

Structure of matter: A five-year outlook

Unity is the prevailing theme of the physical-science chapter in a report to Congress on the prospects for scientific and technological resolution of nationally significant problems.

Robert G. Sachs

What current and emerging problems of national significance can be identified through scientific research? What are the opportunities for, and constraints on, the use of new and existing scientific and technological capabilities toward a resolution of these problems?

These questions were posed by Congress in 1976, when it asked the Office of Science and Technology Policy to prepare a periodic Five-Year Outlook on Science and Technology. The task passed to the National Science Foundation in 1977, and the NSF in turn asked the National Academy of Sciences, in 1978, to help provide the first five-year outlook. The Academy submitted its report to the NSF last March.

The document, which includes a substantial amount of background information, is necessarily written for the educated lay reader. Nevertheless we feel it is of some importance for physicists to know how their field is being represented, and this article therefore summarizes those sections of the report of interest to physicists. As there may well be those who, in this age of specialization, would relish the opportunity to have a broad overview of recent and prospective de-

velopments in physical science, the article has the additional purpose of giving them a taste of such an overview and possibly encouraging them to refer to the report itself. (The complete report, *Science and Technology—A Five-Year Outlook*, has been published by W. H. Freeman, and it costs \$15.00 hardbound, \$9.95 paperback).

Content of the report

The four major sections of the report are:

Science—Planet Earth; the living state; structure of matter

Technology—Computers and communications; energy; materials

Science and the United States—Demography; health of the American people; toxic substances in the environment

Institutions—Academic science and graduate education; institutions for international cooperation.

Not all deserving areas of science and technology could appear within these major sections, but several topics of interest to physicists are included. Most of them are in the chapter on structure of matter, and this article is concerned with that chapter. The box on page 28 lists its table of contents.

Within the time available to us, we could solicit contributions from only a selected few among the physical-science community, those few necessarily representing the great breadth of the field. Then, of the contributions we received, some were modified and some good ones omitted entirely because of space limitations, reactions of reviewers and decisions of the Steering Committee, which bears the responsibility for the final product. (See this page for a list of the Committee members.)

How could we decide which of the topics to include? They were chosen, at least

in part, with the following messages in mind:

► The pervasiveness of matter, energy and the laws of nature throughout the universe.

► The rapid expansion of our knowledge and understanding of the cosmos.

► The continual unfolding of new frontiers in the understanding of the properties and behavior of macroscopic matter.

► The ever-retreating horizons associated with deeper and deeper penetration of matter in pursuit of the question of its ultimate reducibility.

► The ultimate unity of physical science, illustrated by the preceding "message" and expressed by the basic simplicity of the laws of nature.

► The ceaseless increase in complexity of the experimental methods of physical science, and the associated increases in complexity and costs of required facilities and instrumentation.

► The role of progress in physical science as a driving force for technology, and the need for technology as a driving force for the sciences.

► Influences and trends affecting the health of the physical sciences in the United States.

► The importance of the international science scene and the strong but somewhat precarious position of the United States on that scene.

Health of the field

The report points out that the health of physical science in the United States depends on three major factors that have already played a decisive role in establishing the remarkable strength of the field. The first factor is the quality of the personnel; we have benefitted from a rich diversity of scientific manpower selected on a world-wide basis, and from very

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Ralph E. Gomory, IBM Corporation (*chairman*); Bernard Davis, Harvard Medical School; David Hamburg, Institute of Medicine; Julius Harwood, Ford Motor Company; James Hillier, RCA Corporation; Thomas Malone, Butler University; David Rose, Massachusetts Institute of Technology; Jacob Schwartz, New York University; Conrad Taeuber, Georgetown University; Gilbert F. White, University of Colorado, and Robert M. White, National Research Council.

special educational opportunities.

The second factor, the nature of available instruments and facilities, will depend on the industrial and technological environment and the technical ingenuity of the scientists as well as on financial resources.

Finally there is the element of "style," which is not easily defined but is nevertheless of great importance. Style has to do with the balance between risk and certainty, between the most and least expensive way of going about a task and between a simple and complex way of accomplishing a given objective. It relates to the way in which practitioners of the science communicate, especially experimenters and theorists. It is influenced by the objectives of the work, whether it is application oriented or "knowledge" oriented. It reflects the degree of commitment, motivation and faith in a successful outcome on the part of the participants.

Influences and trends

While the science of the structure of matter is generally in good health in this country, there are some danger signals suggesting a weakening of all three of the above factors during the next few years. The traditional setting for fundamental research is the university, and the burden for maintaining the thrust of the research as well as the quality of the personnel falls on universities. A current trend toward reducing this traditional role has significant implications for the future. For one thing, inflation, funding that has leveled off, and the reduction in academic jobs have all reduced the opportunities for academic work and careers. This situation is affecting what has been for three or four decades the very high quality of our scientific manpower, and emphasizes the need for new institutional arrangements.

The growing need for more complex, larger and more expensive instruments is also causing strains. The need has been manifest for many years in fields such as astronomy and high-energy physics. The instruments required to probe deeply into outer space and those required to probe "inner" space, that is, into the depths of the microworld, are large and expensive. However, there are such trends in many other fields as well, resulting in requirements for much more sophisticated small instruments in the laboratory and an increasing need for large centralized facilities. It must be emphasized that this increasing complexity of science, like that of society, adds to our capabilities and productivity and requires added resources, not a simple reallocation of resources. History has shown that when a qualitatively new (and usually more sophisticated) method of attack on any frontier of science is successful, it leads to a substantial increase in the resources available to the technology as a whole.



The major facilities are increasingly large and expensive, so that careful and thoughtful attention must be given to the scientific benefits in making priority decisions among the various possibilities. However, the long time required to build and exploit them perhaps argues in favor of taking even greater chances than those that usually must be taken in an unexplored field. Of particular importance is that more attention be given to providing the means and opportunity for full scientific exploitation, once the decision to provide a facility is made.

Except for astronomy, where the need for centralized facilities has been generally recognized, scientists have always resisted the transition from the small, one-man laboratory to the large, centralized facility. The idea of the independent scientist and a few of his students working with apparatus that he can comprehend completely, and control, has great attractions. However, as physical science has become more complex, it has become increasingly evident in one field after another that the complexity of the apparatus must increase if certain of the important opportunities are to be exploited. This change leads to a major shift in style to team research, to the commuting professor, to the student resident at a facility hundreds or even thousands of miles from his university. The fields of particle physics and space sciences made the appropriate adjustments some years ago; similar adjustments are being made in nuclear physics and are about to be made in some special areas of condensed-matter science.

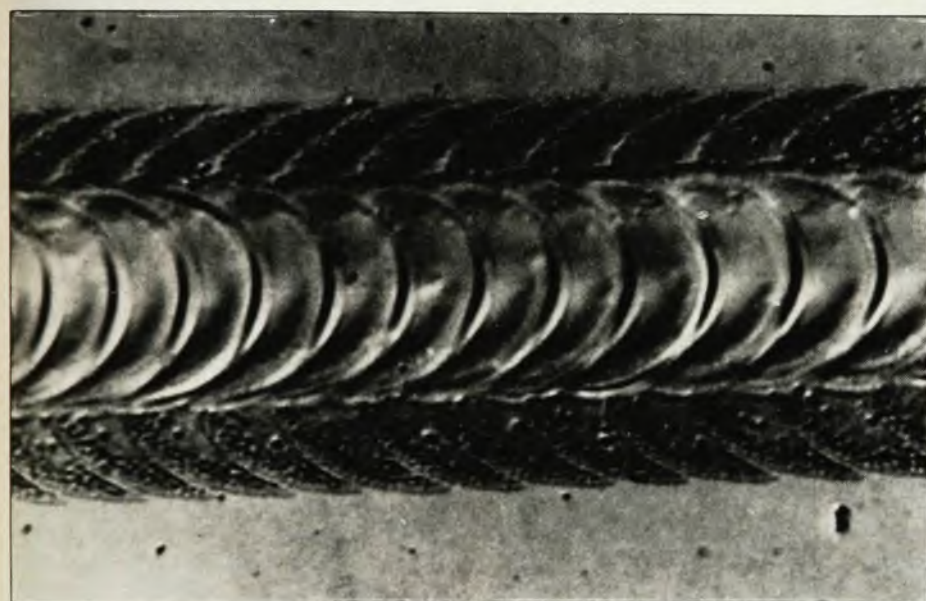
Of course, team effort is not new to engineering research and development. It has been the necessary style in applications of technology on a large scale. New influences have been introduced by the increasing role of recent scientific work in the high-technology areas, such

Condensed-matter research. Synchrotron radiation at 2 to 30 000 eV from the Stanford Positron-Electron Accelerating Ring (SPEAR), shown **above**, is useful for a wide variety of condensed-matter investigations. Molecular-beam epitaxy is a valuable tool for semiconductor-material fabrication; the apparatus **above right** includes effusion ovens, a sample holder, and mass-spectrometer and optical-fluorescence detection equipment. (Courtesy of A.C. Gossard and W. Wiegmann, Bell Labs.) The optical micrograph (**right**) is of spots laser-melted in amorphous silicon on a single-crystal silicon substrate. The central regions exhibit liquid-phase epitaxial regrowth to the single-crystal form.

as nuclear-fusion energy development, to cite an extreme case. This shift leads to, and will continue to lead to, an increasing importance for interdisciplinary work between the basic sciences and engineering.

The ubiquitous computer has also profoundly affected the style of physical research, as it has almost every other information-related human activity. High powered computers, making possible the solution of scientific problems that cannot be treated by other methods, have become essential scientific tools.

These trends are affecting almost all of the subfields of physical science. In the field of astronomy and astrophysics, major new ground-based and space facilities are scheduled or planned, and it is expected that their availability along with the necessary instrumentation and computer power will extend the rapid development of recent years. The construction of several synchrotron-radiation sources will provide for one recognized need in the fields of condensed matter and molecular science, but the United States is lagging behind in making available adequate sources of slow neutrons. Furthermore, the rapid development and deployment of state-of-the-art instru-



mentation is needed at all times both to exploit such facilities and to exploit the opportunities they provide to open new frontiers in traditional "small" science. The latter has become a particularly acute problem because the complexity and costs of such instruments tend to be beyond the means and capabilities of any but the largest university laboratories.

Major facilities making possible the exploration of nuclear structure at small distances by means of strong interactions are available or soon will be, but the need for high-intensity probes of the nucleus using electromagnetic (electron) and weak (neutrino) interactions is just beginning to receive attention. Steps are being taken to extend and expand the accelerator facilities available in the United States for high-energy physics experiments. Of particular importance is the need to provide the instrumentation required to exploit these facilities—instrumentation which is massive, delicate and exceedingly complex because of the

great complexity of the processes taking place at high energy.

Unity of the physical sciences

Unity is a prevailing theme of the chapter, and we emphasize unity because the complex behavior of the physical universe makes the simplicity and unity of the laws of nature very obscure from the viewpoint of the casual observer. Yet it is the fundamental reason for the success and importance of the science.

A basic tenet of physical science is that *all* natural phenomena can be described by a very sparse set of principles and mathematical relationships valid throughout the universe. In view of the great diversity and complexity of natural phenomena, there is no obvious reason for the validity of this assumption, which has its origins in the metaphysical concept of the fitness of things; but our faith in it has been justified over and over again by experience. There is no greater miracle than the continual, successful reduction

of the rich complexity of nature to simple principles comprehensible to humankind.¹

The science of matter is divided into many fields and subfields: the fields of physics, chemistry, astrophysics and cosmology, and subfields of solid state, liquid state, molecular and atomic structure, nuclear science and elementary-particle physics. General principles and common laws are shared by all of them. The consistency of the macroscopic laws of matter, including mechanics, fluid dynamics, electrodynamics, thermodynamics and relativity with the microscopic laws including kinetic theory, statistical mechanics, quantum mechanics and quantum field theory is an expression of this unity. It makes possible the tying together of the behavior of matter in bulk with the reductionist concept that matter is made up of "building blocks," in other words, the elementary entities. The entirety of physical science has an organic quality, the whole of all fields put together is much more than the sum of the parts, and the strength of the whole lies in the strength or weakness of each of the parts.

This synergism is expressed both through the use of results in one field to augment techniques in another and in the sharing of method between fields. A most obvious case is the way in which developments in solid state continue to have an impact on the instrumentation in all fields. However, the fact that theoretical methods should also be shared so successfully between apparently disparate fields is not so obvious, but recent developments have renewed our faith that it will continue to occur. In condensed-matter physics many remarkable and unexpected macroscopic properties, such as ferromagnetism, superconductivity and superfluidity are now understood in terms of principles and theories that also apply to the structure of stellar bodies, to nuclear physics, to particle physics and to field theories. Symmetry principles, and the concepts of gauge theories and spontaneously broken symmetries, turn out to play a common role so that theorists working in one such field may borrow methods from another. Just as all fields have shared in common methods of solution of linear equations, it now appears that new approaches to the solution of non-linear equations, discovered first in connection with hydrodynamical problems, may be of great importance for the understanding of both condensed matter and elementary particles.

These shared successes are a reflection of the deeper unity of the fundamental principles. The history of physics has been marked by a struggle for such unifying principles. Examples of successes are manifold: Newton's connection between Earth's gravity and motion of planets around the sun (called by Victor Weisskopf "the unification of Heaven and

Earth¹²); the unification of heat and energy by Clausius; the unification of electricity, magnetism and optics by Maxwell and Faraday; the unification of chemistry and physics by quantum mechanics; the unification of gravitation and space-time by Einstein, and the current, apparently successful unification of electromagnetic and weak-interaction theories.

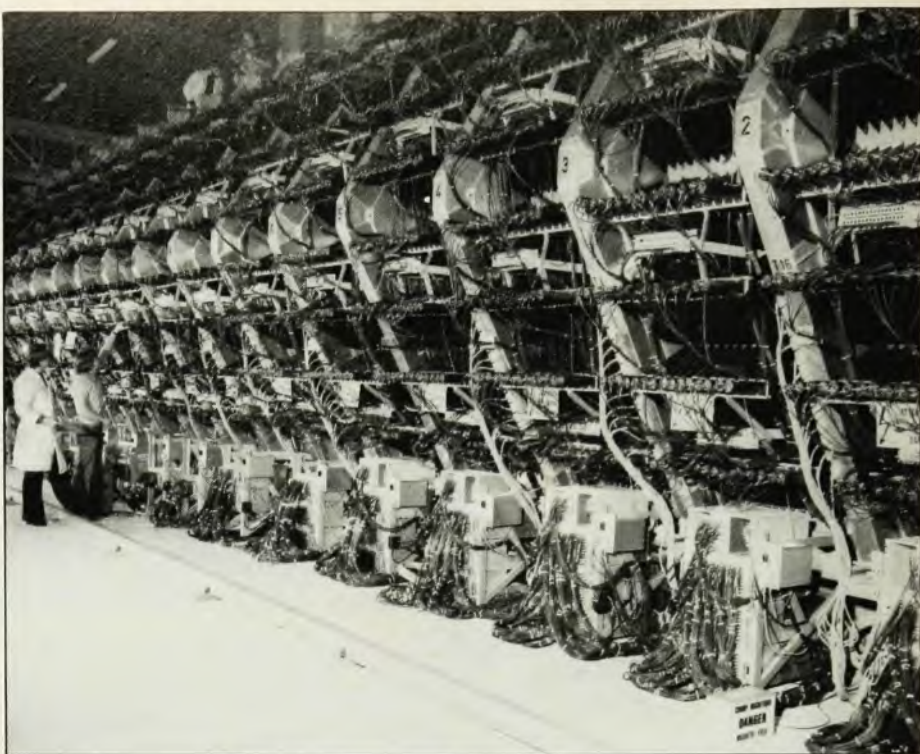
Recent discoveries in the field of high-energy physics have led to optimism about the possibility of extending the unification of electromagnetism and weak interactions to include the strong interactions of particles. There are some indications that we are on the threshold of another great step toward this goal.

Outlook of the science

The examples we chose to explain and illustrate these general aspects of physical science were comprehensive but, again because of space limitations, more exclusive than might have been desirable. The table of contents of the chapter, displayed in the box on this page, should make that clear. Here we summarize briefly the specific point we made in discussing the outlook.

Cosmology and astrophysics. Rapid developments in astronomy and space science have resulted from the combined use of ground-based instruments and space probes to observe cosmic sources of electromagnetic radiations and cosmic rays. The spectrum of radiations covered includes the range from radio waves to gamma rays, neutrinos, electrons, protons, neutrons and a variety of nuclei. These observations have provided support for the Big Bang concept and for the existence of neutron stars, confirming theories of stellar evolution. The evidence for black holes tends to confirm one of the remarkable predictions of the general theory of relativity.

Opportunities in the offing will provide



The neutrino detector with drift chamber at CERN. "Of particular importance [for high-energy physics] is the need to provide instrumentation which is massive, delicate and complex."

additional information concerning the validity of these concepts and will help to resolve some of the grand questions concerning the structure of the universe, such as whether it is open or closed, by increasing our knowledge of the amount of matter in the universe and of the ages of the stars. The facilities required for these purposes are the optical telescope scheduled for the space shuttle, the ground-based multiple mirror telescope, the very-large-array interferometer and the planned gamma-ray space observatory. Eventually, detection of high-energy

neutrinos should provide an entirely new means for observing stellar phenomena.

Solid and liquid states. Condensed-matter science serves both as a paradigm of the structure of physical science and as a technology base for other fields of science and for industrial development. Recent developments in the field show promise for substantial progress in studies of amorphous materials, surfaces, exotic new materials, and systems far from equilibrium, as well as for developments in atomic and molecular engineering. The theories, especially of critical phe-

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"Grand questions concerning the structure of the Universe..." may be resolved with new instruments, such as the Einstein Observatory x-ray space telescope that took this photograph.

nomena and of disordered systems, have become more sophisticated and powerful, and general methods of mathematical physics have resulted, with profound impact in this and other fields of physics. Thus this work beautifully characterizes the unity of physical theory.

Both the increasing complexity and the precision of the experimental work have been made possible by apparatus that has become more elaborate and expensive, and ways of sharing such apparatus among institutions are being explored in order to meet the need. The possibilities for qualitatively new experiments on condensed matter by means of synchrotron radiation sources are being realized. It can be hoped that intense neutron sources, which can be used especially to study the locations and dynamics of light atoms and magnetic fields in condensed matter, will soon become available on a scale comparable to that in Western Europe.

Molecular and atomic structure. Largely because of developments in instruments and spectroscopic techniques paralleling those used in investigating condensed matter, progress has been rapid in the study of the structure of molecules, especially large organic molecules. Nuclear magnetic and electron paramagnetic resonance methods have been especially fruitful. Increased sophistication of these techniques has raised the cost so that new institutional arrangements to replace the one-scientist-one-instrument tradition are needed. Again, synchrotron-radiation sources and intense neutron sources

hold great promise in this field. The use of neutrons is just at its most primitive stage, beginning with small-angle scattering to obtain gross features of large molecules. An order-of-magnitude increase in intensity is needed to provide the opportunity for this technique to realize its potential for studying molecular structure and dynamics.

The coherence, intensity and spectral purity of their emitted light have made lasers a powerful tool for high-precision molecular spectroscopy. For example, they are used to observe the properties of molecular fragments during picosecond intervals and therefore during the process of chemical reaction.

The continued deepening of our understanding at the basic level of processes taking place in and between molecules, especially large organic molecules, holds promise for obtaining insights into the processes of nature that might yield practical applications mimicking biological systems.

Elegant developments in the field of atomic physics have allowed very high-precision tests of some of the fundamental laws of nature. Here again, lasers have played an important role. It has been possible to isolate and study a single atom and also to investigate the structure of "giant atoms" in very highly excited states that occur naturally only in outer space.

With exotic atoms such as muonium, made up of unstable particles that can be produced only at high-energy machines, the fundamental constants of nature can be determined with ever increasing pre-

cision, and other previously inaccessible information about nuclei and particles can be obtained.

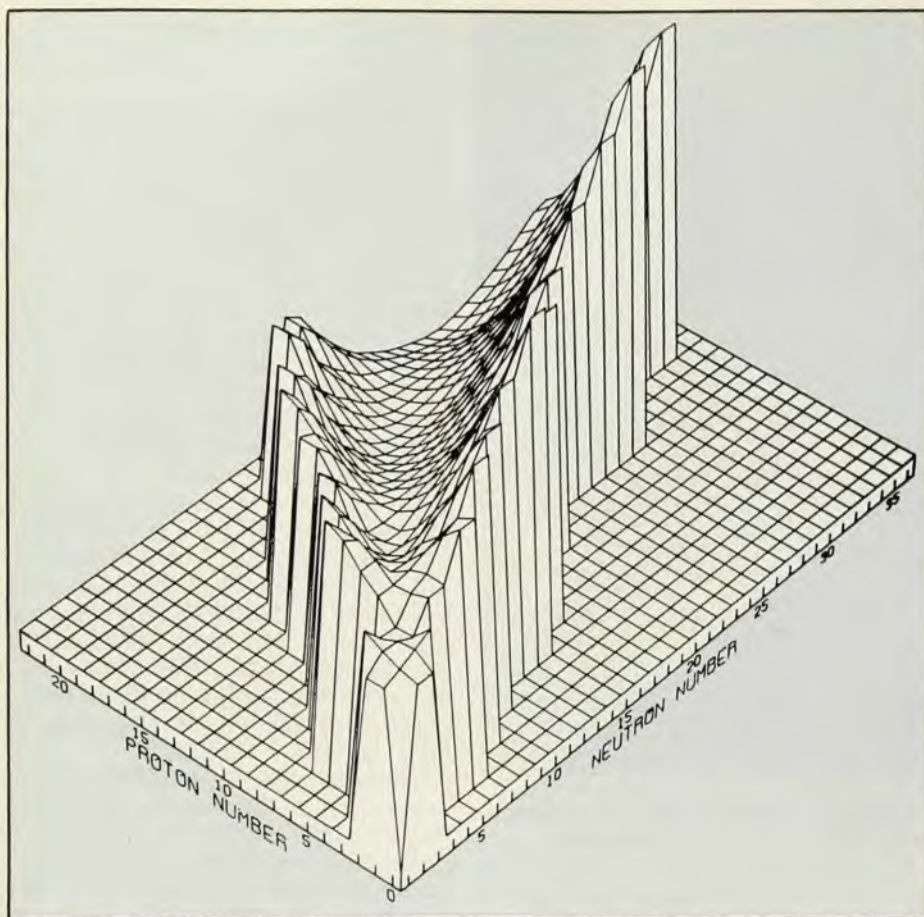
Nuclear structure. The availability of high-energy particles from accelerators for nuclear physics has opened up new opportunities for the study of already known nuclei and the production of heretofore unfamiliar nuclei. Pion, electron, photon and heavy-ion beams are being used to probe the nucleus and to explore the rugged terrain beyond the "valley of stability." The production of nuclei in these unexplored regions and of various forms of grossly deformed nuclei by means of beams of fast heavy ions is just in its earliest stages.

The problems of nuclear theory have much in common with those of the theory of condensed matter, especially those associated with quantum fluids, and there has been a successful sharing of experience between these fields. New states of nuclear matter discovered in this work will shed further light on fundamental questions concerning combinations of large numbers of particles.

Particle physics. A complete change in our concept of the nature of the fundamental building blocks out of which all matter is composed has occurred in recent years as a result of experiments in high-energy physics. These concepts are still going through the process of analysis, criticism and change as the experiments continue to produce unexpected results.

In our present understanding of the situation, one group of particles continues to be qualified as "elementary," by which we mean "indivisible." This group consists of the leptons: electron, muon, tau particle and the neutrinos associated with each. Then there is the "zoo" of more than two-hundred hadrons that differ explicitly from the leptons in that strong forces act between them.

The hadrons differ implicitly in that they are not believed to be elementary; very recent developments have convinced most physicists that hadrons are made up of quarks, and since the quark has not been seen as a separate entity, new theoretical concepts explaining their inseparability have been proposed. The development of these ideas has resulted from a beautiful interplay between theory and experiment—theory governed to a considerable extent by the idea that there is a simplicity and symmetry to nature if one can just get to the root of it. From these developments came the notion of a new quantum number called "charm," subsequently confirmed by the discovery of a new class of mesons associated with charmed quarks. A facet of the unification of weak and electromagnetic interactions is a match-up between the quarks and the leptons: for example, the tau particle, which is a form of electron but 3500 times heavier than the familiar electron, is associated with another quark, the "bottom" quark, suggested by the



The Valley of Stability. One purpose of nuclear experiments is "the exploration of the rugged terrain beyond the valley of stability," shown in this computer plot by Jeff Poskanzer of LBL.

discovery of the "upsilon," a meson having a mass 60 times that of the pion. The existence of the "top" quark is still purely speculative.

The quantum of weak interactions, the W particle, is also strongly suggested by the unified theory of weak interactions and electromagnetism, and a major search for it is being undertaken at CERN, the international accelerator facility in Geneva, while physicists at Fermilab will not be far behind. Since the W is believed to have about 75 times the mass of the nucleon, no existing machine is capable of providing the necessary energy; but methods capable of providing the energy by collision between a beam of antiprotons and a beam of protons are being developed. The discovery of the W would be a great step forward in the unification of physics.

Measurement, symmetry and unity

Precise measurement is a pillar on which the remarkable advancement in understanding of the physical universe is based. Quantitative description of matter leads to mathematical formulations of the laws of nature that may, after many tests of their validity, be regarded as established truth. Accurate reproducibility and predictability are the hallmark of successful physical science. Results ex-

pressed in terms of precisely measured numbers alone are not enough, however—they must fit into rules and principles formulated in mathematical terms in order to establish predictability. It is an axiom of our science that these rules and principles apply everywhere and for all time. The mathematical formulation may be in terms of equations or be the consequences of symmetry principles.

Symmetry plays a pervasive role in scientific thought. The elementary concept of symmetry is that of geometric form as, for example, expressed in geocentric and heliocentric models of the Universe. This urge to take the sphere as the natural geometrical form has its eventual realization in the spherical symmetry of empty space which leads directly to the fundamental law of conservation of angular momentum.

Many other important geometrical expressions of symmetry exist in physical science, including translational invariance responsible for the conservation of linear momentum, the description of crystal structure, the behavior of conduction electrons in metals, and descriptions of the structure of molecules. Quantum mechanics made possible the understanding of the basic chemical behavior of the elements; their behavior is governed by the Pauli Exclusion Principle, which is

itself a consequence of the internal symmetry associated with the identity of electrons rather than of a geometrical symmetry. Generalizations of the concept of internal symmetries having to do with the identity and therefore the interchangeability of particles have been responsible for many of the advances in nuclear and particle physics, including the development of the concept of quarks, whose fundamental identity explains the arrangement of hadrons into multiplets.

The rapid progress expected during the next few years is likely to unravel the relationships between particles and those between forces. We seem to be on the threshold of tying together the weak, electromagnetic and strong interactions. Theoretical progress will almost certainly improve on some of the poor approximations used in solving these problems.

Another driving force on physical science is the desire for unification of apparently different kinds of fields and forces. Einstein sought the unification of gravitational and electromagnetic theories as his ultimate aim. Through the study of quantum effects of gravitational fields, we may see his hope realized on a much grander scale than he ever imagined, as the unification of gravitation, electromagnetism, weak and strong interactions—all of the known forces of nature.

Currently, there is active speculation about how the loop can be closed between nature in the large (cosmology) and nature in the small (particle physics and quantum field theory). Knowledge of the entire spectrum of particles is essential to a full understanding of the consequences of the Big Bang theory of the Universe; a quantum field theory of gravitation is needed for a full understanding of black holes; and there are questions concerning the possible connection between the violation of CP invariance in weak interactions—which is not understood—and the asymmetry of the universe between matter and antimatter—which is also not understood. The recent speculations about the latter point have included the notion that the proton may be unstable, with a finite lifetime of the order of or greater than 10^{32} years. New experiments are underway to push the upper limit on the lifetime above the current value of about 10^{30} years (for some modes). However, these ideas are in such a state of flux that it was not deemed appropriate to try to explain them in this Outlook on the structure of matter. Perhaps there will be a clear enough picture to treat them in the next report.

References

1. See, for example, E. P. Wigner, *Communications on Pure and Applied Mathematics*, 13 (no. 1), February 1960.
2. V. Weisskopf in *Science, Invention and Social Change* (A Rosenfeld, ed.), General Electric Co., Schenectady, N.Y. (1978); page 17. □