monde extérieur comme du monde intérieur. Le rôle de l'Art n'est pas si facile à définir. Il devrait contribuer à une appréciation plus profonde de notre existence et devrait nous aider à supporter notre condition humaine. Malheureusement une grande partie de l'art contemporain est aussi un livre fermé pour une grande majorité de personnes.

Au cours de cet exposé je voudrais présenter une façon nouvelle d'aborder le problème des relations entre l'Art et la Science. C'est un thème qui a été souvent discuté, peut-être trop souvent. Nos idées peuvent sembler contraires à certaines autres couramment exprimées, mais, comme toujours pour des questions importantes, la contradiction entre deux idées n'implique pas que l'une est correcte et que l'autre est fausse. Comme l'a dit fort bien Niels Bohr: "Une vérité superficielle est un énoncé dont l'opposé est faux; une vérité profonde est un énoncé dont l'opposé est aussi une vérité profonde".

Commencons avec la diversité des expériences humaines. Il y a des expériences extérieures, intérieures, rationnelles et irrationnelles, des expériences sociales entre deux ou plusieurs êtres humains, des expériences provenant du monde extérieur à l'homme. Nos réactions à ces expériences sont variées. Nous réfléchissons à partir de ces expériences, nous les utilisons pour améliorer notre vie et pour éviter des privations matérielles et émotionnelles; nous sommes déprimés ou élevés par elles, nous éprouvons joie, amour ou haine. Nous sommes poussés à agir ou à communiquer aux autres, nous essayons de trouver des relations entre elles et notre vie. Nous voulons influencer les gens et notre environnement. Tout cela forme la matière première de la créativité humaine. Quelles sont ses manifestations?

L'esprit créatif se fonde sur nos expériences et leur donne des formes variées: les mythes, les religions, les philosophies, les divers arts et littératures, l'architecture, les sciences, la médecine, la technologie et les structures sociales. Ces manifestations ont plusieurs buts, pratiques et spirituels. Les effets tangibles de ces efforts sont
quelquefois constructifs, quelquefois destructifs, et cela souvent sans beaucoup de rapports avec les intentions de leurs auteurs.

Presque toutes les formes de la créativité humaine ont un aspect commun: la volonté de donner un sens aux impressions variées, aux expériences, aux actions qui remplissent notre vie, et, en même temps, de donner un sens, une valeur et une signification à notre existence. Sens, valeur et signification sont des termes difficiles à définir mais faciles à comprendre. On ne peut pas vivre sans trouver un sens à sa vie; oh si, on le peut, mais la vie devient vide, froide et dépourvue d'intérêt. C'est justement la crise de notre temps dans le Monde Occidental où la recherche d'une raison d'être est devenue sans signification pour tant d'entre nous.

Les différentes formes de la créativité humaine semblent souvent être incompatibles, réciproquement exclusives, ou même contradictoires. Je crois plutôt que la meilleure expression serait "complémentaires", un terme introduit par Niels Bohr. Y a-t-il une complémentarité entre les voies différentes de la créativité humaine, en particulier entre l'Art et la Science?

Nous rencontrons des situations complémentaires dans la physique elle-même. On emploie des notions qui, superficiellement, semblent contradictoires et mutuellement exclusives, mais qui sont plutôt "complémentaires", jugées d'un point de vue plus profond. Elles représentent des aspects différents de la réalité, un aspect excluant l'autre, mais chacun ajoutant quelque chose d'important à la compréhension du phénomène dans sa totalité. Par exemple, l'état quantique d'un électron dans un atome disparaît si l'électron est observé à l'aide d'un instrument précis construit pour le localiser. Mais l'état quantique est retrouvé si on laisse à l'atome le temps voulu pour retourner à son état initial. Les deux aspects, état quantique et position, sont en fait complémentaires; ils sont, tous les deux, nécessaires pour parvenir à une compréhension profonde de la réalité atomique.

Des complémentarités similaires apparaissent dans tous les domaines de la pensée, comme Bohr l'a souvent remarqué. La question est de savoir ce qui convient le mieux. Dans l'atome, l'état quantique est une bonne description pour certains aspects de la réalité, la notion d'une particule localisée l'est pour d'autres aspects. Il y a des façons différentes de percevoir une situation, des façons qui semblent sans rapport entre elles et même contradictoires, mais qui sont toutes nécessaires pour comprendre la situation dans sa totalité. Un exemple très simple suffira. Une chute d'eau peut être l'objet d'une étude scientifique; dans ce cas la distribution des vitesses et la grandeur des gouttes, leur charge électrique sont des données importantes. Elle peut être l'objet d'un poème décrivant la beauté du phénomène; dans ce cas, des qualités très différentes deviennent importantes. Je rappellerai à ce sujet une conversation bien connue entre Félix Bloch et Werner Heisenberg. Ils débattaient de certaines idées nouvelles sur la structure mathématique de l'espace lorsque Heisenberg, sa pensée glissant vers d'autres façons de percevoir les choses s'écria: l'espace est bleu et les oiseaux y volent!

2. Une voie d'approche intégrale

Nous allons tout d'abord essayer de dégager quelques grands thèmes dans l'ensemble très vaste de l'expérience humaine.
Nous vivons dans un monde multidimensionnel et infini, dont le monde décrit par les sciences naturelles n’est qu’une sous-division. La séparation entre le monde extérieur de la nature et le monde intérieur de l’esprit est un problème bien connu en philosophie. Il lui est associé questions et doute. La science naturelle est fondée sur une séparation entre le monde extérieur et le monde intérieur; on considère les objets étudiés comme distincts et indépendants de nos émotions et des pensées qui régissent notre vie intérieure. Mais la Science est une création relativement nouvelle de l’intellect humain. Avant la venue de la Science, la manière d’aborder les expériences humaines avait toujours un caractère intégral. Les mythes, les religions, les philosophies tentent d’exprimer la totalité de l’expérience humaine, extérieure et intérieure, à partir d’un seul principe universel et de lui trouver ainsi une signification précise.

L’Art a toujours été essentiel à cette approche. Il était, dans une large mesure, un serviteur du mythe, de la religion et de la philosophie. L’Art est bien adapté à transmettre des idées et des émotions sous une forme intégrale, en les transformant en des entités concrètes, visibles ou audibles. Pensez aux sculptures grecques, à la poésie d’Homère, aux cathédrales gothiques, aux passions de Bach. Ce sont là des objets d’art, des représentations immédiates et directes d’idées et de symboles, avec toute leur force spirituelle. Ils transmettent directement au spectateur un sens et une valeur générale, un sentiment de grandeur et de beauté, si toutefois le spectateur partage la culture qui a donné naissance aux mythes ou aux religions qu’ils traduisent.

Chaque fois que la ferveur des mythes ou de la religion commence à s’affaiblir, l’Art commence à s’en séparer et acquiert un rôle indépendant, se substituant lui-même de plus en plus à eux. Alors, l’Art devient un puissant mode d’expression des expériences humaines d’une telle période. Il nous fournit des messages de joie ou de tristesse, de grandeur ou de bassesse, de beauté ou de terreur, de salut ou de désolation, messages qui ne peuvent pas être transmis par d’autres moyens. On connaît bien deux périodes d’une telle séparation entre l’Art et la Science: la période helléniste-romaine, et notre période contemporaine. Elle débuta avec la Renaissance et conduit à une séparation presque complète aux temps modernes.

L’Art, comme le mythe et la religion, est une approche intégrale de l’expérience humaine qui transforme et façonne un grand nombre d’impressions, d’idées et d’émotions en une entité unique; qui concentre une grande variété de perceptions intérieures et extériorées dans une création spécifique. Une véritable œuvre d’Art exprime une vérité intégrale, et non pas une vérité partielle ou une approximation de la vérité. Une grande œuvre d’Art n’est pas perfectible, elle ne peut être améliorée ou changée ou refaite pour se conformer à des connaissances nouvelles ou à des idées dont on ne tenait pas compte lors de sa création. C’est une entité intégrale qui exprime ce qu’elle dit de sa propre manière. Elle sera interprétée différemment au cours d’une période ou au cours d’une autre. Elle peut avoir différentes significations et différentes valeurs à des périodes différentes et pour des groupes de gens différents. Mais elle est vraie et a toute sa force seulement dans sa forme originale.
3. **L'aspect scientifique du monde**

La tradition fondée sur une approche intégrale de la totalité des expériences humaines subit un changement important lorsque la science naturelle naît au temps de la Renaissance. Une nouvelle période commence. Au lieu d'atteindre la vérité complète, on commence par poser des questions limitées. On ne se demande pas: "Qu'est-ce qu'est la matière?, Qu'est-ce que l'est la vie, quelle est la nature de l'univers?". Mais on étudie des questions comme: "Comment tombe une pierre, comment circule le sang dans les artères, qu'est-ce qui se passe si on frotte un objet contre un autre?". On évite les questions générales pour des questions particulières, en étudiant des phénomènes spécifiques, pour lesquels il est plus facile d'obtenir des résultats bien définis.

Alors le grand miracle se produit: L'étude systématique des phénomènes détaillés mène à des résultats bien plus généraux. Le renoncement à un contact immédiat avec la vérité intégrale, le détour par la diversité de l'expérience valaient la peine d'être faits. Cette limitation initiale est récompensée et les réponses aux questions partielles mènent à des solutions plus générales. L'étude du mouvement mène à la mécanique céleste et à l'universalité de la loi de la gravitation. L'étude de la friction mène à la thermodynamique, l'étude des muscles des grenouilles mène à l'électrodynamique qui est la base de la structure des atomes. Des réponses raisonnables sont données aux questions intégrales que l'on avait évitées au départ. L'approche détaillée mène à des résultats intégraux. Comme l'a dit Einstein "Ce qui est incompréhensible c'est que la Nature soit compréhensible".

Le caractère intégral des résultats scientifiques est très différent du caractère intégral des mythes, de la religion et de l'art. D'abord, les résultats scientifiques ne reflètent pas directement ce que l'on associe à l'âme humaine, a nos sentiments, nos ambitions et nos idées du bien ou du mal. Ils ne contiennent que les phénomènes physiologiques qui accompagnent ces réalités. Le caractère intégral ne se rapporte qu'à l'unité des phénomènes naturels en dehors de nos âmes. En outre, il est important de réaliser que les résultats scientifiques sont toujours préliminaires. Ils sont sujets à des modifications et à des changements. Ils ont une validité restreinte. Ils sont des perceptions incomplètes et partielles d'une vérité plus grande qui est cachée derrière la plénitude des phénomènes, une vérité qui se dévoile lentement mais sûrement. Chaque pas vers une connaissance croissante ajoute à la valeur des pas antérieurs. Les réalisations scientifiques ne sont pas valables en elles-mêmes, indépendamment des autres, comme les œuvres d'art. Elles ne sont pas des entités séparables. Elles font partie d'un édifice qui est construit collectivement par tous les savants; la signification de cet édifice est basée sur la totalité des contributions. En allemand, on parle du "Welthbild" des sciences naturelles. Newton a dit: "Je prends appui sur les épaules de géants". Son œuvre, comme celle d'Einstein et des autres grands savants ne constitue que quelques pierres de cet édifice, même si ce sont des pierres très importantes et placées à des endroits clefs.

4. **La complémentarité entre l'Art et la Science**

L'Art et la Science nous donnent des aperçus plus profonds de notre environnement. Cet environnement n'est pas le même pour les deux. Pour la Science (naturelle) c'est le monde dans lequel nous vivons et cela inclut aussi notre corps et notre cerveau. Pour l'Art, il contient aussi le monde dans lequel nous vivons, quoique dans un sens différent (souvenez-vous de l'espace décrit par Heisenberg), mais il contient plus, c'est-à-dire nos
idées personnelles, nos sentiments, nos émotions, nos réactions, nos attitudes, nos humeurs et nos relations avec les autres humains. On pourrait dire que tous ces éléments peuvent être aussi soumis à la méthode scientifique comme des phénomènes à l'intérieur de notre cerveau. C'est bien vrai mais la Science aborde les événements extérieurs d'une façon bien différente de l'Art, et c'est aussi le cas pour les événements intérieurs.

Cette différence a un rapport étroit avec la complémentarité de Niels Bohr. Nous avons des façons différentes d'aborder la réalité qui sont souvent contradictoires, et qui s'excluent. L'approche scientifique est complémentaire de l'approche artistique. L'expérience artistique disparait si l'on explore le phénomène par des méthodes scientifiques, en analogie avec la disparition temporelle de l'état quantique lorsque l'électron est localisé. On ne peut pas ressentir le contenu artistique d'une sonate de Beethoven et, en même temps, s'occuper des processus neurophysiologiques associés à sa perception dans notre cerveau. Mais on peut passer de l'un à l'autre.

Les deux aspects sont nécessaires pour obtenir la réalité complète du phénomène. On peut admirer le ciel étoilé qui nous donne l'impression de la grandeur de l'espace et la variété des constellations, mais on peut aussi analyser les processus à l'intérieur des étoiles, étudier leurs mouvements et leur développement, du "Big Bang" jusqu'à leur état actuel. On peut admirer la beauté des couleurs du coucher du soleil, ou méditer sur la signification du coucher de soleil comme le symbole de la fin d'un jour de la vie humaine; mais on peut aussi être impressionné par la réfraction et la diffusion de la lumière sur la matière particulière en suspension dans l'atmosphère.

Le contraste entre ces différentes approches n'est pas nécessairement celui qui existe entre la pensée rationnelle et le sentiment émotionnel. Il est possible de parler rationnellement d'impressions émotionnelles, de musique, de peinture et d'autres formes artistiques. Cependant, il s'agit là d'un type d'analyse très différent, lucide et précis ayant sa propre échelle de valeurs, il devient fragile et vague quand on le juge du point de vue des exigences particulières de l'analyse scientifique. Les deux aspects sont complémentaires et doivent être utilisés tous les deux si nous voulons atteindre une expérience complète. En particulier, un scientifique est conscient de cette nécessité étant donné le caractère unilatéral de sa vie professionnelle: "le matin je vais au mystère à la réalité; le soir je vais de la réalité au mystère". Mais le mystère n'est qu'une autre forme de la réalité. Ce n'est pas par hasard que tant de scientifiques sont activement ou passivement intéressés par la musique, le plus irrationnel des arts.

Cette immense différence ou cette complémentarité sont si évidentes pour qui conque a affaire avec l'Art et la Science que tout commentaire semble être superflu. Mais il existe un sous-groupe de scientifiques qui n'admettent pas cette prise de position. Il s'agit là de ce que l'on pourrait appeler "les scientifiques chauvinistes". Ceux-ci maintiennent que les progrès en neurophysiologie et dans la science du cerveau conduiraient inévitablement à une compréhension scientifique adéquate de ce qui se passe dans notre cerveau quand nous créons ou quand nous ressentons du plaisir devant une œuvre d'art, ou encore lorsque nous nous sentons élevés spirituellement par l'art ou la religion. Allons encore plus loin - et maintenant le sous-groupe est encore plus restreint - certains sont d'avis qu'un jour viendra où il sera possible de créer de l'art de manière scientifique ou de le remplacer par des impulsions nerveuses puisque nous connaîtrons alors sa fonction neurologique.
La notion de pénétration de l'esprit scientifique dans l'essence même de l'art se fonde sur un certain nombre de fausses raisonnements. Il est certain qu'il n'y a pas de limite imaginaire à notre compréhension du fonctionnement du cerveau et à l'identification d'un processus nerveux défini avec des pensées ou des sensations émotionnelles, morales ou esthétiques. Nous pouvons même nous attendre à des progrès spectaculaires dans ce domaine de la science au cours des prochaines décennies. Pourtant, diverses raisons laissent à penser qu'il semble y avoir des limites certaines à la compréhension scientifique en ces domaines. L'une de ces raisons est le fait que toute recherche scientifique est basée sur la possibilité de reproduire des résultats. Certains phénomènes dans nos âmes, qui relèvent de l'art, ne sont pas reproductibles. Chaque être humain a non seulement une série de gènes qui lui sont propres, mais en outre, et c'est encore plus important, il a été soumis à une série d'impressions différentes. Ces différences peuvent être considérées comme négligeables en certains cas - par exemple, un médecin traitera une maladie donnée par les mêmes méthodes, quel que soit le patient, qu'il s'agisse d'un Einstein ou d'un idiot. Mais lorsque cela concerne le développement de la culture humaine et des traditions, les différences deviennent très importantes. La culture humaine est un amplificateur aussi bien des différences génétiques que de celles acquises par l'expérience. Une combinaison unique et non récurrente de ces différences rend l'artiste ou le poète capable de créer une œuvre d'art. Elle détermine également de quelle façon unique un individu donné ressentira cette œuvre d'art. Comment ce processus peut-il être analysé scientifiquement puisqu'il n'a lieu qu'une seule fois? N'y-a-t-il pas ici une situation complémentaire typique entre la structure du système nerveux d'une part et la création et la perception d'une œuvre d'art d'autre part? Assurément, l'unicité spécifique d'une œuvre d'art ne représente-t-elle pas un obstacle fondamental à l'application de l'analyse scientifique au processus de créativité et de perception.

Nous nous trouvons devant le même problème lorsqu'il s'agit des sciences humaines. Des événements non récurrents et uniques surviennent fréquemment dans l'esprit des hommes; ils ont une influence décisive sur l'édifice social de la société en raison de l'effet amplificateur de la culture humaine. Cela peut être un sérieux obstacle à des prédications scientifiques valables en ce qui concerne les sciences humaines; de même cela peut constituer une difficulté fondamentale si l'on veut appliquer aux sociétés humaines la socio-biologie animale.

Il est certain que je puis, moi aussi, tomber dans la même erreur que celle commise par Niels Bohr qui, en son temps, déclara que les processus de la vie étaient complémentaires à la physique et à la chimie. Ses conclusions étaient basées sur le fait qu'une analyse chimique rigoureuse des processus de la vie exige la mort du sujet étudié. En conséquence, il considérait possible que la matière vivante représente un état différent, complémentaire de la matière non vivante, par analogie avec l'état atomique quantique qui est détruit lorsqu'on essaie d'observer les détails de la structure. Il avait tort - la découverte de l'ADN et toutes celles qui ont suivi l'ont clairement démontré. Je ne crois pas commettre la même erreur mais, si tel est le cas, je suis en bonne compagnie.
Je crois qu'entre l'art et la science il existe des différences fondamentales qui ne pourront jamais être combées, de même qu'aucune nouvelle théorie de physique ne pourra jamais éliminer la complémentarité de la nature ondulatoire et corpusculaire des particules.

L'Art et la Science ont cela de commun - ils fournissent une explication et une signification à l'expérience humaine. Mais la signification de cette explication est totalement différente dans l'un et l'autre cas. On a observé que l'Art transforme les expériences générales en une forme isolée et unique, tandis que la Science transforme des expériences uniques et isolées en une forme générale. Le résultat de chacune de ces transformations est une entité intégrale: l'œuvre d'art et la loi de la nature. Mais entre les deux il y a de grandes différences. Nous avons déjà mentionné que notre perception scientifique a un caractère provisoire et jamais terminée. La vérité ne se découvre ainsi que partiellement et petit à petit, tandis qu'une œuvre d'art est achevée et transmet son message pleinement et complètement, bien que ce message se prête à diverses interprétations.

Une différence importante entre l'Art et la Science est due au caractère collectif du "Weltbild" scientifique. Même la plus importante des créations scientifiques n'acquiert sa signification que par rapport à l'ensemble d'autres contributions. Il est vrai que la signification d'une œuvre d'art dépend elle aussi jusqu'à un certain point de ce qui a été créé auparavant. Beethoven n'aurait pu composer sa musique sans la structure fournie par Bach, Haydn et Mozart. L'art de Michelange s'appuie sur le développement de l'art grec et sur celui du début de la Renaissance. Nous comprenons mieux une œuvre d'art lorsque nous la considérons dans le cadre culturel de son temps. Mais sa dépendance est beaucoup moins accentuée et son caractère est différent de l'interdépendance entre les créations scientifiques: La Science est en effet telle, que les contributions individuelles n'ont aucune signification prises isolément. Elles ne sont que des briques dans un édifice commun, et c'est l'édifice qui correspond à une œuvre d'art non les briques isolées.

Le concept d'un édifice scientifique souligne une différence caractéristique entre l'Art et la Science. Il existe quelque chose que l'on appelle le progrès scientifique. Il est certain que nos connaissances et notre compréhension sont plus vastes aujourd'hui qu'elles ne l'étaient hier. La théorie de la gravitation d'Einstein est plus près de la "vérité" que celle de Newton. Si Newton était vivant aujourd'hui il admettrait librement, et probablement avec enthousiasme, que la théorie d'Einstein est plus avancée que la sienne (cette déclaration est difficile à prouver; elle est cependant convaincante pour tous les scientifiques). Le concept de progrès scientifique est relié à l'idée d'un édifice qui devient de plus en plus important. Un tel progrès ne se rencontre pas dans l'Art. Il n'y a aucune raison pour qu'une sculpture gothique soit considérée comme plus belle qu'une sculpture romane ou pour que Raphaeli représente un progrès par rapport au début de l'Art médiéval, ou Mozart un progrès par rapport à Mozart. C'est vrai qu'à mesure que l'on avance dans le temps il y a une tendance dans l'Art à une plus grande sophistication. Les moyens d'expression deviennent, en effet, plus nombreux, plus variés et plus complexes. Une tendance similaire existe également dans les sciences. Mais dans ce cas, elle va de pair avec un réel accroissement de la connaissance et de la compréhen-
sion de la nature. La sophistication plus grande de l'Art a ouvert un domaine plus vaste de possibilités et conduit à une diversité plus grande des formes de création mais elle n'a certes pas abouti à une force d'expression artistique plus puissante.

Le caractère collectif de la science représente une autre différence typique entre une œuvre d'art et une loi de la nature. La présentation d'une telle loi n'est pas liée à la formulation qui lui a été donnée par celui qui l'a énoncée. Au contraire, l'essence même d'une loi naturelle l'élève bien au-delà d'une quelconque formulation personnelle. Personne, sauf un historien de la science, n'est intéressé par la manière dont Maxwell a formulé ses équations. Leur signification est bien mieux saisie grâce à des présentations plus récentes et plus complètes. L'unicité d'une œuvre d'art est une notion totalement différente de l'unicité d'une loi de la nature. Une œuvre d'art représente une entité personnelle qui est transmise à d'autres individus et ressentie par eux comme une expérience personnelle. Une loi de la nature est une entité impersonnelle, résultat abstrait d'une multitude d'expériences spécifiques directes ou indirectes et des idées apportées par de nombreux individus; elle est comprise par d'autres individus en tant qu'entité intellectuelle générale et impersonnelle. L'œuvre d'art provoque dans celui qui la perçoit des sentiments de joie, de tristesse, d'élevation spirituelle ou de tragique accablément qui sont une partie essentielle de son message. La perception d'une loi de la nature produit également des sentiments et des émotions tels que la joie de la connaissance, la satisfaction, la crainte, etc. Mais tout ceci n'est pas une partie essentielle du message.

On dit souvent que le rôle de l'intuition est un facteur commun à l'Art et à la Science. Ce n'est que rarement qu'un progrès scientifique s'effectue sans une perception intuitive des rapports latents. Dans l'Art, il va de soi que l'intuition est la force motrice de l'acte créateur. Toutefois, l'intuition scientifique et l'intuition artistique n'ont pas toujours le même caractère. Il est vrai que l'étincelle originelle d'une idée ou la première vision de quelque grandiose unification s'apparente chez le scientifique à ce même éclair d'intuition inexplicable qu'est la révélation artistique, même si le plus souvent, l'intuition scientifique découle de la perception inconsciente ou subconsciente d'une connaissance de concepts dont on n'a pas encore pris conscience. Cependant, toute intuition scientifique doit ensuite être validée rationnellement avant d'être incorporée dans l'édifice scientifique. En revanche, l'intuition artistique est le principal instrument de la création et ne nécessite pas de validation ultérieure; elle domine et règne en tant qu'instance de jugement suprême, au-dessus et au-delà des styles et des modes.

5. L'espoir

De quel façon peut-on attribuer un sens à l'univers? Dans le sens où vous sentez un sens. Je crois qu'un vrai scientifique sent ce sens, conscientiement ou inconsciemment. S'il ne le faisait pas, il ne pourrait pas procéder avec cette ardeur commune aux scientifiques, dans sa recherche de quelque chose qu'il appelle la vérité. Certainement cette ardeur contient une grande part d'ambition, carrière, Prix Nobel, etc., mais on ne peut pas nier l'existence de cette ardeur. Elle provient de la conviction que ce que l'on fait comme scientifique vaut la peine et mènera à une connaissance croissante, quelque chose qui a, sans aucun doute, une grande valeur, même si l'humanité s'en sert pour de mauvaises applications, car une profonde connaissance mène à un pouvoir agrandi, et un grand pouvoir même toujours à de grands abus.
Le déclin du sens de la vie et la croissance du cynisme dans notre culture ont certainement aussi contaminé la communauté des scientifiques, et ont affaibli les convictions des chercheurs. Mais il reste encore une bonne partie de cette confiance dans ce qui est le but et la motivation de leur œuvre collective. À mon avis, les scientifiques sont encore un "happy breed of men" (une communauté de gens heureux) parmi tant d'autres qui se débattent avec les problèmes du sens et de la valeur à donner à la vie.

Le développement de la science moderne nourrit évident l'enthousiasme et l'ardeur des scientifiques. Les grands principes d'unité qui sont à la base de toutes choses deviennent plus clairs avec chaque décennie. L'esquisse d'une histoire de l'univers depuis le "Big Bang" jusqu'au cerveau humain commence à apparaître, et ces idées deviennent plus plaissantes avec les nouvelles découvertes. Qu'y a-t-il de plus saisissant et mystérieux que l'observation récente de la réverberation optique du commencement de l'univers sous la forme d'une radiation froide qui emplit l'espace? Qu'y a-t-il de plus impressionnant que l'accroissement continu de notre connaissance de la structure de la matière, de la molécule à l'atome, aux noyaux, aux électrons, nucléons et quarks, et notre compréhension croissante des forces fondamentales de la nature? Qu'y a-t-il de plus éloquent que la découverte du fondement chimique de la vie, où la stabilité quantique des molécules apparaît comme la raison d'être du fait que les mêmes fleurs apparaissent chaque printemps?

Trouve-t-on une ardeur et une motivation comparables parmi les autres groupes humains? Certainement. On la trouve parmi ceux qui veulent leurs efforts aux activités créatrices artistiques, et aussi parmi ceux qui essaient d'améliorer la structure sociale de notre temps. Cependant, ils se trouvent en face de défis plus sérieux. Les problèmes de la science naturelle sont plus purs et moins étroitement mêlés à la complexité et à la fragilité de l'homme. Il est plus facile de percevoir un ordre fondamental dans le cours des événements si le comportement humain peut être exclu.

Le déclin des valeurs du passé qui étaient là pour fournir un sens à la vie a laissé un vide dans nos esprits, un vide qui désire être rempli. Chaque être humain a le désir ardent d'un but, d'une signification, d'un sens à son existence. Les réponses à ces désirs doivent être intégrales. Il faut qu'elles résument la totalité des expériences humaines et leur rendent l'œil et le cœur célèbre. Après le déclin des mythes et des religions, tout ce qui reste est l'Art autonome et indépendante de la religion, et un développement intellectuel très vigoureux: la Science. Ces deux entreprises peuvent-elles fournir un sens et une direction à l'homme? Goethe a dit: "Ceux qui ont l'Art ou la Science ont aussi une religion; Mais ceux qui n'ont ni l'un ni l'autre devraient avoir la Religion".

Cette remarque de Goethe exprime une idée importante qui est commune à l'Art et à la Science: leur vraie signification n'est pas facilement accessible à une grande partie de l'humanité. Il y a certainement beaucoup de formes d'Art et de Science qui sont acceptées par la plupart des gens, comme l'art populaire, la science populaire et la science fiction. Toutefois, ces manifestations ne sont pas les vecteurs efficaces d'un sens profond. Les plus grandes créations et les grands accomplissements de l'Art et de la Science sont des sources d'inspiration uniquement pour une petite minorité de l'humanité. Ces valeurs ne sont pas susceptibles d'une large diffusion. La grande majorité des gens ne peut pas trouver un sens ou une raison d'être profond dans ces sources. Ils ont besoin d'une sorte de religion, comme le dit Goethe. Mais le grand problème d'aujourd'hui, c'est que le besoin d'un sens n'est plus satisfait pour tous par les religions, et il n'y a rien qui le remplace.
Ce que la Science signifie pour les scientifiques n'a pas pu satisfaire ce besoin pour les autres, même si nous sommes tous conscients de vivre dans un âge dominé par la Science et la technologie. Au contraire, tout le monde est conscient que des applications pratiques, parmi lesquelles les applications militaires et les effets destructifs de la technologie, jouent un rôle important. Les perspectives scientifiques de la grandeur de l'univers dans l'immensité de l'espace et de l'atome dans l'immensité du petit n'ont pas pénétré dans l'esprit des gens. C'est probablement la faute des hommes de science car ils n'essayent pas assez de transmettre l'exaltation qu'ils éprouvent pendant les grands moments de leur travail. Ils sont trop plongés dans leur étroites spécialités et ils ne cherchent pas suffisamment à exprimer les significations profondes fournies par leurs découvertes. Mais c'est aussi la faute des artistes et des écrivains qui ont négligé leur devoir. N'est-ce pas le devoir de l'Art que de décrire tout ce qui est grand et imposant dans notre culture et de lui donner une forme qui enivre l'âme? Il est bien possible, cependant, que les grandes idées de la Science ne puissent pas inspirer une exaltation à ceux qui ne sont pas du métier.

Qu'est-ce qui est alors exprimé par l'art contemporain? L'art contemporain représente une recherche frénétique d'un sens quelconque en allant vers des directions inexplorées. Nous observons l'explosion de voies et de formes nouvelles. De temps en temps quelque chose réellement grand et bon est créé, mais le plus souvent nous ne trouvons que les résultats d'expériences insensées accomplies dans le seul but de se différencier de ce qui avait été fait avant. Cette recherche frénétique est peut-être un symptôme de l'absence d'un sens et d'une direction. La plupart des créations de l'art contemporain, en particulier de la littérature, déploient la tragédie et la profondeur de l'absence d'un sens à notre vie. Par cet effort, l'Art est fortement persuasif, navrant et déprimant dans toute sa profondeur. Il agit comme un amplificateur de ce vide dans nos esprits. Il suit en cela une grande tradition de l'Art en élevant ce vide à la hauteur d'une grande tragédie. Même le cynisme a été emporté par l'art contemporain. Nous ne trouvons cependant pas souvent les éléments de l'Art que les autres époques possédaient: l'espoir et la beauté.

Entre temps, les membres du groupe de Goethe reçoivent le lustre et l'éclat de la vie par des révélations scientifiques, ou par des œuvres d'art. Ils les reçoivent plutôt par les œuvres classiques qui ont encore toute leur force et leur signification. Ces œuvres sont peut-être même plus impressionnantes aujourd'hui car elles contiennent ces éléments qui font défaut à l'art contemporain.

Pour les autres, et c'est la grande majorité, le fardeau est plus lourd. Notre monde matériel et spirituel n'a plus d'harmonie et est en danger de destruction. Les grandes révélations de la Science et de l'Art ont peu d'impact sur la plupart des gens car ces valeurs ne sont pas assez liées à leurs pensées.

Mais on voit parmi les jeunes des signes et des indications qui montrent le désir d'un sens et d'une motivation qui deviennent de plus en plus forts. On cherche des voies qui mènent à la dignité de l'individu et à une vie plus remplie d'accomplissements individuels. Ce mouvement prend des formes qui sont quelquefois constructives et quelquefois destructives. On observe des efforts pour améliorer le climat social et spirituel, mais il existe aussi des cultes et des sectes semi-religieuses qui mènent à un mysticisme.
dangerous et à une concentration égoïste en supprimant les relations nécessaires avec la société. Le danger existe toujours que la liberté intellectuelle dont nous jouissons dans cette période sans but soit mise en péril si un nouvel ordre apparaissait.

Un jour viendra peut-être où l'esprit scientifique et l'esprit artistique pourront se combiner et prendre part à la création d'un nouveau sens et d'une nouvelle signification, qui remplira le vide dont j'ai parlé. La conscience croissante de ce besoin est déjà un élément important car elle rassemble les gens et produit des valeurs communes et même des excitations. Il reste toujours un espoir: que naîsse l'espoir.
ART AND SCIENCE

1. Space is Blue

What could be more different than Science and Art? The former is considered as a rational, objective, and cool study of nature; the latter is often regarded as a subjective, irrational outburst of feelings and emotions. One may also consider scientific discoveries as the products of imagination, of sparks of sudden insight, whereas Art could be viewed as the product of painstaking work, carefully adding one part to the other by a rational thinking process. Surely Art and Science have a lot in common; they both are ways to deal with our experiences and to lift our spirits from the daily drudgery to universal values. But the roles of Art and Science in society certainly are very different. Science, unfortunately, is a closed book for most people outside the scientific community; its influence, however, on society is decisive in two ways. One is via Science based on technology, the other is via the philosophical implications of scientific insights which supposedly support a materialistic, rationalistic view of the world around and within us. The role of art is not so easy to define. It does or should contribute to a deeper appreciation of our existence and should help us to endure the human predicament. Unfortunately, much of contemporary art is also a closed book to a large majority.

This essay adds another approach to the numerous discussions of the relations between Art and Science. It may contradict some current views, but, as in so many important issues, contradiction does not necessarily mean that one view is correct and the other is false. Niels Bohr used to say: "A shallow truth is a statement, whose opposite is false; a deep truth is a statement whose opposite is also true."

Let us start with the diversity of human experiences and the diversity of what we are doing with them. There are outer and inner experiences, rational and irrational ones, social experiences between two or many human beings, and experiences with the non-human part of nature. Our reactions to these experiences are manifold and varied. We think and ponder about these experiences, we make use of them to improve our lives and to avoid material and emotional hardships, we are oppressed or elated by them, we feel sadness and joy, love and hate. We are urged to act and communicate them to others; we try to relate them to the pattern of our lives. We want to influence people and our environment. All this is the raw material of human creativity. What are its manifestations?

The creative spirit deals with our experiences and shapes them into various forms: the myths, the religions, the philosophies, the diverse arts and literatures, architecture, the sciences, medicine and technology, and the social structures. These manifestations are directed towards many aims, practical and spiritual; the actual effects upon humankind are sometimes positive and constructive, sometimes negative and destructive; often without much relation to what the creators intended.

Most forms of human creativity have one aspect in common: the attempt to give some sense to the various impressions, emotions, experiences and actions that fill our lives, and thereby to give some meaning and value to our existence. Meaning and sense are words difficult to define but easy to grasp. We cannot live without meaning; o yes, we can, but life is empty, cold and 'meaningless'. It is the crisis of our time in the Western world, that search for meaning has become meaningless for so many of us.
The different forms of human creativity often seem to be incommensurable, mutually exclusive, or even contradictory; I believe, however, a better word is complementary, a term that has acquired a more focussed significance since its use by Niels Bohr. The main purpose of my talk will be to point out the complementarity, in the sense of Bohr, between the different avenues of human creativity, in particular, between the arts and the sciences. Even within physics itself, we deal with concepts and discourses that, on the surface, are contradictory and mutually exclusive, but on a deeper level they are what Bohr aptly has called "complementary". They represent different aspects of reality, one aspect excluding the other, yet each adding to our understanding of the phenomenon as a whole. The quantum state of an atom evanesces when it is observed by a sharp instrument designed to locate the electron. The state is restituted when the atom is left alone and given enough time to return to its original state. Both aspects - quantum state and location - are complementary to each other; they are necessary concepts to get a full insight into atomic reality.

Similar complementarities appear in all fields of human cognition as Bohr often has pointed out. They have to do with the question of relevance. In the atom the wave picture (quantum state) is relevant for certain aspects of its reality, the particle picture for others. There are different ways of perceiving a situation, ways which may seem unconnected or even contradictory, but they are necessary to understand the situation in its totality. A simple example may suffice for the moment. A waterfall may be an object of scientific study, in which case the velocity distribution and the size of the droplets and their electric charge are relevant; or it may be the object of a poem describing the beauty of the phenomenon in which very different properties become relevant. I remind you of the well-known conversation between Felix Bloch and Werner Heisenberg about the subject of space. Bloch reported to Heisenberg some new ideas about the relevance of certain mathematical structures of space when Heisenberg, his mind drifting into other avenues of experience, exclaimed: "Space is blue and birds are flying in it!".

2. The Holistic Approach

Let us now try to discern certain categories within the vast expanse of human experience. We face a world of many dimensions and infinities, of which the "world" of the natural sciences is only a subdivision. The separation of the natural world "outside" ourselves from the "internal" world of the mind is an ever recurring problem of philosophy and subject to questions and doubts.

It should be emphasized, however, that modern quantum mechanics should not be considered as a source of such doubts. Complementarity within physics does not establish a direct relation between mind and matter. The "influence" of the observer upon the observed which is often correctly quoted as the basic tenet of quantum mechanics, plays an important rôle only for the purpose of defining the concepts that are used for the description of atomic phenomena, such as position or speed of an electron in an atom. The actual phenomena, however, are independent of the observer. In most cases we are not interested in the exact position or speed of an electron; hence we do not attempt to localize an electron or to determine its speed. For example, when quantum mechanics describes the light emitted by an electrical discharge in a gas, or the properties of a metal, we do not interfere with the quantum states of the object. How could quantum mechanics be so
successful for the understanding of what is going on in the stars, where any direct influence on the object certainly is excluded?

Natural science, of course, is built upon some kind of separation of the external from the internal world; it regards the objects of its study as distinct and independent from the emotions and ideas that permeate the inner self. But science is a relatively new creation of the human intellect. Before its appearance the approach to human experience has been essentially holistic. Myths, religions and philosophies have tried to derive the totality of human experience, external and internal, from one leading principle and thus provide it with a well-defined meaning.

Art, which is one topic of this essay, has always played an essential part in this holistic approach. It was to a large extent a servant of myth, religion and philosophy, being a most suitable instrument to transmit holistic thoughts and emotions by transforming them into concrete visible or audible entities. Think of Greek sculpture, of Homer's poetry, of the Gothic cathedrals, of Bach's Passions. There they stand, the works of art, representing ideas and symbols immediately and directly with all their spirit and power. They impose upon any beholder their meaning and their general validity, their grandeur and beauty, if the beholder is part of the human soil from which the myths or religions grew.

It is often said that there is another source of art: the immediate urge to embellish and decorate objects of special value and significance. There is not much difference between this and the intensification of symbols and ideas. The embellished objects are symbols that art renders significant; they acquire a meaning beyond their ordinary rôle through decoration and embellishment.

Whenever the mythologic and religious fervour begins to weaken, art tends to separate from these realms and acquire an independent rôle. It then replaces myth and religion to an increasing extent. It continues to create realization of ideas and emotions that are important and meaningful for the culture of the time, although they may no longer be derived from a myth or a religion. Then it is art that serves as a powerful synthesizer of human experiences of the day, presenting to us meaningful messages of joy or sadness, greatness or meanness, beauty or terror, salvation or torture that cannot be transmitted in any other way. Two periods of separation between art and religion are well known: one is Hellenistic-Roman art, the other is the period in which we live, that started in the Renaissance and resulted in an almost complete separation in modern times.

Art, just as myth and religion, is a holistic approach to human experience. Every true work of art transforms and moulus a complex of many varied impressions, ideas or emotions, into one unique entity; it compresses a great variety of internal or external perceptions into a single creation. It expresses a whole truth, if this word may be applied here, and not a partial one or an approximation to the truth. If it is a great work of art, it cannot be improved or changed or redone in order to comply with new insights that were not taken into account in the first creation. It is an organic whole that says what it says in its own unique way. At different epochs it may mean different things to the beholder or listener or reader. It will be interpreted in different ways, it may be more meaningful at one period and less at another. It may mean different things even to different groups of people. But it is valid and effective only in its original unique form.
3. The Scientific World View

The tradition of holistic approach to the totality of human experience suffered an important change with the birth of a natural science in the Renaissance. A new era began. Instead of reaching for the whole truth, people began to ask limited questions in regard to the natural world. They did not ask questions such as: What is matter? What is life? What is the nature of the universe? Instead they asked: How does the water flow in a tube? How does a stone fall to the earth? What makes the blood flow through the veins? What happens if you rub two objects against each other? The general questions were shunned in favour of the investigation of separable phenomena, where it was easier to get direct and unambiguous results.

Then, the great miracle happened: by the systematic study of many detailed phenomena whose relevance were not obvious at all at the start, some fundamental insights into the basic structure of nature emerged. The renunciations of immediate contact with absolute truth, the detour through the diversity of experience paid off. The restraint was rewarded as the answers to limited questions became more and more general. The study of moving bodies led to celestial mechanics and an understanding of the universality of the gravitational law. The study of friction and of gases led to the general laws of thermodynamics. The study of the twists of frog muscles and of voltaic cells led to the laws of electricity that were found to be the basis of the structure of matter. Some sensible answers emerged to those holistic questions that were shunned at the beginning. The non-holistic approach led to holistic results. Einstein said once, "the eternally incomprehensible fact about the world is its comprehensibility."

The holistic character of scientific insights greatly differs in character from that of myth, religion and art. First of all, it does not directly include what we commonly refer to as the human soul, our feelings of awe or desolation, our ambitions, our convictions of right or wrong. It includes only the physiological phenomena accompanying these realities. The holistic character refers to the unity of natural phenomena outside of our "souls". Furthermore and equally characteristic, the scientific insights are always tentative, open to improvement and changes; they have restricted validity. They appear as incomplete perceptions of parts of a greater truth hidden in the plenitude of phenomena; a truth that is slowly but steadily revealed to us. Every step towards more insight adds to the value of previous steps. The scientific creations do not stand each by themselves as the works of art; they cannot be regarded as separable entities. They are parts of a single edifice that is collectively assembled by the scientists and whose significance and power is based upon the totality of contributions. In German it is referred to by the untranslatable term: "Das 'Weltbild' der Naturwissenschaften". Newton said: "I stand on the shoulders of giants". His work, as that of Einstein or other great scientists, comprise only a few stones of this edifice, albeit rather large ones at pivotal locations.

4. The Complementarity of Art and Science

Both art and science are here to give us deeper insights into our environment. But this environment is not at all the same. For Science - only natural sciences are considered here - it is the natural world in which we live, including our own body and brain. For Art, it also contains the natural world, albeit in a different way (remember Heisenberg’s space), but it mostly consists of the vast realm of personal ideas, feelings,
emotions, reactions, moods, attitudes, and relations between human beings. One might object to this and assert that all these elements are also subject to a scientific approach as phenomena within our brain. This is certainly true but, just as Art approaches external natural events in a thoroughly different way than Science, so does it approach the internal landscape of what one may call our souls.

This difference has very much in common with Niels Bohr's complementarity. There are several contradictory, mutually exclusive approaches to reality. The scientific approach to a phenomenon is complementary to the artistic approach. The artistic experience evanesces when the phenomena are scientifically explored, just like the quantum state is temporarily destroyed when the position of the particle is observed. We cannot at the same time experience the artistic content of a Beethoven sonata and also worry about the neurophysiological processes in our brains. But we can shift from one to the other.

Both aspects are necessary to get at the full reality of the phenomenon. We can admire the starry sky by being overwhelmed by the vastness and variety of star patterns or by contemplating the physical nature of the stars and star systems, of their motions and their developments from the big bang to their present stage. We can be impressed by a clear sunset because of the beautiful blending of colours or because of some thoughts connected with this symbol of the end of a day in human life; but we also can be impressed by the processes of refraction and scattering of light in the atmosphere or by suspended particulate matter.

The contrast between those different approaches is not necessarily the one between rational thinking and emotional feeling; one can and does talk rationally about emotional impressions and about music, painting or other arts. But it is a very different type of discourse; lucid and concise within its own intrinsic scale of values, but fragile and indefinite when judged by the peculiar requirements of scientific intercourse. One view complements the other. We must use all of them in order to get a full experience of life. In particular, as a scientist one may be aware of this need, since his or her professional life is rather one-sided in this respect: "In the morning I go from mystery to reality, in the evening from reality to mystery". But mystery is another form of reality. No wonder, that so many scientists are actively or passively interested in music, the most irrational of arts.

The vast difference or complementarity ought to be obvious to anybody who has to do with Art and Science; it should need no further comment. But there exists a sub-group of scientists who do not subscribe to this statement. Let us call them the science chauvinists. They maintain that the progress of neurophysiology and brain science will finally lead to an adequate scientific understanding of what is going on in our brain when we create or enjoy a work of art or when we are spiritually elevated by art or religion, so as to sense a deeper meaning in it. Going one step further - now the sub-group becomes noticeably smaller - they maintain that we then may be able scientifically to create art or replace it by certain nerve stimulations since we then would know that its neurological function is.
The notion of a scientific insight into the essence of art is based on a number of fallacies. Sure, there is no imaginable limit to our understanding of brain action, and of the identification of definite nerve-processes with emotional, moral or aesthetic thoughts or feelings. We may expect tremendous progress in this field of science within a few decades. But there are several reasons why there seems to be a definite limit to fundamental scientific understanding of such matters. One reason has to do with the fact that any scientific research is based upon reproducibility of results. Certain phenomena in our soul that are relevant to the arts are not reproducible. Not only has every human being a different set of genes; more importantly, he or she was subject to a different set of impressions. Some of these differences may be considered as irrelevant in certain respects. A medical doctor will treat a disease successfully by the same methods, whether the patient be Einstein or a halfwit. But for the development of human culture and traditions the differences become most relevant. Human culture is an amplifier for both the genetic differences and those acquired by experience. A non-recurring unique combination of such differences makes an artist or poet capable of creating a work of art. It also determines the unique way in which an individual experiences that work of art. How can such a process be scientifically analysed when it occurs only once? Do we not face here a typical complementary situation between the structure of the nervous system on the one side and the creation and perception of a work of art on the other? Indeed does not the specific uniqueness of a work of art represent a fundamental obstacle to the application of scientific analysis to the creative and perceptive process?

The same problem also appears in the social sciences. Non-recurring and unique events occur frequently in the minds of human beings and they have decisive impacts upon the social fabric of society because of the amplifier effect of human culture. This may turn out to be a serious impediment to reliable scientific predictions in social science; it may also be a fundamental difficulty when animal sociobiology is applied to human societies.

I must confess that I may run into the same error that the great Niels Bohr has committed when, some time ago, he argued that the processes of life are complementary to physics and chemistry. He based his conclusion upon the fact that a strict chemical analysis of life processes requires the death of the investigated creature. Therefore, he considered it possible that matter alive may represent a different state of matter, complementary to the non-living state, in analogy to the atomic quantum state which is destroyed by any attempt to look at its detailed structure. He was wrong as the discovery of DNA and all that followed have clearly shown. I do not think that I commit a similar error. If I do I am in good company. Indeed, I believe that there are fundamental differences between art and science which cannot be bridged over, just as no new physical theory will ever get rid of the wave-particle complementarity.

Art and science have this in common - that they provide meaning and sense to human experience. But the sense of the meaning is thoroughly different. It has been observed that art transforms general experiences into a single and unique form, whereas science transforms detailed single experiences into a general form. Either of the two transformations results in a holistic product: the work of art and the law of nature. But there are vast differences between the two. We already have mentioned the tentative and
unfinished character of our scientific perception of nature. It represents only part of a
truth that is developed step by step, whereas a work of art is finished and transmits its
full message at all times, although the messenger may not be always interpreted in the same
way.

An important difference between Art and Science comes from the collective charac-
ter of the scientific "Weltbild". Even the most impressive single scientific creation
makes sense only within the web of other contributions. Surely, the significance of a work
of art also depends to some extent upon what has been created before: Beethoven could not
have composed his music without the framework of Bach, Haydn and Mozart. Michelangelo's
art builds upon the development of Greek art and of the early Renaissance. We understand
a work of art much better when it is considered within the cultural framework of its time.
But this dependence is much more tenuous and different in character. The interdepend-
ence between scientific creations is such that individual contributions have no significance
whatsoever in isolation. They are bricks in a common edifice, and it is the edifice that
corresponds to a work of art and not the individual bricks.

The concept of a scientific edifice points to a characteristic difference between
Art and Science. There exists something that may be called scientific progress. We defi-
nitely know and understand more today than we did before. Einstein's theory of gravity is
nearer to the "truth" than Newton's. If Newton were alive today he would freely and
probably enthusiastically admit that Einstein's theory is a progress compared to his (a
statement which is hard to prove; nevertheless it is a convincing one for every scientist).
The concept of scientific progress is tied to the idea of a scientific edifice to which
every scientist contributes, an edifice which definitely is larger today than it was before.
No such progress can be found in Art. There is no reason why a gothic sculpture should be
considered better than a romanesque one, or why Rafael is progress compared to early medie-
val art, or Mahler compared to Mozart. True enough, there is a tendency of increased
sophistication in art as time proceeds. The means of expression become more manifold,
varied and more intricate. Of course, a similar tendency exists in the sciences. In the
latter case, however, it is connected with a genuine increase of insight and understanding
of nature. The increased sophistication of art may have led to a wider scope of subject
matters and a greater variety of creative forms but hardly to a more powerful force of
artistic expression.

The collective character of science leads to another typical difference between a
work of art and a law of nature. The presentation of the latter is not bound to the formu-
lation given to it by the creator. On the contrary, the very essence of a natural law
elevates it far beyond any personal formulation. Nobody but a historian of science is
interested how Maxwell formulated his equations. Their significance is much better under-
stood from later more comprehensive presentations. The uniqueness of a work of art is a
notion completely different from the uniqueness of a law of nature. The former represents
a personal entity, which is transmitted to and reexperienced by other individuals again as
a personal experience. The latter is an impersonal entity, an abstraction from a multitude
of specific direct or vicarious experiences and creative ideas of many individuals; it
is understood by other individuals as an impersonal general intellectual entity. The work
of art produces in the recipients feelings of joy, sadness, spiritual elevation or tragic
dejection that are an essential part of the message. The insight into a law of nature also produces feelings and emotions, such as awe, joy of insight, satisfaction and the like. But they are not an essential part of the message.

It is often said that the role of intuition is a common factor in Art and Science. There is rarely a progress made in science without an intuitive perception of some idea or of some hidden relations. In art, of course, intuition is the essential driving force of creativity. However, scientific and artistic intuitions are not always of the same character. True enough, the first spark of an idea or the first glimpse of some grand unification may come to the scientist in a similar unexplainable flash of insight as an artistic revelation. But, more often than not, scientific intuition comes from an unconscious or half-conscious awareness of existing knowledge or of connections between concepts that have not yet been consciously realized. But any intuitive scientific insight must be rationally validated afterwards before it can be incorporated into the scientific edifice. In contrast, artistic intuition is the main instrument of creation and does not require any additional validation; it reigns superior and is the highest instance of judgment, over and above the mould of style and fashion.

5. Hope

In what sense does the universe make sense? In the sense you sense a sense. Every true scientist feels a sense, consciously or unconsciously. If he did not, he would not go ahead with that fervour, so common among scientists, in his search for something that he calls the truth. Surely there is a large amount of ambition, mixed into this fervour - acclaim, tenure and Nobel prize - but there is no denying that this great fervour exists. It is based upon a conviction that what he does is worthwhile and will lead to an increase of insight, something that is great and valuable beyond any doubt, even if the fallibility of mankind makes the wrong use of it. Great insight leads to great power; great power always leads to great abuse.

The decay of a sense for meaning and the increase of cynicism in our culture has also contaminated the community of natural scientists and has shaken that conviction in various degrees for various members of that community; but there is still a good deal of belief in the purpose and meaning of their collective work. I cannot help feeling that they represent a "happy breed of men" among so many others who grapple with the problems of meaning, sense and purpose.

The emerging scientific "Weltbild" contains much to support the enthusiasm and fervour of its propagators. The great unifying principles that underlie the plethora of events become clearer with every decade. An outline of a history of the universe from the big bang to the human brain is taking shape and becomes ever more convincing with the discoveries and insights that emerge from year to year. What is more startling and uncanny than the recent observation of the optical reverberation of the origin of the universe in form of the cold radiation that fills all space? What is more impressive than the steady growth of our insights into the structure of matter, from molecules and atoms to nuclei, electrons, nucleons and quarks, and the growing understanding of nature's fundamental forces? What is more overwhelming than the recognition of the chemical basis of life, in which the stability of the molecular quantum state emerges as the true basis of the fact that the same flowers appear again every spring.
Do we find a similar fervour and a sense of purpose among other groups? Surely we do; we find it among those who are devoted to creative, artistic activities and among those who try to improve the social fabric of our times in many different ways. However, they face a much greater challenge. The problems of natural science are much less messy and much less interwoven with the complexity and fragility of the human mind. It is much easier to perceive an underlying order in the flow of natural events if human behaviour is excluded.

The decay of the previously existing sources for a meaning, sense and purpose, such as myth and religion, has left a big void in our bellies, a void that craves to be filled. Every human being craves for a meaning and a sense to his existence. The answers to these cravings must by necessity be holistic. They must embrace the totality of human experience and endow it with luster and light. With the decay of myth and religion all that was left was an autonomous art that has made itself independent of any prevalent religion, and a new most vigorous intellectual development: Science. Can these two enterprises serve as providers of meaning and sense? Goethe has said: "He who has Art and Science has also a religion; but those who do not have them better have religion".

Goethe's remark points out one important element common to both expressions of the human mind. Their true significance is not easily accessible to a large part of mankind. Of course, there are many expressions of art and some of science that are indeed appreciated by large groups of people, such as folk art, popular art, popular science and science fiction. However, these manifestations are not the most effective providers of sense and meaning. The grandest creations and achievements of art and science serve as inspirational sources only to a small minority of humans; their values seem to be not suitable for a wider spread. The large majority cannot get meaning, sense and purpose from these sources. They must have some sort of religion as Goethe says. Perhaps it is the greatest problem of our day that this craving is no longer fulfilled by the conventional religions and that there is nothing to replace it.

The kind of meaning that Science provides to its perpetrators has not proven to satisfy this craving, in spite of the fact that everybody is fully aware that we live in an age dominated by science and technology. On the contrary, this awareness is tied to a large extent to practical applications among which the military ones and the destructive effects of technology on the environment play an important rôle. The scientific insights into the greatness and unity of the universe in the large and in the small have not penetrated much into the minds of the people. It probably is the fault of the scientists who do not try hard enough transmitting the elation they feel at the peak moments of their work. They are too much immersed in their narrow specialities and do not sufficiently seek to express the deep connections which their insights have provided. It also is partly the fault of the artists and writers of today who neglect this task. Is it not the duty of art to remould all that is great and awe inspiring in our culture and to lend it a form that stirs the souls of men? It may be, however, that the great ideas of science are not suitable for inspiring outsiders with any true elation.

What is it then that contemporary art expresses? It reflects a frantic search for some kind of meaning by trying to go in many hitherto untried directions. We observe an outburst of new ways and forms of expression. From time to time indeed something really
great and beautiful is created but, more often than not, we see the results of wild experimentation with new ways, for the sake of being different from what has been done before. Perhaps this frantic search is a symptom of a lack of sense and meaning. Perhaps it is a method to arrive at a meaning.

Many of the creations of contemporary art, especially in literature, deal with the tragedy and the depth of our lack of purpose and meaning. In this effort our art is powerful, heart-rendering and deeply depressing. It acts as an amplifier of what is meant with the aforementioned void in the belly; it follows the great tradition of art by elevating it to grand tragedy. Even cynicism has been ennobled by contemporary art. But we do not find often enough the ingredients that permeated art in past centuries: beauty or hope.

In the meantime the members of the Goethe group get some luster of life from scientific insights if they can, or from works of art; not in the least from the classical works of art which have retained their power and significance; perhaps they seem today even more powerful and significant because they contain so much of those ingredients that are missing in much of contemporary art.

For the others among our fellow men, and that is the vast majority, the burden is much harder. Our material and spiritual world is in disorder and in danger of destruction. The great insights and elevations of Science as well as of Art have not much impact on most of the people because these values are not connected with a ground swell of meaning permeating the collective mind. But there are many signs and portents among the younger generation of a mounting craving for sense and purpose and for the dignity of the individual. This ground swell appears in various forms, some are constructive, some are destructive. There are promising efforts to improve the social and spiritual climate, there are cults and semi-religious sects. All too often, some of these cults and sects have lead to a misconceived mysticism and to a concentration on the inner self without the necessary relations to society. Maybe there will come a day when scientific and artistic meaning will combine and help to bring forth that ground swell of meaning and value for which there is so great a need. The growing awareness of this need is in itself an important element that brings people together and creates common values and even elations. There is always hope - for hope.
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