The ultimate constituents of matter*

K. V. L. Sarma

What is the world made of? What are its ultimate constituents? How do they interact with one another? According to the current view, the fundamental building blocks of matter are quarks and leptons, which interact by exchanging gauge bosons.

In ancient times, answers to such questions were sought in the qualitative features of matter: earth, water, fire, air and ether as the fundamental elements. The atomic hypothesis of matter was proposed 24 centuries ago by Democritus. The word 'atom' in Greek means something indivisible and eternal; according to some, the words 'atom' and 'atma' have the same root. In India the 'kana' hypothesis was advocated by Kaanaada Maharishi around the fifth century A.D.

Early developments

Particle physics was born in 1897 with the discovery of the electron by J. J. Thomson. This discovery demolished the earlier view by showing that atoms are divisible. The electron accelerator of Thomson was the cathode ray tube. It is amusing that this accelerator is being admired by the millions today as they keep staring at the TV screens.

Next came the experiments of Rutherford and his group, wherein α-particles from the radium decay were fired at gold atoms. The results were unexpected. At that time the atom was pictured as a diffuse distribution of positive charge with a few electrons stuck in it here and there, like the seeds in a water-melon.[1] Rutherford thought he was firing small steel balls into such stuff, but the results surprised him as much as some of the balls were to turn back and hit him on the face. He interpreted the results in terms of a model in which all the positive charge of the atom is concentrated at the centre and electrons are running around it – a dynamic model of the atom. It was the strong Coulomb repulsion of the gold nucleus that caused a few of the α-particles to scatter back.

I recalled this well-known 1911 proposal of the point nucleus because it got repeated in a slightly different way in 1968. The genius of Feynman was needed to interpret the observed large rate of inelastic scattering of electrons; the model was that a proton is made of point constituents called 'partons'. The charged partons were later identified with the quarks.

Till 1932 the fundamental particles were electrons and protons. Developments in particle acceleration techniques enabled the study of nuclear reactions, from which it was deduced that atomic nuclei consist of protons and neutrons. The strong nuclear force working at the nuclear distances was invented to keep the nuclear constituents bound together. The story gets repeated – to keep the partons bound inside the proton, the 'colour' force of QCD (quantum chromodynamics, which is the modern theory of the strong force) is invented.

Isospin

In spite of their unequal charges, proton and neutron have very nearly equal masses: the neutron–proton mass difference is ~ 0.1% of the average mass. In 1932 itself (the year Chadwick discovered the neutron), Heisenberg came up with the profound idea of isospin symmetry. This was the first approximate symmetry that entered particle physics.

Heisenberg reasoned that just as the spin-up and spin-down states of the electron are two possible states of the same particle, proton and neutron could be regarded as the 'up' and 'down' states of a nucleon possessing isospin (short form of isotopic spin). He suggested the symmetry group SU(2), the special unitary group in two dimensions. This symmetry, however, is inexact; it is broken by the electromagnetic interaction, which can distinguish a proton from a neutron. Nevertheless, the isospin symmetry has turned out to be extremely useful. It inspired the proposal of SU(3) symmetry, which led to the hypothesis of the u, d, s quarks.

SU(3) Symmetry and quark hypothesis

Strangeness is an attribute like the electric charge. It was invented to explain the long lifetimes (10^{-8}–10^{-10} s) of certain particles which were produced in nuclear collisions (having a characteristic time scale of 10^{-23} s). The hypothesis is that strangeness is conserved as long as either the strong nuclear force or the electromagnetic

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*Based on a talk given at the Inter University Consortium, DAE Facility, Indore, on the Annual Day, 14 December 1994 force operates, but strangeness is not conserved when the weak force operates. Since the weak force is slow to work, strange particles live long. Around the early 1960s experiments revealed the existence of many excited states called 'resonances'. They included resonances with one or two units of strangeness but all had short lifetimes $\sim 10^{-23}$ s; it was observed that all their decays conserved strangeness, as expected.

In order to include the strange particles in the scheme of isospin symmetry, Gell-Mann and, independently, Ne'eman, suggested grouping particles according to the unitary symmetry SU(3). The multiplets suggested were the octets {8} and decuplets {10} of the SU(3) group. As an approximate symmetry, the SU(3) unitary symmetry is cruder than the isospin symmetry SU(2) because in some cases the mass differences could be as large as ~30% of the average mass in the multiplet. However, adopting a special procedure to break the SU(3) symmetry, it was possible to explain the relative masses, production rates and decay rates of the strange and nonstrange particles in the multiplets. Finally, in 1964, the experimental finding of the predicted Ω^-, a baryon carrying three units of strangeness, came as a spectacular triumph for the SU(3) symmetry scheme.

It was, however, curious that the particles were always occurring as either octets or decuplets or singlets of the SU(3) group. To explain this feature, in 1964 Gell-Mann and, independently, Zweig speculated that three fundamental particles called *quarks* could be the constituents of the hadrons (a common name for baryons and mesons). They are the u (up), d (down) and s (strange) quarks; they are assigned fractional electric charges: u with $\frac{2}{3}e$, d and s each with $-\frac{1}{3}e$. A baryon is a bound system of three quarks, and meson is a bound system of quark–antiquark pair; thus, the main constituents of p are (uud), those of n are (udd), those of K^- are ($\bar{u}$s), etc.

More flavours

Today we have more quantum numbers besides strangeness, or, to use the modern jargon, we have more 'flavours'. A quark is invented for each flavour. How are the new flavours discovered? We expect a massive particle to be short-lived, because it has many more channels to decay into than a lighter particle. But certain resonant states (J/ψ, Υ, ...) which can be formed in electron–positron annihilation were found to have high masses and unusually long lifetimes (about 10^3 times longer than expected). A state of this type could be interpreted as bound systems of $Q\bar{Q}$, where Q denotes a heavy quark carrying a new flavour, like the strangeness. The related spectroscopy is similar to that of the positronium (e^+e^-) states. The postulated heavy quark Q also implies the existence of other bound states: Q with a light antiquark ($Q\bar{q}$) as a new meson, and Q with a pair of light quarks (Qqq) as a new baryon, and their excited states.

So far two heavy flavours have been discovered, *charm* in 1974 and *bottom* in 1977. At present the search is continuing for the *top* flavour. In the recent years great interest has come to be associated with the bottom mesons B, which have picosecond lifetimes, as some of their decays are expected to exhibit sizeable violations of CP symmetry. For studying these issues, intense sources of bottom mesons known as 'B-factories' are currently being built (at Stanford and at KEK, Japan).

Leptons

Besides hadrons, matter consists also of leptons. The word lepton connotes something light or feeble. Leptons cannot feel the strong nuclear force. There are two varieties of leptons, charged (like the e^-) and uncharged (like the neutrino ν_e).

Neutrinos are tiny neutral particles carrying very little or no mass. They were originally invented by Pauli to ensure the conservation of energy, etc., in beta decay processes. They cannot 'feel' the strong interaction or electromagnetic interactions; their only interaction with matter being weak, it is difficult to detect them. The electron-antineutrino $\bar{\nu}_e$ emitted in the nuclear beta decay was first detected around 1954 by Cowan and Reines. An antineutrino is an antilepton.

Muon is a charged lepton which entered the scene as an uninvited guest. Even today we are baffled by its presence. It is heavy with a mass of $207m_e \approx 106$ MeV, and is unstable with a mean life of 2.2 µs. In all its interactions with matter the μ^- behaves just like the e^-. Thus, we may regard the muon as 'the electron' of a different *generation* whose members for some unknown reason happen to be heavy. We say that e belongs to the *first generation* and µ belongs to the *second generation*.

The decay of a muon involves its own brand of neutrino denoted by ν_μ. How is this neutrino different from the ν_e? Consider a beam of high-energy neutrinos impinging on a nuclear target. In the nuclear collision a ν_e can change into an e^- by causing a corresponding increase of charge among the nuclear fragments, but it cannot change into a μ^-. On the other hand, a ν_μ colliding with nuclei can turn into a μ^- but not into an e^-, a fact which was experimentally demonstrated in 1962 and for which L. Lederman, M. Schwartz and J. Steinberger shared the 1988 Nobel Prize. All it means is that a neutrino of a given generation can produce a charged lepton only of that generation. Today at the particle accelerators we can work with either a neutrino beam or an antineutrino beam of the 'muon' kind.

In 1975 another charged lepton, called the *tau lepton*, was discovered through the reaction $e^+ + e^- \rightarrow \tau^+ + \tau^-$.

The tau lepton was classified as belonging to the *third* generation. This is the heaviest and also the shortest-lived lepton today; its mass is 1.98 GeV and its mean life is 0.3 ps. Experiments indicate the absence of a lepton heavier than τ and lighter than 45 GeV. It is expected that the tau lepton has its own brand of neutrino ν_τ but it is still to be experimentally demonstrated that a ν_τ does produce a τ^-.

In summary, the following three generations of leptons have been identified so far:

$$(e^-, \nu_e), (\mu^-, \nu_\mu), (\tau^-, \nu_\tau).$$

Can there be more generations? The high precision data on the decay properties of the neutral weak boson Z limit the neutrino types to three. From this it is concluded that there are no more neutrinos of the standard kind, and hence no more lepton generations to be discovered.

Quarks are for real

The 1990 Nobel Prize in physics went to J. Friedman, H. Kendall and R. Taylor for their experimental work on deep inelastic scattering of electrons on nuclear targets. Their first work was done in 1968 using 20 GeV electrons from the linear accelerator at Stanford. Their group measured the energy and momentum transferred to the nucleon in the reaction $e^- + p \rightarrow e^- +$ hadrons (Figure 1).

Let us define the following four terms:

Electron energy transfer $\nu = E - E'$, where E and E' are the initial and final electron energies.

Momentum transfer variable $Q^2 = 4EE' \sin^2 \frac{\theta}{2}$, where θ is the electron scattering angle in the laboratory. A large value of Q^2 means a large resolving power of the photon (γ) which is probing the proton structure.

Deep inelastic scattering corresponds to taking 'large' values of Q^2 and ν (in units of proton mass $M \approx 1$ GeV).

Bjorken scaling variable $x = Q^2/2M\nu$.

Earlier experiments showed that the cross-section for elastic scattering $e^- + p \rightarrow e^- + p$ (which corresponds to $x = 1$) decreases dramatically with increasing Q^2; the data indicated a proton charge distribution which is continuous and decreases exponentially with radial distance. In inelastic scattering at high energies, $E \gg 1$ GeV, although many hadrons are created, one may choose to observe only the electron. In such 'inclusive' experiments, consider the 'deep inelastic scattering' regime, which simply means considering large Q^2 and large ν values. It was noticed that the corresponding collision rates remained sizeable even at high values of Q^2, i.e. even with increased resolution the scattering rate did not come down.

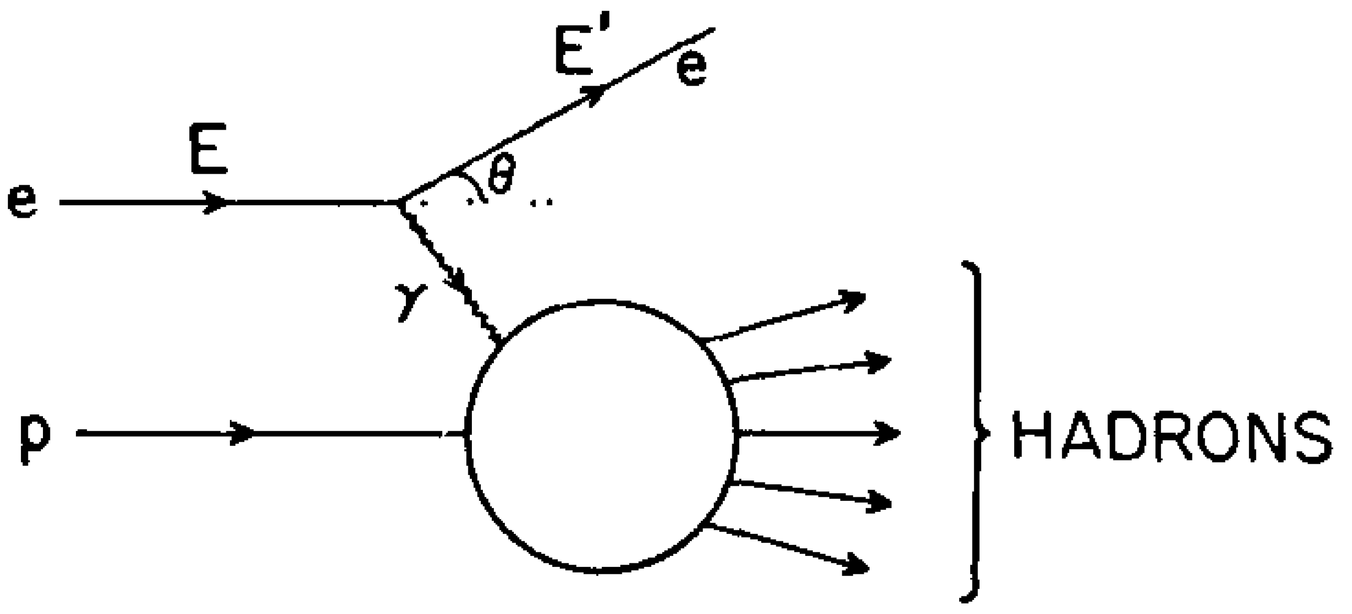

Figure 1. Deep inelastic scattering of electron on a proton described by the exchange of a virtual photon

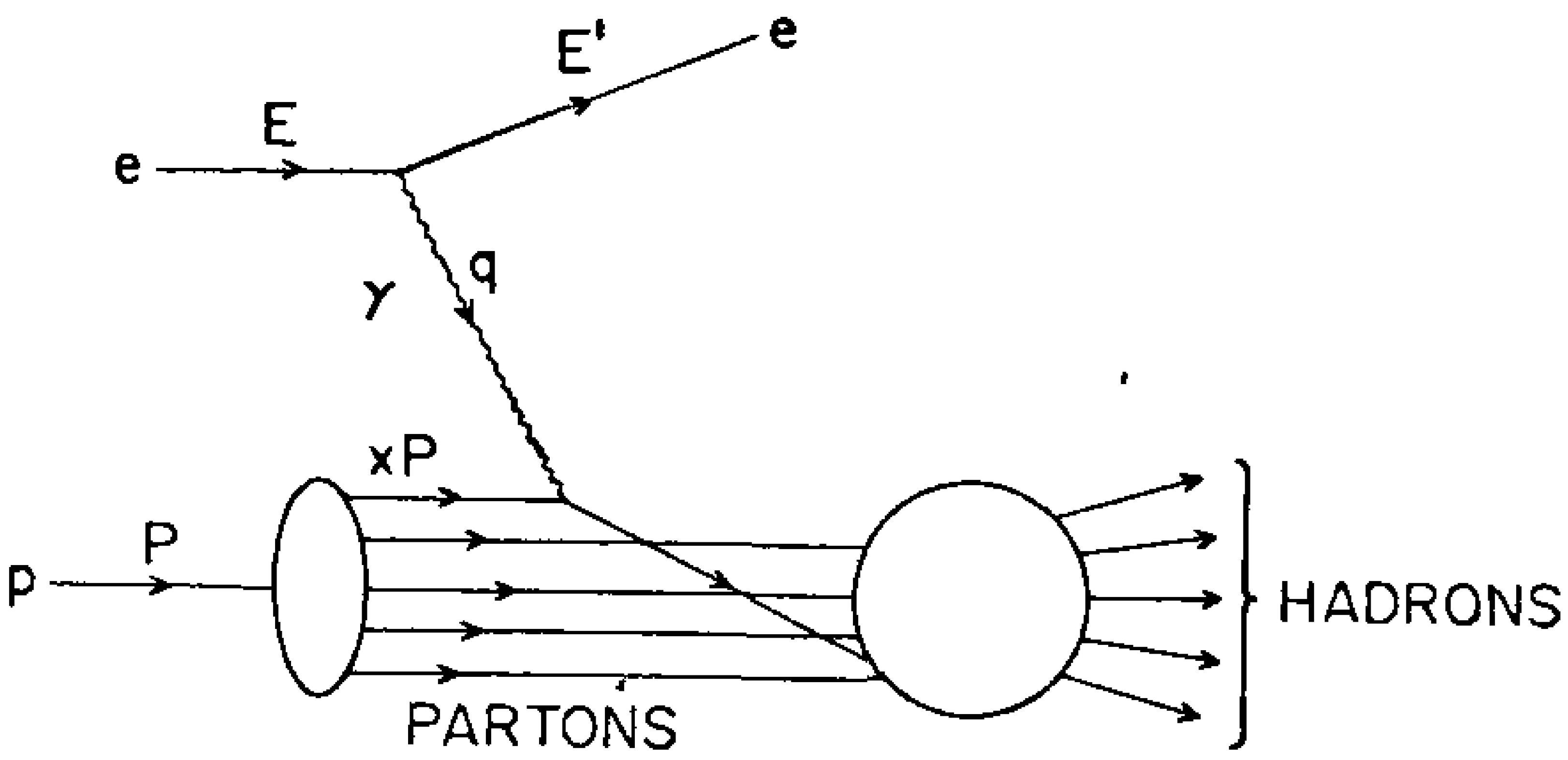

Figure 2. Parton model description of the deep inelastic electron-proton scattering

To be more precise, let us consider the structure functions F_1 and F_2 of the inelastic scattering cross-section,

$$\frac{d^2\sigma}{dQ^2 d\nu} = (\ldots) F_1 (x, Q^2) + (\ldots) F_2 (x, Q^2),$$

where the dots denote some known functions of the experimental observables. Now, although the functions F_i are unknown, experiments revealed that their Q^2 dependence occurred only as scaled by $2M\nu$ through the dimensionless variable $x = Q^2/2M\nu$ and after that very little Q^2 dependence remained,

$$F_i(x, Q^2) \approx F_i(x).$$

This is known as the 'scaling of the structure functions'. But what does it signify?

Partons

The physical meaning of the scaling variable x and the structure functions $F_i(x)$ were elucidated by Feynman. He postulated the existence of partons which are *point constituents* in the proton. The deep inelastic scattering process is interpreted as the elastic scattering of electron on a quasi-free parton, which is a 'part' of the proton (Figure 2). The scattering parton by virtue of its point charge leads to large scattering even at large angles (recall Rutherford's point nucleus).

The variable x is interpreted as the fractional share of the parton in the nucleon's momentum. The structure function $F_2(x)$ is related to the probabilities for finding specific charged partons, each carrying a fractional momentum x of the target nucleon.

Data on the ratio of structure functions (F_1/F_2) showed that the parton spin is consistent with $\frac{1}{2}$. Data from the deep inelastic scattering experiments using ν_μ beams and $\bar{\nu}_\mu$ beams showed that the electric charges of the partons are consistent with $\frac{2}{3}e$ and $-\frac{1}{3}e$. In this way the partons of Feynman have come be identified with the quarks postulated earlier.

The standard model

This model is a culmination of several decades of experimentation and development of many theoretical insights. It is a field theory in which the notion of gauge invariance plays the central role. The standard model (SM) has two strands – one is the unified theory of the electroweak forces invented by S. Glashow, A. Salam and S. Weinberg, who won the 1979 Nobel Prize, and the other is the QCD theory of the strong colour forces.

As for the fundamental particles, there are two kinds (Figure 3): the first kind are spin $-\frac{1}{2}$ fermions and they make up the matter in the universe. They are the six quarks and six leptons, arranged neatly in three generations. Every matter particle has its antiparticle. The second kind of fundamental particles are spin-1 bosons, and they are the 'force carriers'. There are four carriers of the electroweak force: the massless photon γ, the two charged weak bosons W^+ and W^- and the neutral weak boson Z. The weak bosons are massive and short-lived; they were discovered in 1983, although effects of the Z were noticed in 1973 in the celebrated discovery of weak neutral currents. The QCD force is transmitted by eight gluons; they are massless and interact with the 'colour' charge.

Quarks feel both the electroweak force and the QCD force. Leptons being colourless cannot experience the QCD force.

SM also needs a mythical particle called the 'Higgs'. It bears the name of the physicist Peter Higgs who invented (in 1964) a mechanism by which, in a field theory obeying gauge invariance, we can have gauge bosons that are massive. This subtle mechanism was a key ingredient in unifying the long-ranged electromagnetic interaction (mediated by the massless photon) with the short-ranged weak interactions (mediated by the massive bosons W and Z).

How does the SM fare? Today all the experimental results are in good agreement with the predictions of the SM. There are, however, some gaps in its verification.

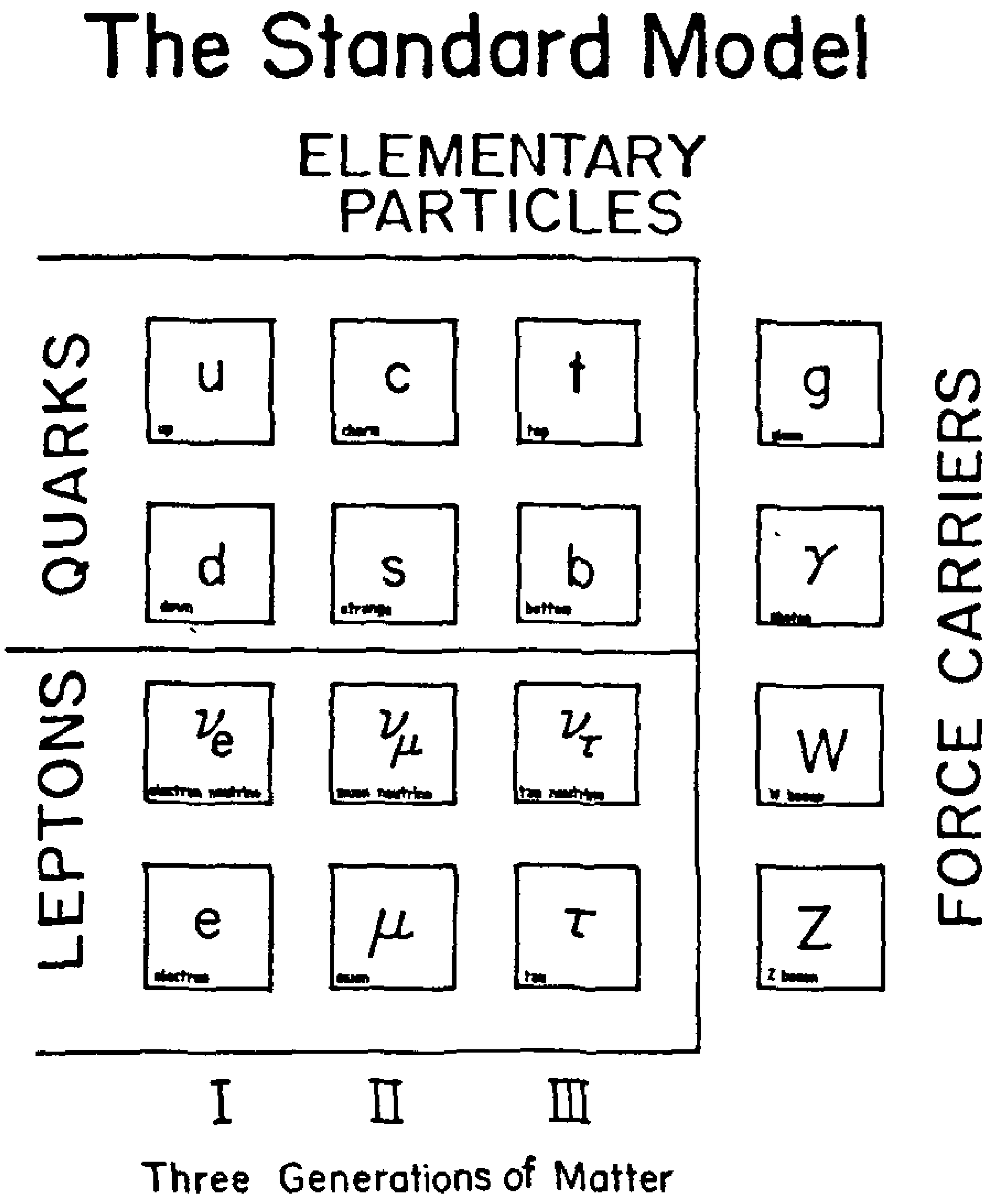

Figure 3. Elementary particles of the standard model

Two of the matter particles the top quark t and the tau-neutrino ν_τ are still to be identified. We have no clue about the existence of the Higgs boson.

SM certainly cannot be the final theory. It has many free parameters (~18) which are presently taken from experiments. One of the shortcomings of SM is that it cannot explain why leptons and quarks repeat in 'generations'.

Style of research in high-energy physics

Experimental research in high-energy physics is no longer an effort of a few individuals. It has now reached the level of a global enterprise out of sheer necessity. The size and complexity of today's particle detectors are truly fantastic. The required material and manpower resources have become so immense that no single institution or country can support them.

For instance, the DZero group working at the Fermilab Tevatron has a detector weighing nearly 5000 tons and a few storeys high. It took nearly 10 years to build it at a cost of about 100 M$. When the group publishes a paper the authors total about 420, hailing from 40 institutions, including three Indian teams from TIFR, Delhi University and Panjab University. This is a typical Multinational Collaboration (MNC). At present several such

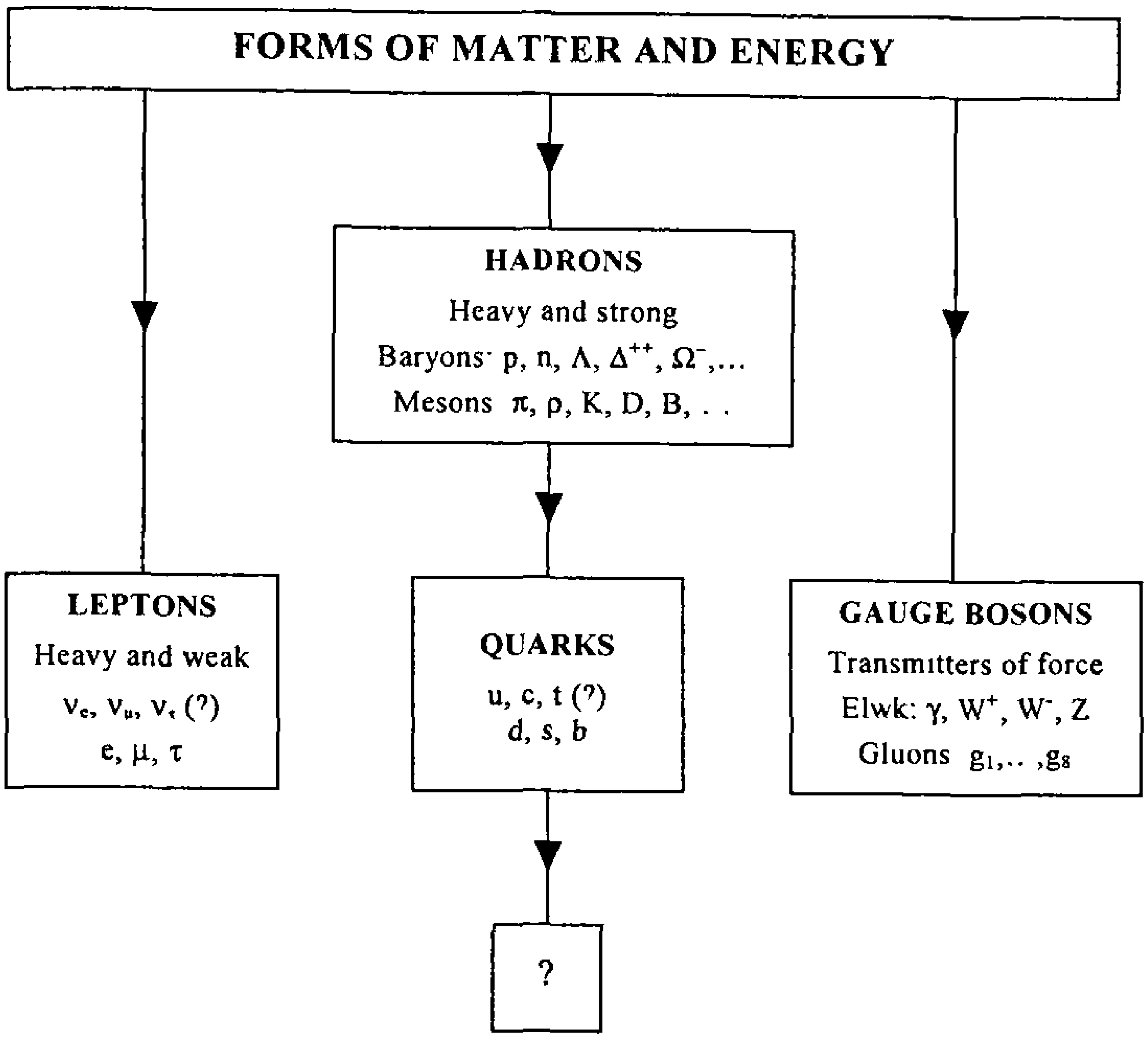

Figure 4. Forms of matter and energy

MNCs are functioning at the major accelerator facilities such as the LEP collider in Geneva and HERA in Hamburg.

Future MNCs are going to be even bigger! By 2004, CERN plans to build a pp collider LHC (large hadron collider) giving 9 TeV energy. The CMS (compact muon solenoid) group, which desires to do experiments at LHC, may have about 1200 people coming from 125 institutions (about 30 people from five groups in India). The estimated budget of CMS is 300 M$ (≈ Rs 1000 crore). Its rival group, called ATLAS, may be similar in most respects.

Some questions of sociology of the MNC may be interesting: How does a MNC take shape? Who will decide on the work to be allocated to a subgroup, and how is it supervised? Is the work subcontracted out? How are the various kinds of contributions to be costed and accounted? (This was the main point of the recent dispute between France and Germany in the CERN funding.) What kind of scientific freedom will people have? How is the interest sustained for long periods (7–10 years) during the detector construction? How can Ph D students work so long without getting any physics results? Unusual talents are needed in managing such huge scientific teams. When a MNC publishes a paper it should go to the credit of the entire physics community, for is it not a positive affirmation that people can work together?

Conclusion

In the recent years there have been two fundamental advances in our understanding of the physical world. First is the recognition that quarks and leptons are the fundamental constituents of matter, second is that they interact by exchanging the gauge bosons (Figure 4).

We have a successful model, called the standard model, which requires six quarks and six leptons. Of these, the top quark and the tau-neutrino are yet to be identified experimentally. We do not understand why quarks and leptons repeat in generations, and why there are three generations. Perhaps there is an underlying 'shell' structure as in the repeating chemical properties in the periodic table.

I end by quoting J. R. Oppenheimer: 'By calling a particle fundamental we mean only that it has not proven possible, profitable, or useful to regard it as made up of something else.' We wait for the peeling of the next layer of the 'onion'.

Some explanatory notes

Tevatron. At present the most energetic particle accelerator on earth is the Tevatron, located at Fermilab near Chicago. Here bunches of p and $\bar{p}$ get accelerated in opposite directions and are made to collide with each other. Every second about 250,000 collisions take place.

The total collision energy involved is 1.8 TeV (TeV = tera eV = trillion eV = 10^{12} eV ≈ 1066 $(Mc^2)_{proton}$). This energy is available for the production of new particles. Some particles should be produced along with their antiparticles; the threshold energy for producing a $t\bar{t}$ pair could be about 0.4 TeV.

Is the top quark discovered? In April 1994 the CDF (collider detector at Fermilab) group announced evidence for the top quark t on the basis of a handful of events. The mass given was 0.174 ± 0.017 TeV, which is 35 times larger than the mass of the bottom quark b.

Due to its large mass, the top quark is expected to be very short-lived (~10^{-25} s; the bottom quark lives comparatively longer, ~10^{-12} s), and top decays should involve too many particles. The decay products W might also be short-lived and lead to many decay products. Among them the neutrinos always escape detection. Further, the top does not decay the same way every time. More worrisome is the so-called 'background', which is to do with statistics. Top signal is expected to be rather weak, with the signal-to-noise of about one in a billion. The nagging doubt is whether the interesting event is just a statistical fluctuation of the usual kind of events. The only way to be sure is to accumulate more events. This means that the accelerator has to be run more efficiently and for longer time.

The rival group DZero working at the Tevatron had reported no evidence for the top as of now. To be sure, therefore, we have to wait for more definitive evidence.

Colour. This is a degree of freedom which is invented to respect the Pauli principle among quarks. Consider, for example, the baryon Ω^- in the spin state $J = \frac{3}{2}$, $J_z = \frac{3}{2}$. It ought to be the ground state of three strange quarks (sss) all in the same spin state, but such a configuration is disallowed by the Pauli principle. As a way out of such problems a three-valued label called 'colour' was invented, and people even use the words red, green and blue to label this degree of freedom. As the white light is composed of colours, all the observed hadrons are colourless while their quark constituents are coloured. A proton is colourless but each of its three main constituent quarks has a different colour.

QCD. Quarks can interact by exchanging the colour label. The corresponding force carriers are called 'gluons', which are similar to photons. The theory of interactions of quarks and gluons is quantum chromo (or colour) dynamics (QCD). It is based on the colour symmetry group $SU(3)_C$ (which is unrelated to the earlier-mentioned flavour group of Gell-Mann and Ne'eman). QCD is a field theory patterned along the lines of the well-known quantum electrodynamics (QED). The unusual feature is that gluons carry colour and hence can interact with other gluons (besides the quarks). QCD has eight kinds of gluons.

Quark confinement. An isolated quark has not been observed so far. If proton consists of quarks and gluons, why cannot we knock them out in high-energy collisions? There might be forces which become strongly attractive with increasing distance and prevent the quarks from getting out of the hadron. It is believed that this type of confining force is a special feature of QCD.

Asymptotic freedom and infrared slavery. Parton model assumes the quarks inside a hadron to be nearly free. How can we justify this when the quarks in a hadron are so tightly bound as to be never able to leave it? Around 1973, it was demonstrated that the QCD force has the property that it becomes feeble as the distance decreases, contrary to the Coulomb force. Since short distances can be probed only at high energies, this aspect of the quark force is named the 'asymptotic freedom'. On the other hand, hadron is like a prison and partons are like slaves who roam around freely in the prison; but when one tries to escape, the others pull it back. This long-distance feature of the QCD force is whimsically termed 'infrared slavery'.

Jets. What happens when a quark is hit hard? The quark immediately radiates a gluon, which can break into two gluons or three gluons or a quark–antiquark pair; these in turn lead to more gluons and more quark pairs until the energy is dissipated. From such an amalgam, colourless states of quark–antiquark pairs and three-quark states emerge as observable hadrons. The net result is a hadron shower manifesting as a highly collimated 'jet' of hadrons in the direction of the struck quark. Hadron jets of this kind are seen in many experiments and they are regarded as 'hadronization' of energetic quarks or gluons.

Spontaneous symmetry breaking (SSB). Consider the theory of a charged scalar field ϕ such that the state in which $\phi = 0$ everywhere is not the lowest-energy state (recall the double-well potential). The state with the lowest energy will have a nonzero ϕ field; in other words, the expectation value of the field in the vacuum state is nonzero, $\langle\phi\rangle \neq 0$.

The analogy here is to the ferromagnetic ordering below the Curie temperature where the domains in the ferromagnetic material appear spontaneously even when the overall magnetization is zero. Both the translational and rotational invariances are lost although the original electromagnetic interaction conserves these symmetries. This is an example of the spontaneously broken symmetry.

SSB always leads to the prediction of massless spinless particles called 'Goldstone bosons'. There is no experimental evidence for such particles.

Higgs mechanism. The nature of this mechanism is abstract. It is concerned with the spontaneous breaking of the gauge symmetry. By this mechanism the Goldstone boson can be banished (by using the freedom in choosing the gauge) and, simultaneously, the gauge vector boson which is meant to transmit a short-ranged force can be made to acquire mass. Thus, the unwanted Goldstone boson is 'fed' to the gauge boson, which becomes massive and is capable of mediating a short-range force.

In the electroweak gauge theory there are four gauge bosons. Assuming the gauge symmetry to be spontaneously broken and appealing to the Higgs mechanism, it is possible to keep the electromagnetic field quantum γ massless and the three weak bosons $W^{\pm}$ and Z massive. It is the massive nature of the W and Z which makes the 'weak' force weak. To put it differently, the Higgs mechanism gives us a way to create the asymmetry between the left-handed and the right-handed particles – an asymmetry which is manifest as the well-known parity violation in weak interactions.

But what is the price for invoking the Higgs mechanism in the SM? After making the three weak bosons massive, one component of the original neutral ϕ field is left over. This relic should be existing as a neutral scalar particle with unknown mass, and this is the Higgs boson of the SM. Its characteristic feature is that its coupling to a fermion pair is proportional to the fermion mass. Present data rule out the Higgs boson lighter than about 60 GeV.

Supersymmetry. It proposes a spin-doubling of the elementary fields: a fermion is associated with a boson of equal mass, and vice versa. Thus, an electron is associated with 'selectron' having zero spin, a quark with a spinless 'squark', a photon with a 'photino' having spin 1/2, etc. So far there is no shred of evidence for such particles in the experiments. Signals for even broken versions of the supersymmetry are not visible in the available experimental data.

String theory. In quantum field theory we deal with point particles. In the string theory the fundamental objects are one-dimensional entities called strings. In the laboratory the stringiness of the particles will not be evident because the string length is extremely small (of the order of Planck length ($\sim 10^{-33}$ cm); a string to an atomic nucleus is smaller than the nucleus to a mountain). As of now, string theory has not given any verifiable consequence nor explained any observed fact in particle physics.

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REVIEW ARTICLE

Monoclonal antibodies in the study of architecture of plant viruses

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Monoclonal antibodies have been used as probes to study the architecture of several plant viruses over the past decade. These studies complement the information obtained through X-ray crystallography and help in delineating epitopes on the surface of the virus. The monoclonal antibodies that recognize distinct epitopes also aid in unravelling the mechanisms of assembly/disassembly of virus particles. Group-specific and strain-specific monoclonal antibodies are widely used in the classification of viruses. The significant developments made in this emerging area are reviewed here with specific examples.

VIRUSES, a term coined by Beijerinck and Baur[1,2] to describe the causative agents of certain plant diseases, are obligate parasites that cause considerable damage to plants. Viruses are broadly classified on the basis of their particle morphology as helical, icosahedral or complex. There are about 33 groups of plant viruses, of which 22 are icosahedral, 9 are helical and 2 are complex[3].

Over the past decade the molecular architecture of these viruses has been studied using a variety of methods such as electron microscopy, X-ray low-angle scattering, single-crystal X-ray diffraction, sedimentation and other solution properties. An analysis of the three-dimensional X-ray structures of spherical plant, animal or insect viruses determined so far has shown that the viral coat protein most often has the same polypeptide fold irrespective of the origin of the virus. The coat