Some emerging trends in physics*

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As physics advances, once in a while there are major events or steps of unification — the number of distinct fundamental forces keeps decreasing. These momentous events are few and far between, but they are really dramatic.

Let me begin with some remarks about our understanding of the nature of matter, and of fundamental forces in nature. As we all recall, Mendeleev created the Periodic Table of Elements around 1870. There were close to a hundred distinct chemical elements, or forms of matter, at that stage. But the physical understanding of this arrangement, and an enormous simplification, came with the Rutherford-Bohr model of the atom as a nucleus made up of protons and neutrons at the core, with electrons orbiting on the outside. This development took close to fifty years. And out of this development was born quantum mechanics — that uniquely 20th century conception — as a new language for describing physical phenomena. It really grew out of atomic physics and low energy electromagnetic processes, but as a language it continues to be adequate — so far as we can tell — for many other forces in nature and areas of physics. Thus both the strong nuclear force and the weak nuclear force — one of the forms of radioactivity — are describable by quantum mechanics in conjunction with special relativity. It also works over an enormous range of energies — all of particle and nuclear physics, condensed matter physics and physical chemistry come under its sway. I will come back later to the story of quantum mechanics in recent times.

The one union that has not yet been arranged is that of quantum mechanics and general relativity, or the classical theory of gravity. Here a remark of Penrose is pertinent. He points out that both quantum mechanics and general relativity theory are beautiful theories, each in its own way; and this fact must be respected, and neither forced to yield to the other in combining them. This is well worth keeping in mind.

Soon after quantum mechanics, in the late twenties and very early thirties, the nature of matter appeared quite simple — all matter seemed made up of three basic building blocks, namely protons, neutrons and electrons. And then there were photons, the quanta of electromagnetic radiation. But soon complications arose. First came the idea of the neutrino, which was experimentally detected much later in 1956. Then followed the positron and the general concept of antimatter. These developments threw the question of the ultimate nature of matter really wide open. During the thirties and forties many new particles were seen in the cosmic radiation, such as μ mesons and π mesons, K and $\bar{K}$ mesons, hyperons and so on. From the fifties onwards, the accelerators also joined the effort and produced many strong interaction resonances like Δ, ρ, ω, K^*, Λ, Σ, Ξ, N^* and so on. Soon one ended up with a collection of almost 200 so-called elementary particles — about twice the size of Mendeleev's Table. This was the situation by about 1960.

Naturally one point of view that arose then and was quite popular for a while was that the concept of elementarity had come to the end of its usefulness. The idea was that all the 200 or so particles were made up of one another; none were more basic than the others and all were equally fundamental. This was the philosophy of Nuclear Democracy and it was to be implemented via S-matrix theory. But this development was short-lived, and by 1961–62 the idea of quarks arose.

To begin with there were just three kinds of quarks — up, down and strange — along with their antiquarks. And all the 200-odd particles were various combinations of quarks and antiquarks, two or three at a time. This was similar to building up the entire Periodic Table with just protons, neutrons and electrons, and led to the subject of quark spectroscopy. So there was again a great simplification, and a relief. This line of development succeeded, and today we believe all matter consists of quarks and leptons — members of the electron and μ meson families and their cousins. But to this by now many new particles have been added — three more kinds of quarks, coloured quarks, gluons, W and Z bosons, Higgs particles, and of course the photon. Again the number has risen to near 50, and there may be more. A special feature of quarks and antiquarks is that they are never supposed to be seen individually or isolated one at a time, but always only indirectly and in combinations of two or three.

An important consequence of quantum mechanics and special relativity is that the concepts of constituents

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and substructure are energy dependent. To see what happens at very short distances one needs probes with very high energies. Thus we say — down to 10^{-16} cm or energies of about 10^5 MeV the electron and the μ meson are structureless. As we go to higher energies, we may find new structures and new surprises. This is quite similar to the statement that for atomic physics and chemistry the internal structure of the nucleus is irrelevant; and that for low energy nuclear physics the quark structure of protons and neutrons may be ignored.

Now let us turn to the understanding of the different fundamental forces in nature. As physics advances, once in a while, there are major events or steps of *unification* — the number of distinct fundamental forces keeps decreasing. Admittedly of course these momentous events are few and far between, but they are really dramatic. First in 1665 or thereabouts, Newton unified terrestrial and celestial gravity into one Universal Law of Gravitation. Then two centuries later, in 1865, Maxwell unified electricity, magnetism and optics into one comprehensive scheme. From the 1930's till the mid sixties we all learnt that there were four basic forces in nature — gravity, the weakest of all; then beta radioactivity or the weak interactions; then electromagnetism; and, strongest of all, the nuclear force among protons and neutrons. Then around 1967–68, Salam, Weinberg and Glashow showed that electromagnetism and the weak interactions are two faces of a unified electroweak force. At this step the number of basic forces or interactions in nature came down to three. The problem though is that this unity can be seen only in processes at energies of about one hundred GeV or higher, that is, at and above one hundred proton masses!

This step of unification has been enormously successful. Soon after came a theory of the strong interactions among quarks, quantum chromodynamics or QCD, and the two together make up the so-called Standard Model of particle physics. Everything except gravity seems to be satisfactorily handled by it, but yet it cannot be the last word since there are some twenty independent parameters in it to be taken from experiment. So there are constant efforts to test and see what may lie beyond the Standard Model.

One such attempt is to unify the QCD theory with the electroweak one into a Grand Unified Theory. If this happens, the theoretical indication is that this unity will be seen only at energies of 10^{15} GeV and higher. To get a feeling for this, recall that the proton mass is about 1 GeV. Present accelerators and those expected in the next decade or so are in the range of a few thousand GeV. But grand unification is only expected at 10^{15} GeV — so no hope of reaching such scales in laboratories, and in nature too such events must be extremely rare. How do we test such ideas at all?

This brings us to cosmology. We mentioned earlier that the problem of unifying quantum theory and gravity is still open. Under what conditions might such a combination be relevant? Quantum theory involves Planck's constant $\hbar$; while general relativity, being a relativistic theory of gravitation, involves both the Newtonian constant G and the speed of light c. Combining these we come up with certain characteristic 'Planck units':

Planck time $=(\hbar\, G/c^5)^{1/2} \simeq 5\times 10^{-44}$ sec;

Planck mass $=(\hbar\, c/G)^{1/2} \simeq 1.2\times 10^{19}$ GeV/c^2;

Planck temperature $= 1/k(\hbar\, c^5/G)^{1/2} \simeq 1.4\times 10^{32}$ K

In processes characterized by these scales, quantum gravity would be relevant. When did such conditions ever exist? Very early in the history of the universe, immediately after the big bang! In fact, during the first 10^{-43} sec following the big bang. That is the place to look for clues about quantum gravity and speculations about particle physics at extremely high energies. And that is how the immensely large, the incredibly small and the unbelievably old ultimately meet. One is reminded of William Blake's lines:

> To see a world in a grain of sand,
> And a heaven in a wild flower,
> Hold infinity in the palm of your hand,
> And eternity in an hour.

As for the history of the universe, and its growth after a fiery birth, it is truly amazing that with a fair degree of confidence one can give a detailed picture of what happened. For the opening 10^{-43} sec, with temperatures around or above 10^{32} K, we have the era of quantum gravity. Then as the temperature dropped to about 10^{13} K over 10^{-6} sec, events are dominated first by grand unification and then by quark physics. We have to wait as long as one second for the temperature to come down to 10^9 K and for nuclei to form. Neutral atoms appear after 10^{12} sec when the temperature was around 10^4 K. At that point, matter and radiation part company and go their separate ways. It is the latter, now cooled to just below 3 K, that we see today as a nearly isotropic cosmic micro-wave background radiation.

It is quite incredible that such theories, involving conditions so far from experience and so long ago, can be made believable today. Of course there are problems — large scale structures in the universe, horizons, flatness, dark matter and so on. Many inventive solutions also abound — inflation, baby universes, bubble universes, worm holes and the like. We seem to be really in an age of free inventions of the human mind.

At this point let me return to quantum mechanics and its problems. It was discovered, or invented, during

1925–26. Ever since it has been spectacularly successful in every application, and there is no sign of any failure yet. But right from the start there have been problems of interpretation and philosophy. Prominent among the 'conscientious objectors' were Einstein, de Broglie and Schrodinger. And the principal 'defending champions' were Bohr, Born, Heisenberg and Dirac. In this context it is interesting to recall what happened in the case of general relativity theory. For a long time after its completion in 1915, many more senior people would turn to this subject, as a second career or after retirement; and at least in India it was generally taught only in mathematics departments. Only since the late fifties and sixties has general relativity become a really active subject of study and research even by young people, helped along of course by spectacular experimental advances in astrophysics and cosmology. In the case of quantum mechanics, for close to fifty years after its discovery, most users of the subject simply ignored the philosophical problems—questions of reality and existence independent of observation, locality, causality and so on. As the song says, it was mostly 'ivy covered professors behind ivy-covered walls', that is, philosophy professors, who worried about such matters. Today that has changed dramatically since the work of John Bell in 1965. Having been satisfied with the practical successes of quantum mechanics in every domain so far tested, now there is a great deal of effort to probe the theoretical foundations and test the limits of quantum mechanics, especially as we approach macroscopic phenomena. Again new technology not available in the days of Einstein and Bohr has made a great practical difference. Today even young students are joining in this effort, and we are surely in for much excitement and new insights.

When one sees all these developments—the vastness and scale of processes in the cosmic universe, and equally the vastness of the microscopic world—one surely feels humbled. On the other hand our life scientist friends are waiting to tell us that we are just bits of biological hardware—maybe no more than elaborate tricks thought up by DNA to reproduce itself. So we seem to be hit from both sides. Still the challenge to understand and comprehend nature, and the pleasure at each success, are undeniable. On the nature of understanding, one is reminded of Heisenberg's characterization of it as almost simply coming to terms with the unfamiliar, and adjusting to it. This has really happened again and again. For Newton, after the discovery of the law of universal gravitation in mathematical form, it was a struggle to accept the idea of action at a distance. This took over a century to sink in, and by the time everyone had more or less accepted it, along came Faraday and Maxwell with the idea of propagating fields of force. Again we know how hard it was, after Maxwell had found the mathematical equations of electromagnetism, to adjust to this new concept, and to avoid the idea of the aether. Then with quantum mechanics came the wave function, whose interpretation and behaviour is still a matter of debate. This continues with the many fantastic and almost bizarre concepts current in physics today. So there is more than a little truth in Heisenberg's statement:

> Almost every progress in science has been paid for by a sacrifice, for almost every new intellectual achievement previous positions and conceptions had to be given up. Thus, in a way, the increase of knowledge and insight diminishes continually the scientist's claim on 'understanding' nature.

Be that as it may, let us hope that in the years to come many a first rate young Indian scientist will announce a first rate discovery to the world.

CEL wins award

Central Electronics Limited, Sahibabad (UP), the nation's largest producer of solar photovoltaic cells, modules and systems, has been awarded the *National Award for R&D Efforts in Industry* in electrical and electronics industries sector from the Department of Scientific & Industrial Research for the year 1991–92.