Contemporary Frontiers in Physics

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Physics has become such an enormous field of science that a short summary of the work in its frontier areas must of necessity be incomplete and biased (*1*). Today every physicist is a specialist in some narrow part of the field, and it is impossible to have critical insights into the whole of our science. I ask indulgence from those whose fields are not treated adequately here. Still, we must not forget that the unity of science remains the main tenet of every scientist and the basis of his view of nature. We believe in the existence of fundamental laws that govern everything in nature. Some of the great unifying principles of physics are listed in Table 1.

Although quantum mechanics is listed among the unifying principles in Table 1, it also brought about a division of physics into different realms of phenomena. This is because there exists a threshold of excitation for any dynamical system. The threshold becomes higher as the dimensions of the system decrease. I refer to this ordering principle as the quantum ladder (see Table 2). The first rung is the atomic and molecular realm, in which the energy exchanges are so low (up to a few thousand electron volts) that the atomic nuclei remain unexcited and therefore all nuclear (or subnuclear) processes remain dormant. The second rung is the nuclear realm, which becomes active when the energy exchanges between atomic units reach the order of 1 million electron volts. The third is the subnuclear realm, which is activated around energies of 1 billion (10^9) electron volts. In general, at a lower rung we can forget about processes at a higher rung, except when we employ them intentionally as tools, as Rutherford did when he used alpha particles to determine the structure of atoms and as we do today, for example, when we study molecules by use of nuclear magnetic resonance.

Thus the quantum ladder divides physics into more or less independent parts, such as atomic physics (including the physics of atomic aggregates), nuclear physics, and subnuclear or particle physics. The first part is the most extensive and richest one, both because it deals with our immediate environment and because the electrical neutrality of the atoms and the vast possibilities of forming electron states around several nuclei permit an enormous variety of structures and combinations. We have gases, liquids, solids, membranes, macromolecules, and, finally, living structures with all their complexity and organization.

Recent Discoveries

The last decades have been unusually fruitful in almost all parts of physics. Many important discoveries have been made and a few fundamental insights have been gained. There is a special reason why so many new discoveries were made in these decades, namely the exuberant growth of new instrumentation and the maturing of many previous innovations, which became ready for full exploitation. A partial list of examples includes lasers, plasmas, new types of microscopes, synchrotron radiation, low-temperature techniques, rockets, accelerators, colliding beam devices, detectors, and, most important, computers.

The laser made it possible to produce large concentrations of highly excited atoms and molecules, to observe collective phenomena of excitation such as superradiance, to produce nonlinear effects of light in matter, and to create tremendous concentrations of electromagnetic energy.

The techniques of plasma production, handling, and analysis have been widely developed. New types of instabilities have been found and effects of trapped particles have been studied.

Among the new microscopes I include the scanning electron microscope. I also include the use of focused particle beams to study small regions of matter by observing the emitted secondaries, as well as the new image intensifiers.

Synchrotron radiation has provided us with x-ray intensities about 10^6 times stronger than those of the best conventional machines. The study of extended x-ray absorption fine structure (EXAFS) makes it possible today to investigate a molecular environment with a resolving power down to almost 0.1 angstrom.

New techniques of low-temperature physics have opened up wider perspectives in the realm of superconductivity and superfluidity. Of particular interest is the study of superfluid helium-3, whose amazing properties lead to new vistas of collective behavior in condensed matter.

Rockets have changed the character of astronomy by making it possible to conduct direct observations outside the atmosphere with all kinds of probes and, in the nearest future, with space telescopes.

Accelerators are now able to produce proton beams with energies of up to half a tera-electron volt (10^{12} eV), and the technique of colliding electron and proton beams has been developed. New types of particle detectors (wire chambers, streamer chambers) allow us to study particle collisions with much greater precision and sensitivity.

Last, but perhaps foremost, the development of computer hardware and software has made it possible to deal with the deluge of data streaming from the new instrumentation devices. Modern physics without modern computers is unthinkable.

New Insights

The new insights into the workings of nature won in the last decades are more difficult to pinpoint. My judgment may differ from that of my readers, and our common judgment may turn out to be mistaken. Nevertheless, I would certainly include the new approach by L. Kadanoff, M. Fisher, and K. Wilson, which finally has shown a suitable way to deal successfully with the problems of critical phenomena. It leads to a deeper understanding of what happens at the critical point and gives an account of the different powers n by which the various parameters change with $(T - T_c)^n$, where T is temperature and T_c is the critical temperature. This approach showed clearly the general nature of the problem, which is largely independent of the special properties of the systems.

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I would include the successful attempt by S. Weinberg, P. Higgs, G. T'Hooft, J. Ward, and A. Salam to unify weak and electromagnetic interactions; their predictions are being verified one after the other. I would include the recognition of the quark structure of protons, neutrons, and mesons, which has become increasingly convincing as more experimental evidence has been gathered. With some hesitation, I would also include quantum chromodynamics, an attempt to describe the strong interaction between quarks by analogy with quantum electrodynamics.

Other more tentative ideas are being discussed which aim at a new fundamental view of things. Examples are the ideas of supergravity and supersymmetry, the quantum treatment of the black hole phenomenon which indicates a possible new type of particle creation, and the use of nonlinearities in the field equations (corresponding to solitons and instantons) to obtain structures that might be models for elementary particles. At best, these daring attempts are promising beginnings.

Let us look into the future. Of course, it is impossible to predict major advances in basic science. A major advance might best be defined as one that was not foreseen. Indeed, I suspect that the most significant steps forward will occur where we expect them least. All I can do here is describe a number of growth points in physics—that is, areas in which some new discoveries or insights are probable in the near future. Again, the list will be incomplete, and biased by my restricted knowledge and experience. The order in which the growth points are listed has nothing to do with their relative importance.

Disorder

It has long been known that the deviations from ideal order in solid crystals have a decisive effect on the properties of materials. Still, we do not have a systematic way of describing grain boundaries, dislocations, and other lattice defects, or of predicting the circumstances under which they occur. Furthermore, it has been found that amorphous solids have properties that were previously ascribed only to crystals. We are beginning to understand the reasons. Effects of random distributions of spins, of foreign atoms, and the like are being studied in greater detail and a theoretical treatment of such problems has become possible. To quote Philip Anderson: "The next decade is very likely to be the most 'disorderly' decade in theoretical physics."

Surfaces

The structure and composition of surfaces is becoming increasingly interesting to theorists and experimenters. The new instrumentation methods permit much more accurate investigations of surface phenomena, and there are new theories to deal with them. J. M. Kosterlitz, D. V. Thouless, and A. Berezinski showed that new states of aggregation should be expected in two-dimensional arrays, and some of their predictions have been verified. The process of the melting of a two-dimensional system has now been investigated theoretically and experimentally, and the results may help us to better understand three-dimensional melting. Clearly, the study of surfaces is important for understanding catalysis and action of membranes.

Nonlinear Physics

Whenever nonlinear relations occur in physics, mathematical understanding becomes difficult. Therefore the description of natural phenomena always begins with the parts where linear dependences are predominant, or where nonlinearities are small. Nonlinearities can then be considered as perturbations and treated by successive approximation. This is the reason why quantum theory has had so many successes. Because of principle of superposition of wave functions, the behavior of many simple systems can be described by linear relations with small nonlinear perturbations. Furthermore, because of the smallness of the coupling constant e^2/hc (where e, h, and c are, respectively, the electron charge, Planck's constant, and the speed of light) for the interaction with the electromagnetic field, the most important interactions—the electromagnetic ones—can be treated by successive approximations. But in contemporary physics we are more frequently encountering problems where that method no longer works. When nonlinearities become important, instabilities occur and new forms of behavior set in. One finds examples in almost every field; the best known example is turbulent flow. Plasma physics abounds with such instabilities. This is an illustration of how nature is much more varied than we can guess, even when we know exactly the fundamental equations that underlie the processes.

Nonlinearities are important in particle physics because of the strong interactions, which are not amenable to approximation methods. Among the new forms of behavior introduced by nonlinearities are the so-called solitons—local large disturbances of a field that behave not unlike particles. They may even turn out to be what we observe as elementary particles. In all fields of physics new methods developed to deal with nonlinear relations may become important tools for the understanding of many hitherto unexplained phenomena.

Collective Phenomena

I expect that our understanding of collective phenomena will greatly increase in the near future. Many-body problems

Table 1. Unifying principles of physics.

Principle	Author or theory
Unity of natural laws in heavens and earth	Newton
Unity of heat and mechanics	Mayer, Helmholtz, Joule
Unity of electricity, magnetism, and optics	Faraday, Maxwell
Unity of space, time, matter, and gravity	Einstein
Unity of physics, chemistry, and materials science	Quantum mechanics
Unity of atomic, nuclear, and subnuclear phenomena (?)	Field theory (?)

Table 2. The quantum ladder.

Subject	Energy range (eV)	Location
Atomic and molecular realm		
Chemistry, optics, materials, biology, complexity, organization, order-disorder	Up to 1000	Earth and planets of other stars
Nuclear realm		
Radioactivity, nuclear reactions, fission, fusion	10^5 to 10^7	Interior of stars
Subnuclear realm		
Antimatter, mesons, heavy electrons, short-lived entities, quarks	10^8 to ?	Big bang, neutron stars, unknown

Table 3. Elementary particles, 1978.

Fermions				Bosons (carriers of interactions between fermions)		
Quarks		Leptons		Type of interaction	Source of interaction	Carrier
Name	Charge	Name	Charge			
u	2/3	e	1	Strong	Quarks (color)	Gluon*
d	−1/3	ν	0	Electromagnetic	Electric charge	Photon
s	−1/3	μ	1	Weak	All particles (weak charge)	Intermediate boson*
c	2/3	ν'	0	Gravity	Energy (mass)	Graviton*
b	?	τ	1			

*Hypothetical.

are receiving much more attention than before and are encountered in almost every field of physics. In the solid state and the liquid state, for example, increasingly complex collective phenomena have been discovered and are only partially understood. In particular, the properties of superfluid helium-3 have revealed unusual features and it was found that the phenomenon of superfluidity is much richer than was anticipated. Many new phases have appeared, and the interactions that produce them seem to cause an alignment of nuclear spins due to the action of the molecular field when the atoms are in p states relative to each other.

The physics of the liquid state, plasma physics, nuclear physics, and even astronomy are full of unsolved problems of collective behavior. A new method invented in one field may help to solve problems in others. Unfortunately, there is not enough cross-fertilization today, and the same idea is often reinvented in different fields.

Heavy-Ion Physics

The study of energetic collisons between heavy nuclei opens up new vistas in nuclear physics. It enables us to observe nuclear matter at high compression. Under these conditions it is no longer possible to describe it as an assembly of protons and neutrons. The pressure causes the appearance of excited nucleons and pions, and a phenomenon called pion condensation may occur. Indeed, the simple proton-neutron description of nuclei has turned out to be insufficient even to account for more precise measurements of the charge distributions in ordinary nuclei. In the future physicists studying nuclear structure will have to take into account the existence of excited states of nucleons and mesons; nuclear structure will thus be much more closely connected with particle physics than it is today.

Furthermore, a collision between nuclei of high atomic number Z creates temporarily a nucleus with an abnormally high charge: $Z > 150$. Such charge concentrations are expected to produce strange effects, not only by way of vacuum polarization but by the appearance of negative electron clouds around the nucleus, which reduce the effective charge. Future experiments may test these unusual consequences of quantum electrodynamics.

Astrophysics

Up to 10 or 15 years ago, the sky was considered essentially unchanging except for planets, comets, and very rare events such as novas and supernovas. Today, when studied with radio antennas, infrared receivers, and x-ray telescopes, the sky presents an ever-changing picture of fluctuating intensities within almost any time interval, from milliseconds to months. If this were translated into visible light, the sky would present a dramatic picture of stars, clusters, and nebulae flaring up and fading away. Some of these phenomena are understood, but many are still mysterious or open to various interpretations.

As mentioned before, the further use of rockets and the introduction of space telescopes will greatly extend the range of "seeing" in astronomy. We may expect the wave of new cosmic discoveries to continue unabated for some time.

The discovery of pulsars and their interpretation as neutron stars of very high density are already familiar. This was a momentous development—starting with the observation of small regular flickerings and growing into the recognition of the existence of large chunks of dense nuclear matter. The amount of knowledge gained about the most abnormal state of matter from so few observations is impressive. It led to new ideas, not only about nuclear matter in general, but also about what happens to a star that has exhausted its nuclear fuel: it explodes and implodes at the same time, producing a supernova and a neutron star. The compression of ordinary magnetic fields during the gravitational collapse to a neutron star produces fields of the order of 10^{12} gauss, which would completely distort atoms to elongated electron tubes. Much new information about the physics of supernova explosions and about nuclear matter under high gravitational compression will be gained in the near future by further studies of these phenomena.

The existence of black holes follows from an extrapolation of Einstein's theory of gravity by many orders of magnitude beyond the range for which its validity has been established. Rarely has a theoretical idea been extended so far, but Einstein's ideas are so convincing that most experts in this field consider those structures to be a real possibility. The present vague indications of the existence of black holes should be confirmed or refuted in the foreseeable future.

X-ray astronomy is now an established observational method and the x-ray sky has been thoroughly investigated. Many new x-ray sources have been found, some of them double stars, where matter streams from one partner to the other; the latter may be a neutron star or perhaps even a black hole, as in the x-ray source Cygnus X-1. Future extensions of these observations may reveal many new and unexpected cosmic phenomena. Observations of infrared light are just beginning to add to our knowledge of what is going on in stars and nebulae. Infrared studies will soon develop into an essential branch of astrophysics.

It is generally believed that energy production in stars such as the sun is well understood as a process of fusion of hydrogen to helium, but failure to detect the neutrino flux from the sun expected on the basis of this model is a problem. It now seems well established that too few neutrinos from beryllium reach the earth, and there is no good explanation for this fact. To be sure, the undetected neutrinos are supposed to result from a side effect of the fusion process, and it should soon be possible to measure neutrinos produced when deuterons are formed from two protons, which is part of the direct process of energy production. If the latter neutrinos are also not detected, our knowledge of stellar structure will be deeply shaken.

Perhaps the most impressive, if not uncanny, recent discovery was the observation of blackbody radiation of about 3 K filling all space. It is tempting to interpret this as an optical remnant of the big bang about 15×10^9 years ago—direct evidence for the explosive creation of the universe from an extraordinarily high concentration of energy. Future research, observations, and theories may bring us closer to understanding the very beginning of the universe. They may also resolve the question of the average density of mass, which determines whether the universe will endlessly expand or whether it undergoes periodic expansions and contractions with an unending series of big bangs. A third and not so improbable possibility may be that these alternatives are based on a wrong interpretation of the observed facts, and that the evolution of the universe is completely different from what we now believe.

Nevertheless, the observed 3 K radiation determines an absolute coordinate system, the one in which it appears to be isotropic. Small deviations in isotropy have been observed which indicate motion of our solar system—not only the expected rotation around the center of the galaxy but also motion of the galaxy toward the Virgo cluster. The dream of Michelson and Morley has come true—to find the absolute motion of our solar system, not in respect to an ether but to a gas of photons.

Particle Physics

A decade ago the view that quarks are the constituents of baryons and mesons (hadrons) was considered a vague hypothesis, perhaps only a simple ordering scheme of hadron families that had little to do with reality—the hadrons behave "as if" they are made of quarks. Now there is hardly any reason to question their existence. There is not much doubt today that the nucleons and their excited states are composed of three quarks and that the mesons are made up of quark-antiquark pairs. A turning point was reached with the results of J. Friedman, H. Kendall, and R. Taylor, who observed deep inelastic scattering of fast electrons with nucleons at the Stanford Linear Accelerator Center (SLAC). The observations had all the characteristics of electrons being scattered by charged subnuclear particles much smaller than protons. It was the Rutherford experiment of subnuclear physics, since it revealed the existence of small concentrated charges within the nucleon. The quarks were indeed seen, just as Rutherford saw the atomic nucleus.

Similar deep inelastic scattering studies were later made with beams of neutrinos, which were scattered by quarks through weak interactions. These experiments confirmed and extended the findings of the electron-scattering experiments and thus provided additional support for the quark hypothesis. Quarks were found to be particles with spin 1/2; they carry fractional charges such as +2/3 and −1/2; they are pointlike and not very strongly bound to each other when confronted with a large momentum transfer. Several different types ("flavors") of quarks were identified, with different masses. Protons and neutrons consist only of the first two types, the so-called u and d quarks, but it was necessary to introduce more types—three more up to today—in order to explain the numerous heavier short-lived mesons and baryons found in nature. The different quark types transform into each other only through weak interactions. Moreover, it was necessary to ascribe an internal degree of freedom to each quark—a trivalued spin called color—which permits the quark to exist in three distinct quantum states.

So far it has not been possible to "ionize" the hadrons—that is, to liberate a quark from a hadron and observe it as a free particle. However, in high-energy collisions jets of mesons have been observed with a large momentum exactly in the direction in which quarks should have been ejected. This process of "mesonization" of quarks is to some extent understood as the creation of a trail of quark-antiquark pairs by the ejected quark. The behavior of quarks has led to the conclusion that the forces holding them together are soft—that is, weak against a large momentum transfer (actions at small distances) and strong against a smaller momentum transfer (actions at larger distances). Indeed, the confinement of quarks (impossibility of ionizing them) indicates that the potential of the quark binding force goes to infinity for large distances.

Quantum chromodynamics (QCD) goes a long way toward explaining some of these features. It describes the strong interactions between the quarks by a non-Abelian gauge-field theory, a generalization of quantum electrodynamics, in which the quarks are the sources of a "gluon" field and their "charge" is given by their trivalued color degree of freedom. In this theory the field carries charge, a feature that is characteristic of a non-Abelian field theory. So far, the calculable results of this theory seem to agree with observations, such as the weakness of interactions for large momentum transfer, but the most important feature of quark-quark interactions, the confinement of quarks, has not yet been derived from this theory. It has not been shown, however, that the theory definitely cannot account for it. Still, we are far from having a reliable theory of quarks and quark interactions. The next decade may produce many new insights into this mysterious subnuclear realm of nature.

Such new understanding is essential, since QCD cannot tell us how many quark types exist and what their masses are. It does not deal at all with this question. Indeed, the fact that there are more than two types of quarks is already a deep riddle. The two quark types with the lowest mass are the constituents of neutrons, protons, and pions; they make up nuclear matter as we know it under terrestrial and most stellar conditions. It is completely unknown why nature needs the heavier quarks that are the constituents of the "strange" and "charmed" hadrons, which are all short-lived products of energetic collisions that quickly decay into more ordinary particles such as nucleons, electrons, and neutrinos. Most probably, the number of known quark types will increase in the near future, since we expect more discoveries of quasi-stable structures that are quark-antiquark combinations. The initial discovery of the J/ψ particle—a combination of a charmed quark and its antiparticle—by Burton Richter and Samuel Ting in 1974 was one of those seminal experiments. It has already had one sequel indicating the existence of a fifth quark; many more may follow.

Two new quarks discovered within a period of 4 years should be enough, but physicists have also discovered a new heavy electron, the τ particle of a mass near 2 GeV, which together with the e and the μ now form a triad of charged leptons. The future will show whether it also has its own neutrino, as do the other two electrons. The existence of at least three electrons differing only in their mass is a tantalizing problem. Here, too, we have no idea about the role in nature of these heavy electrons, which decay by weak interactions into ordinary electrons after emitting suitable neutrinos. Just as QCD does not tell us why there are several quark types, quantum electrodynamics does not yet offer any explanation for this proliferation of electrons.

Recently a number of exciting experimental and theoretical developments took place in the field of weak interactions. They are connected with the construction of a unified theory of weak and electromagnetic interactions, which

I mentioned earlier. An attempt was made to unite these two phenomena by introducing a common field transmitting these interactions. The field has several components, one representing the photons as carriers of electromagnetism, others representing the carriers of the weak interactions. This unification not only solved some of the internal contradictions in the previous theory of weak interactions, it also required the existence of neutral currents—that is, weak interaction processes without transfer of charge. During 80 years of study of weak interaction processes it was assumed that they are all connected with a charge transfer: a radioactive nucleus changes its charge when it decays, and the charge is transferred to the emitted electron; a heavy electron does not change into a light one but into a neutrino, emitting another electron-neutrino pair. Processes without charge transfer escaped discovery, but a few years after their prediction by the unified theory, such processes were observed in neutrino-induced reactions, first at CERN and then elsewhere. Quite recently, in an interesting and difficult experiment at SLAC, the same neutral weak interaction was also observed between electrons and protons by making use of the violation of parity, which distinguishes it from the much stronger electromagnetic interaction. The theory predicted these and other weak interaction phenomena with astonishingly quantitative accuracy.

The existence of the carriers of weak interactions (intermediate bosons) has not yet been experimentally verified. If the theory is right, weak and electromagnetic phenomena will merge at high energies in a predictable way, and a new type of particle (the Higgs particle) will appear. Time will show whether the theorists are on the right track, but one thing is almost certainly true: at these high energies (center-of-mass energies of 100 GeV or higher), both the weak and electromagnetic phenomena will exhibit properties very different from those to which we are accustomed.

Unquestionably, particle physics today is in a state of flux. The future will bring many new fundamental insights, in particular if the construction of higher-energy accelerators and colliding beam devices continues to be supported. This state of flux is illustrated in Table 3, which shows elementary particles and their interactions as of 1978. There are two groups of elementary particles—the fermions and the bosons. The fermions are particles of spin 1/2 and they fall into two subgroups—the quarks and the leptons. The quarks are the constituents of all hadrons and do not seem to exist as free entities; the leptons are the different electrons and neutrinos. The second group, the bosons, are particles of spin 1 or 2 and are the carriers of the different interactions between the particles. In the past year one new quark (the b quark) and one new electron (the τ particle) were added. Moreover much more evidence for the common nature of the weak and electromagentic interaction was accumulated. Still, three of the four field carriers—the carriers of the weak and strong interactions and the graviton—have not yet been observed. Here we expect the new accelerators and new gravitational devices to deliver some positive or negative evidence within the near future.

It may be fitting to end the survey of particle physics by enumerating the outstanding problems in that fundamental field. Our immediate environment—in which I include most galaxies—is governed by the properties and interactions of its constituent structures, namely electrons, protons, neutrons, neutrinos, and photons. We consider the protons and neutrons to be made up of u and d quarks. Why does nature need the other quark types?

The relation of the charge of the electron and the proton to other natural constants—the ratio $e^2/hc = 1/137$—is not understood. Furthermore, the ratio of the proton mass to the electron mass $M/m = 1836$, is still unexplained. The values of these two ratios are decisive for the character of matter as we know it: the small value of e^2/hc is essential for the structure of atoms, and the large value of M/m is the basis for a well-defined molecular structure. We have no idea where those values come from, except perhaps that the large value of M/m is connected with the fact that the strong interactions (forces between quarks) are much stronger than electromagnetic forces.

In spite of our growing knowledge of the interior structure of protons and neutrons, we still do not have much insight into the nature of the forces between protons and neutrons that keep these particles together in atomic nuclei. Heitler and London explained the chemical interaction between atoms on the basis of atomic structure, but the Heitler and London who will explain the nuclear forces from the structure of the nucleons have not yet appeared.

Furthermore, we still face four different fundamental forces—the strong, electromagnetic, weak, and gravitational interactions. A connection between the second and third kinds has been found. But is there a connection between those two and the others that will lead to a grand unification of all known interactions between particles?

The question of why there are short-lived higher states of matter made of heavier quarks and heavier electrons is still unanswered. Neither do we know how many of these heavier particles exist. It may well be that quarks and electrons are also composite systems and that the proliferation of new types is nothing but the beginning of a series of excited states of these systems. Will we find an unending series of worlds within worlds when we continue to penetrate deeper into matter to smaller distances and higher energies? The answers to most of these questions can be found only by more observations. The great progress of physics in the last decades was based on the development of better, larger, and finer tools and instruments, and so will be the development in the future. Teilhard de Chardin (*2*) said that "The history of [natural science] can be summarized as the elaboration of ever more perfect eyes within a cosmos in which there is always something more to be seen."

References and Notes

1. Because the names of the contributing physicists obviously cannot be quoted in extenso, I have not mentioned any names except where they are necessary to identify a theory or an experiment.
2. P. Teilhard de Chardin, *The Phenomenon of Man* (Harper & Row, New York, 1959), p. 31. I have changed the original words "the living world" to "natural science."