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THE CHARACTER OF PARTICLE PHYSICS

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From the time humans began to ask questions about themselves and their world, people have wondered what the world is made of and how it behaves. Over and over, in different ages and with different methods, people have tried to answer the questions, "What is the smallest possible piece of matter? What are the fundamental forces of nature?" From the time of the Greeks, with their designation of the elements Earth, Air, Fire, and Water, this ongoing quest has yielded extraordinary advances in knowledge that make our universe more understandable. Today, the fundamental science of high-energy, or particle, physics continues to pursue answers to these most ancient, and most modern, of questions.

Over the centuries of thought and experiment, there has gradually arisen a powerful belief in a simple framework underlying the seeming complexity of the universe. For example, in the 19th century, the periodic table of elements born of the Mendeleevian revolution gave simple family relationships to the welter of new elements that chemists had discovered, and led to the recognition that matter is made of atoms. In the early 20th century, further simplification came from the identification of the electron, proton and neutron as the constituent parts of atoms.

In the 1950's and 1960's, the discovery of hundreds of additional "fundamental" brothers and sisters of these three atomic constituents appeared to complicate these simple patterns. The query "Who needs so many building blocks?" led to a new level of understanding of the fundamental structure of matter. To explain the myriad particles, physicists conjectured even more elementary particles called quarks – the quarks that have now, in turn, been observed in experiments. Many studies world-wide have affirmed our current picture of the fundamental world of matter: all the particles of matter are composed of varying arrangements of six quarks (and their antimatter partners) and a corresponding set of six leptons, grouped into three pairings, called generations, with similar properties.

At the time the quarks and leptons were proposed, it was by no means understood that they came in three generations. In the original conjecture, three quark types – named 'up', 'down', and 'strange' – sufficed to explain the observations. Four leptons were also known. In

1974, experiments at Stanford Linear Accelerator Center (SLAC) and at Brookhaven National Laboratory identified a fourth quark. The mass of the new 'charm' quark was noteworthy – five times that of its strange quark partner in the second generation. For the moment, the symmetry of two generations of quarks and leptons seemed to signal the end of the road of particle discovery. Then, in 1976, an additional pair of leptons was found at SLAC. The following year, experiments at Fermi National Accelerator Laboratory found one more quark, the 'bottom', with a mass about three times that of the charm quark.

From theory we expect that the number of quarks and leptons should be equal, and several experiments implied that there are but six leptons. This symmetry thus strongly suggested that a final quark should exist – the 'top' quark, the partner to the bottom. The hunt for the top quark began in a series of ever more sensitive experiments at laboratories around the world. Near the end of the DPF study process, in early 1995, a dramatic confirmation of this picture was made with the discovery at Fermilab that the top quark does indeed exist. Indeed, the working group reports of this study contain many plaintive references to the need for the knowledge of the top quark's existence, its mass and its properties.

But the completion of the "periodic table" of matter comes with a twist: the top quark finally weighs in with a mass of about 40 times that of the bottom quark! And so, along with the satisfaction of completing the search for the elementary bits that everything is made of, come intriguing new questions. Is there a deep reason for the extraordinary massiveness of the top? Does it hold some clue to the underlying reason for nature's provision of mass to matter's building blocks? Why are there three full generations of quarks and leptons, and not one, two or more? The world we actually see and touch is in fact made of quarks and leptons of only the first generation. Why are there more?

Our understanding of the fundamental forces has evolved along with our growing knowledge of the particles of matter. Early observations identified the gravitational, electric, and magnetic forces as distinct, but the multitude of everyday phenomena seemed to be governed by a long list of idiosyncratic forces, each operating in special circumstances. A large step toward simplification came in the mid-19th century with Maxwell's unification of the electric and magnetic forces into a single electromagnetic entity. Fifty years later came the recognition that the newly discovered atoms are also governed by the same force. By the late 1800's, all commonly observed phenomena could be understood with only the electromagnetic and gravitational forces.

At the turn of the century, new experiments began to explore the subatomic world. They revealed the necessity for a very short-range 'strong' force to bind together the elements of the nucleus, and a similarly short-range 'weak' force to account for radioactive decays. All four forces – electromagnetic, gravitational, strong, and weak – became more understandable when the development of quantum mechanics and the quantum theory of fields allowed physicists to postulate the existence of the force-carrying particles called bosons. In our current understanding, the electromagnetic and weak forces are further unified as the electroweak force, carried by combinations of the ordinary photon of light and three very heavy bosons called W^+, W^-, and Z^0. The W and Z bosons were discovered in 1983 at European Center for Nuclear Research (CERN), and demonstrated that at very large energies, the weak and electromagnetic forces merge into a single entity.

The understanding of the strong force that binds the nucleus has also undergone stages of simplification over the past 30 years. Early descriptions focused on dozens of force-carrying particles and a tangle of difficult-to-determine parameters. Again a single force-carrier operating at the level of quarks was postulated. This theory, called quantum chromodynamics or QCD was based on the properties of electromagnetic theory (QED). QCD postulates the existence of massless gluons, bosons which mediate the strong force; these were discovered in the 1970's experiments at the Deutsches Elektronen-Synchroton (DESY) in Germany.

Of all the forces, gravity remains the odd man out. We expect there to be a force-carrying graviton, but gravity is such a weak force that observation of the graviton has thus far eluded experiment.

However the satisfying simplicity and harmony of the picture of the forces again evokes questions. Having gone from many forces to just three, we ask whether further unification cannot be made. It seems plausible to join the electroweak and QCD forces. This would satisfy our intuitive guess that nature is at root simple and elegant. In our dreams, we envision still further unification incorporating quantum gravity as well. We even know roughly at which energy the various forces should reach equal strength and thus exhibit their underlying unity. But present experiments have also shown us that with only the three generations of quarks and leptons now known, it would seem unlikely that the forces we observe in our labs today could evolve to the unification scale. The price to be paid for tidiness and the dream of further unification of forces may thus be a further revolution in our picture of the fundamental constituents!

Particle physics has brought answers to many questions that once seemed all but unanswerable. Through the study of particles and forces, we have found crucial keys to the way the universe itself developed in the first moments following the burst of energy called the Big Bang. We see that the pattern of particles uncovered in our present-day laboratories influenced the initial conditions of the universe so as to produce the particular world that we experience today. Among the most mysterious links between cosmology and particle physics are two seemingly disparate observations. First, by observing the heavens, we see that the universe contains a preponderance of matter over antimatter. We thus conclude that the laws of nature must somehow discriminate between these opposite forms. Second, our seemingly unrelated study of particles tells us that the simplest pattern of quarks that allows for such matter-antimatter distinction requires at least three generations of quarks. In the past two years, striking new progress in understanding the distinction between matter and antimatter has come from experiments at the Cornell Electron Storage Ring.

Thus, in a broad, and perhaps unsatisfying anthropomorphic manner, we can suggest that in order for matter – that which now forms stars, people and proteins – to exist without having been annihilated in the very early universe, we need the three pairs of quarks and leptons that had on first sight seemed redundant. In this surprising turn, our own existence seems to depend upon the existence of the newly discovered top quark, whose life lasts but a trillionth of a trillionth of a second and whose earthly utility is hard to imagine!

We recognize that our present understanding of the constituents of matter and fundamental forces, though conceptually pleasing and consistent with all our observations so far, is likely to be only a stage on the way to deeper appreciation of the structure of our world. We know the taxonomy of particle and forces, but we know little as yet of what underlies our classification system. Nevertheless, the questions we can now think to ask were unthinkable a few years ago. "What is the origin of the mysterious attribute of matter called mass?" "What causes the peculiar pattern of quarks and leptons with their strong family relationships but differing individual characteristics?" "How did the particles we see in the laboratory influence the character of the universe at large?" "Can we find connections between such seemingly disparate phenomena as black holes and fundamental particles, as twists in space-time?"

The reports of this DPF study describe many opportunities for progress in the exploration of these fundamental questions, both with the facilities now in operation and through the building of new accelerators and experimental detectors based on proven technologies. The study is the product of many of the active particle physicists in the U.S, a group consisting of some 2000 individuals ranging from university faculty and laboratory scientists to postdoctoral and predoctoral students. It is an assessment of the promise and possibilities for scientific progress from the point of view of the participants – not necessarily those of the the existing laboratories or governmental funding agencies – and addresses the field from the perspective of global physics opportunities.

The global character of particle physics should be underlined. The U.S. community of about 2000 individuals is strongly interconnected and is embedded within the world community of about 6000 particle physicists, both in coordinated attack on inter-related questions and through a web of mutual collaborations in experimental and theoretical studies.

Much of the experimental research is conducted at particle accelerators at Fermilab, SLAC, Brookhaven and Cornell in the U.S. and at facilities at CERN and DESY as well as those in Japan, Russia, China, and Italy. These accelerators bring a variety of particles into collision – electrons and positrons, protons and antiprotons, and nuclei – with differing combinations, energies and intensities. Each has particular advantages for studies of elementary structure and forces. Together they give complementary views of phenomena.

There are some questions for which the accelerators do not provide the relevant capability. Fundamental questions such as the possible instability of the proton; observation of neutrinos produced by our sun, in the earth's atmosphere or by supernova collapses; or studies of rare nuclear decays require specialized facilities, often in deep underground or underwater experiments shielded from the bombardment of cosmic rays. Particle physics also has very strong interconnections with astrophysics and cosmology through experiments directed at the search for cosmological dark matter candidates, for gravitational waves, and studies of such astronomical phenomena as supernovae, black holes and distributions of galaxies in the universe.

The experimental particle physics activity is intertwined with the theoretical community, interacting daily at the universities and Laboratories, with each subcommunity stimulating advances within the other. The theorists play dual roles in interpreting and correlating the experimental findings and in developing new frameworks and conjectures which guide further experimental study. The health of the field depends crucially on the close and supportive roles of theory and experiment.

Finally, there is a crucial group of physicists focussing upon the development of more incisive instruments. The research into accelerators, with both experimental and theoretical components, is a crucial fulcrum upon which progress depends. Similarly, the development of experimental detectors, electronics, computing and data-handling techniques is a prerequisite to the field's ability to meet the challenges ahead. Again the interfaces between these endeavors and the other sub-communities are critical. In many cases, individual physicists contribute to more than one of the three main sub-communities.

Our report first discusses the current status and future prospects of particle physics and then issues related to infrastructure and the tools required for further progress with our research. The physics discussions are separated into those topics which build upon our present paradigm called the Standard Model, and those which look beyond it. Each is the product of the appropriate mix of experimentalists, theorists, and instrumentalists and accelerator physicists.

The topics relating to the physics of the Standard Model are divided into four chapters: the electroweak force properties of the W and Z bosons together with the interplay of these with the top quark and the Higgs boson; the study of the constituents of the proton and the elucidation of the strong QCD force; the properties of the heavy quarks (strange, charm and bottom) and the violation of matter-antimatter symmetry; and the exploration of the properties and interactions of neutrinos both in accelerator experiments and underground detectors.

The topics beyond the Standard Model include three chapters: new physics which could serve to unify all forces and explain some of the mysterious patterns observed in current data; the connections between particle physics and astrophysics; and the outlook for the theoretical investigations which extend and simplify presently disparate observations.

The discussion of the structural aspects of our discipline comprises four chapters: the prospects for the development of new accelerator techniques; the possibilities and means for advancing new detector technologies; the evolution of computing for acquiring and analyzing the data from particle experiments; and the structures for governing the progress of the field, nurturing the young physicists and educating the broader public.

This overview has focused on the evolution of particle physics to the present level of understanding, and on the nature of the questions that we are poised to explore. It is indeed true that the basic urge to pursue such studies originates in our innate desire to understand the character of our world. Analogies are often made with our urge to create and enjoy music, art or literature, as a fundamental aspect of our humanity. However, this is not to gainsay the pragmatic benefits of scientific research. Every basic scientific field of study has enriched society by the new understanding gained. The ability to produce the materials to clothe, feed and serve us results from the understanding of atoms, molecules and the chemical bond. The understanding of the enormously complex couplings of organic macromolecules has led to tremendous improvements in our ability to heal and prolong life. Our electric power and transportation industries are dependent on esoteric studies of electric, magnetic, and thermal phenomena of a century ago. Our computer-based information age rests upon the intellectual foundation of the quantum revolution early in this century. All scientists are proud that our studies can simultaneously serve to illuminate the fundamental character of the world that we inhabit and contain a spark that, somewhere down the road, enriches our individual and collective lives.

From the present vantage point, we can appreciate both the panorama of past achievements and the next range of peaks to climb. It is with pride that we review in this study the recent path that we have scaled in understanding the constituents of matter. We find it an achievement of impressive proportions that we have glimpsed the regularities and order inherent in the physical world.

In addition to describing our field we have attempted to present and explain, as well as we can foresee, what opportunities exist for the next ten years, and where the best chances for real progress lie. In the year that we have made these studies, we have already seen discoveries that open new vistas. We have begun to plan for the next stage at new accelerators in this country and abroad. We find reason to hope for increasing internationalization of an already global community, and look for the experience in particle physics to encourage other world-wide collaborative efforts. Most of all, we are delighted that the range of absorbing and fundamental questions, far from ending with the discovery of the "last" quark, can be expected to lead to new understanding that enriches our culture and benefits our society.