QUARKS

During the last decade high energy physics research has revealed that hadrons (*i.e.*, strongly interacting particles: neutrons, protons, hyperons, mesons) are not elementary objects but have themselves a finer structure when probed at the scale of $\lesssim 10^{-15}$ cm with projectiles of several tens to hundreds of GeV. The elementary fermionic constituents at this scale are the quarks introduced in 1964 by Gell-Mann and Zweig. The fundamental strong interaction theory of to-day, employs quark fields to describe the fermion degrees of freedom, at the sub-hadronic scales.

To describe the variety of hadronic states discovered till to-day it is found necessary to introduce the first five types of quarks listed in table 1—each type, referred to as a "quark-flavour", carries its typical "flavour" as an additive quantum number—and it is generally believed that the sixth quark type listed will be discovered in future experiments at energies not yet available. There may, of course, be more.

TABLE 1
Quarks

Quark flavour		Electric charge (Q) (unit: proton charge)
down	(d)	$-1/3$
up	(u)	$+2/3$
strange	(s)	$-1/3$
charm	(c)	$+2/3$
bottom	(b)	$-1/3$
top	(t)	$+2/3$

The quarks are (spin 1/2) fermions and carry baryon number B= 1/3 (the unit used is the baryon number of the nucleon). From a study of the spectroscopy of hadrons it has become clear that each quark, besides carrying its typical flavour quantum number, also carries yet another attribute called "*colour*" which takes one of the three values referred to as "red", "blue" and "green" (or denoted by numerical indices 1, 2, 3). Thus, in effect, we talk to-day in terms of $6\times 3 = 18$ quark fields.

In spite of many experimental searches so far no firm evidence has been found for the existence of quarks in a free state unbound in a hadron. A belief has been gaining ground that quarks are permanently confined inside the hadrons on account of a peculiar nature of the forces that bind them into hadrons. The concepts of mass and life-time of a quark are thus rather problematic.

LEPTONS

At the distance scales probed so far, we have another set of elementary (spin 1/2) fermions in nature that, however, unlike the quarks, do occur in free unbound states. These are collectively called the leptons—the earliest discovered example of which is the electron (J. J. Thomson 1897) and the most recently discovered one is the τ-lepton (M. L. Perl 1975). To-day we believe that we have at least six flavours of leptons also. These are listed in table 2. The sixth of these has not been established by direct observation so far

TABLE 2
Leptons

Lepton flavours	Electric Charge Q (unit: proton charge)	mass (MeV)	Life time (sec)
e	-1	$\simeq 0.5$	stable
ν_e	0	$<6\times 10^{-5}$	stable
μ	1	$\simeq 106$	$\simeq 2.2\times 10^{-6}$
ν_μ	0	<0.57	stable
τ	1	$\simeq 1784$	3.10^{-13}
ν_τ	0	(not observed)	

Leptons, unlike the quarks, do not take part in strong interactions. They all take part in weak interactions and the electrically charged ones also interact electromagnetically.

THE FIRST UNIFICATION: ELECTROMAGNETIC

The first unification of apparently different kinds of forces of nature was achieved by the physicists of the mid-nineteenth century. Maxwell's equations, governing electromagnetic fields, electric charges and currents, were the expression of that unification, combining electricity and magnetism. After the formulation of quantum mechanics by Schrödinger and Heisenberg (1925–26) . Dirac not only discovered (with the electron in view) the currently accepted relativistic equation for an elementary spin-1/2 fermion field, but also wrote down the quantum theoretical formalism for the electromagnetic interaction. This theory—called Quantum Electrodynamics (QED)—was developed in the later 1940's by Tomonaga, Feynman, Schwinger and Dyson into a form that has been tested to an extremely high degree of precision. It is the prototype of what is called a renormalizable local quantum field theory. Renormalizability, it may be noted, is the property, enjoyed by a very restricted class of theories, that allows introduction of physical parameters in such a way that the commonly occurring infinities in the perturbation solutions of most local quantum field theories can be removed in a systematic manner.

Let $\psi(x)$ stand for the (4-component spinor) Dirac field corresponding to an elementary fermion of charge e. It is governed by the (local) Lagrangian density function

$$\mathscr{L}_0(x) = i\bar{\psi}(x)\gamma^\mu\partial_\mu\psi(x) - m\psi(x)\bar{\psi}(x) \quad (1)$$

in the absence of any electromagnetic field, while in the presence of an electromagnetic field with four-vector potential $A_\mu(x)$, the Lagrangian density is given by

$$\mathscr{L}(x) = i\bar{\psi}(x)\gamma^\mu\partial_\mu\psi(x) - m\bar{\psi}(x)\psi(x) + eA_\mu\psi(x)\gamma^\mu\psi(x) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (2)$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field tensor.

The Lagrangian function $\mathscr{L}_0(x)$ of eq. (1) has the important property of invariance under the global (*i.e.* independent of the space-time point x) transformation

$$\psi(x) \to \psi'(x) = \exp(i\alpha Q)\psi(x),$$
$$\bar{\psi}(x) \to \bar{\psi}'(x) = \exp(-i\alpha Q)\bar{\psi}(x), \quad (3)$$

where α is an arbitrary x-independent real parameter and Q stands for electric charge ($Q = e$ here). Such a transformation is an example of an element of a 1-parameter unitary group generated by Q and denoted by $U_1(Q)$. If the parameter α is taken to be a function of the space-time point x, *i.e.*, if we make a "local" $U_1(Q)$ transformation, then $\mathscr{L}_0$ is not invariant because of the presence of the derivative operator ∂_μ in it. Invariance under local $U_1(Q)$ transformations—also called $U_1(Q)$ gauge transformations—is, however, easily seen to be a property of the Lagrangian function $\mathscr{L}(x)$ of eq. (2), provided the electromagnetic field potential transforms according to the rule

$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x), \quad (4)$$

under which the electromagnetic field tensor $F_{\mu\nu}(x)$ remains unchanged.

Thus demanding gauge invariance, forces us to introduce the field A_μ interacting with $\psi(x)$ in the manner of the standard QED, described by eq. (2). QED is thus a $U_1(Q)$gauge invariant theory. The vector field $A_\mu(x)$ is called the gauge field—and its introduction is necessary for setting up the U_1 gauge-invariant theory. Note also that eq. (2) has no place for a mass term for the gauge field (a term proportional to $A_\mu A^\mu$) as it would break the gauge invariance, being nonvariant under the transformation of eq. (4). The long-range nature of the electromagnetic interaction corresponds to the absence of such a mass term for the gauge field.

Corresponding to the gauge field of QED, we have quanta which are the well known photons. Thus photon is an example of an "intermediate boson" corresponding to a field mediating a gauge-invariant interaction among charged particles.

THE SECOND UNIFICATION: ELECTROWEAK

A renormalisable local quantum field theory that unifies the weak as well as the electromagnetic interactions has been formulated in recent years. This is the Glashow-Salam-Weinberg theory. Like QED described above, it is also a gauge theory. However (unlike QED) the gauge group is not the one parameter (abelian or commutative) U_1 group, but rather the non-abelian $SU_2 \times U_1$ group whose elements are characterised by $3+1=4$ real parameters (corresponding generators will be denoted by $I_{1,2,3}$ and Y). Corresponding to these four gauge parameters four gauge vector fields must now be introduced to set up the gauge invariant Lagrangian. Unlike QED, this gauge-invariant theory must be set up in such a way that the invariance is "spontaneously broken" in the solutions of the invariant equations, leaving only the $U_1(Q)$ gauge invariance of QED intact. This is necessary to ensure that the intermediate bosons of weak interactions become massive (corresponding to their short range $\approx 10^{-16}$ cm), the photon remains massless, and at the same time the field theory is renormalisable.

Denoting by u_L, u_R the 2-component left- and right-handed (Weyl) projections of the Dirac field corresponding to the u-quark, etc., the quark and lepton fields are deployed as doublets and singlets of SU_2 with appropriate U_1 quantum number Y as shown below (electric charge $Q = I_3 + Y$, where I_3 is the diagonal generator of SU_2):

Quark doublets (each colour):

$$\begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad \begin{bmatrix} c_L \\ s_L \end{bmatrix}, \quad \begin{bmatrix} t_L \\ b_L \end{bmatrix}, \qquad Y = \frac{1}{6} \quad ;$$

Lepton doublets:

$$\begin{bmatrix} \nu_{eL} \\ e_L \end{bmatrix}, \quad \begin{bmatrix} \nu_{\mu L} \\ \mu L \end{bmatrix}, \quad \begin{bmatrix} \nu_{\tau L} \\ \tau_L \end{bmatrix}, \qquad Y = -\frac{1}{2} \quad ; \qquad (5)$$

all R-components of quarks and leptons are SU_2 singlets with $Y = Q$. The primes on d, s, b indicate that quarks of the same charge appear mixed in weak processes. Notice, the family of fermions so far discovered separates into three "generations": (i) $\{u, d, e, \nu_e\}$, (ii) $\{c, s, \mu, \nu_\mu\}$ and (iii) $\{t, b, \tau, \nu_\tau\}$.

To achieve spontaneous breaking of the $SU_2 \times U_1$ gauge symmetry a doublet of complex scalar fields—the Higgs fields—has also to be introduced. For such a scalar doublet it is possible to choose an invariant potential term in such a way that its minimum occurs for a suitable non-zero value of the neutral component. This makes the ground state of the theory non-invariant under the gauge group and thus introduces the desired spontaneous breaking of the gauge symmetry. As a result the vector gauge bosons $W^\pm$, Z^0 (with electric charges ± 1, 0) acquire masses while the photon remains massless. The interaction part of the Lagrangian obtained in this manner is

$$\mathscr{L}_{int} = \exp \left[A_\mu j_\mu^{em} + \frac{2}{\sin(2\theta_W)} Z_\mu \left(J_\mu^3 - \sin^2\theta_W j_\mu^{em}\right) + \frac{1}{\sqrt{2}\sin\theta_W}\left(W_\mu^+ J_\mu^{1+i2} + h.c.\right) \right] \qquad (6)$$

Here j_μ^{em} is the current of the electric charge Q J_μ^a, $a = 1, 2, 3$ is the current of the generator I_a of SU_2 (e.g., $j_\mu^{em} \sim \bar{\psi} Q \gamma_\mu \psi$, $J_\mu^a \sim \bar{\psi} I_a \gamma_\mu \psi$ are typical terms corresponding to a Weyl fermion field ψ); $J_\mu^{1+i2} \equiv J_\mu^1 + iJ_\mu^2$; $\sin\theta_W$ is a parameter to be determined from experiments and the vector boson masses are given by

$$m_W \simeq 37.3 \text{ GeV}/\sin\theta_W, \; m_Z = m_W/\cos\theta_W. \qquad (7)$$

Apart from the specific finite ranges of the weak interactions determined by the masses m_W and m_Z appearing in this theory, the most spectacular feature that emerged was the prediction of the Z-mediated "neutral current" weak interactions. These were discovered for the first time in 1973 in high energy ν_μ interations. This gave a great encouragement to the theory. Since then, a variety of detailed weak neutral current effects have been studied in a very broad range of energies—electron-volts (parity violation in atomic physics) to several tens of GeV ($e^+e^- \to \mu^+\mu^-$, ν_μ-reactions)—and all are consistent with the model with a value of $\sin^2\theta_W \approx 0.22$.

A final spectacular verification of the theory will be the discovery of $W^\pm$ and Z^0 bosons at masses $m_W \simeq 78$ GeV, $m_Z \simeq 88$ GeV according to eq. (7). The energies required have recently become available at the CERN (SPS) $p\bar{p}$-collider ($\simeq 500$ GeV in centre of mass); however, the luminosity attained is not quite high enough yet.

Further, *the theory demands the existence of* at least one neutral scalar Higgs particle. Its mass is, however, not fixed by the theory. The Higgs fields have gauge invariant Yukawa couplings with the fermion fields, used to generate, *through the spontaneous symmetry breaking*, the mass parameters of the fermions. The theory fails to fix the values of these parameters. Presence of the large number of theoretically undermined parameters such as these and $\sin^2\theta_W$ *indicates that, inspite of the progress made*, we are still quite a distance from an "ultimate" unified theory.

In the foregoing discussion of the electroweak interaction the colour label on the quarks has been merely a dummy index. The electroweak interaction really works among the flavours–hence the often used term "flavour dynamics" for it. The dynamic role of colour will be described next.

QUANTUM CHROMODYNAMICS (QCD)

During the past decade a gauge theory of strong interaction has also emerged. Operating on the three valued colour label (or index) carried by a quark field we can introduce the group of 3×3 unitary matrices with unit determinant. This non-abelian group is called SU_3 (colour). Demanding invariance, under SU_3 (colour) gauge transformations, leads to the (non-abelian) gauge theory in question-appropriately named Quantum Chromodynamics (QCD) by Gell-Mann. Since the transformations of the group SU_3 are 3×3 unitary matrices of determinant 1, the number of real parameters required to specify them is 8. Correspondingly, we have to introduce a set of 8 gauge vector boson ("gluon") fields to set up the SU_3 (colour) gauge invariant theory.

In contrast with QED, where the gauge field A_μ does not carry any charge, in QCD the gluon octet, having nontrivial SU_3 (colour) transformation properties, couple to themselves besides coupling to the colour-currents carried by the quarks. This non-linear interaction of gluons among themselves has profound consequences. In QED, a charged *particle polarises the vacuum* by creating virtual pairs and attracting the oppositely charged and repelling the like charged member of a pair. This leads to a screening of the charge of the particle and as a result the effective "renormalised charge" appears *smaller at large* distances and larger at short distances. In QCD, on the other hand, the mutual nonlinear gluon interaction leads to an "anti-screening" effect so that the effective "renormalised coupling constant" (*the analogue of electric charge in QED*) decreases at short distances and increases at long distances. This property of the effective renormalised coupling constant of QCD is referred to as the property of "*asymptotic freedom*". It is due to this property that an understanding has finally been achieved of the strange fact discovered experimentally, that at higher and higher energies in highly inelastic collisions with high momentum transfers of leptons with hadrons, the latter appear as made up of more and more freely acting elementary constituents (the "partons" of Feynman). In recent high energy electron-positron annihilation experiments direct evidence of hadronic jets, signalling quarks and gluons, has also been obtained.

In the asymptotically free region of large energies and large momentum transfers, perturbative calculations based on QCD are legitimate and have been reasonably well tested in a variety of processes. On the other hand, a proof of the other expected property of QCD-that of explaining permanent confinement of quarks and gluons inside hadrons- has not been achieved yet. At large distances (at the hadronic size of $\approx 10^{-13}$ cm). the effective QCD coupling becomes strong and perturbation theory is inapplicable. For this reason Wilson's formulation of QCD on a space-time lattice is being used for nonperturbative numerical calculations (by Monte Carlo techniques) on large computers. In this way some success has been achieved in calculations of hadron masses and in obtaining indications of confinement.

THE THIRD UNIFICATION: GUT.

We have seen that at the level of quarks and leptons all three interactions (leaving out gravitation) are described by a gauge theory based on the group $SU \times U_1 \times SU_3$ (colour). The $SU_2 \times U_1$ gauge theory is spontaneously broken down to $U_1(Q)$ gauge invariance to generate masses of the weak interaction bosons $W^{\pm}$, Z^0. If we are at energies far above these masses the symmetry breaking becomes negligible. And since at large energies and momentum transfers, *i.e.*, at short space-time distances, the effective coupling parameter decreases for the non-abelian theories based on SU_2 and SU_3 (more rapidly for the latter) and increases for the abelian theory based on U_1, in typical logarithmic manner, it can transpire that the three relevant parameters approach a common value and all three types of interactions become unified into a single gauge theory based on one simple group that contains all these three groups.

The simplest example of such a "grand unified theory" (GUT) is the SU_5 gauge theory proposed by Georgi and Glashow in 1974. In this theory, fermions of each "generation" are placed in one 5-dimensional and one 10-dimensional representations of SU_5; *e.g.*,

$$\begin{array}{l}\{\bar{d}_1, \bar{d}_2, \bar{d}_3, e, \nu_e\}_L, \\ \{u_1, u_2, u_3, \bar{u}_1, \bar{u}_2, \bar{u}_3, d_1, d_2, d_3, \bar{e}\}_L;\end{array} \qquad (8)$$

where 1,2,3 are colour indices, a bar indicates the antifermion, and L the left handed projection. It is important to note that the same representation contains both quarks as well as leptons, relating uniquely their charges and other attributes (the idea of combining quarks and leptons in representations of a gauge group for a higher unification was first put forward by Pati and Salam).

The transformations of SU_5 are parameterised by $5^2-1 = 24$ real parameters. Correspondingly the SU_5 gauge invariant theory will involve 24 gauge vector boson fields. Of these 8 are the SU_3 (colour) gluon-fields and 4 the $SU_2 \times U_1$ electroweak gauge fields. We thus have additional 12 gauge fields–a complex colour triplet called X-bosons and another complex colour triplet called the Y-bosons.

To spontaneously break the SU_5 gauge symmetry down to the level of symmetry seen at present laboratory energies ($\lesssim 100$ GeV) two sets (a 24-plet and a 5-plet) of scalar Higgs fields are employed. At the first step

$$SU_5 \xrightarrow[\gtrsim M_{X,Y}]{} SU_2 \times U_1 \times SU_3(\text{colour}),$$

and the second step

$$SU_2 \times U_1 \times SU_3(\text{colour}) \xrightarrow[\gtrsim M_{W,Z}]{}$$

$$U_1(Q) \times SU_3(\text{colour}).$$

The two symmetry breakings take place at mass scales $M_{W,Z}$ and $M_{X,Y}$ indicated below the arrows.

The X and Y gauge bosons couple to new currents corresponding to SU_5 transformations that can transform quarks and leptons into one another in such a way that we obtain processes in which baryon number and lepton number are violated. This would lead to proton decay. For example we can have the decay process $P \to e^+\pi^0$. From dimensional considerations we see that the proton life time

$$\tau_p \approx M_X^4 / m_p^5.$$

If $\tau_p \approx 10^{30}$ yrs, we would have $M_{X,Y} \approx 10^{14}$ GeV.

At the Paris Conference, Menon presented three events detected by the Indo-Japanese Collaboration searching for proton decays in a detector deep underground in the Kolar Gold Field. The experimenters interpret these as proton decay events and give a value of $\tau_p \simeq 7 \times 10^{30}$ yrs. Several other experiments are underway in other parts of the world to look for proton decays.

An important result of the SU_5 GUT is the successful computation of the experimental value of $\sin^2\theta_W$, the parameter occurring in electroweak interaction, at energies $\lesssim 100$ GeV.

Baryon number violation is a common feature of all GUT models. It has profound implications in cosmology. A way is made available thereby to tackle the problem of understanding the observed asymmetry between baryons and antibaryons and of the observed large ratio of the number of photons to that of nucleons in the present universe.

Another important issue related to GUT's got prominent attention at the Paris Conference due to a recent work of Rubakov. When a gauge symmetry such as SU_5 breaks down to a gauge group containing the $U_1(Q)$ gauge group of electromagnetism, then it is an inevitable theoretical consequence that a 't Hooft-Polyakow topological magnetic monopole (superheavy with mass $\approx 10^{16}$ GeV) must exist. Rubakov claims to have shown that in such a theory the monopole can catalyse baryon number violation with a strong interaction rate. In view of the recently reported passage of a monopole in a superconducting ring set up by Cabrera at Stanford, the Rubakov result naturally caused a great deal of stir. This will expectedly stimulate much theoretical and experimental activity. Searches for slow superheavy monopoles using large plastic detectors reported at Paris, have given negative results so far.

PROBLEMS OF UNIFICATION

Several problems come up on this march towards unification of forces. Almost all of them are connected with the Higgs scalar fields that have to be introduced to generate masses of the gauge bosons and of the elementary fermions.

(i) First the number of Higgs bosons increases to an uncomfortably large number as one goes from the second to the third unification. Along with the Higgs fields enter a large number of theoretically undetermined parameters. Attempts have therefore been made in the recent years to develop schemes with only fermion fields, generating Higgs bosons dynamically as condensates made up of fermions and antifermions. Unfortunately such schemes – the technicolour and the extended technicolour schemes – have severe problems of their own and have essentially failed.

(ii) Even with elementary Higgs fields we have the so called mass hierarchy problem. It is difficult to understand how such widely different mass hierarchies ($M_W \simeq 100$ GeV, $M_X \simeq 10^{14}$ GeV) are to be understood in a natural manner. Even if we simply accept the hierarchy as given by the phenomenology of the interactions, it is even more difficult to maintain the desired mass relations when higher order corrections are considered, for the various parameters of the scalar field potentials have to be fine tuned to an incredible accuracy at every order. This is highly unsatisfactory from the theoretical point of view. To cure these problems several authors have proposed the use of supersymmetry (boson-fermion symmetry) along with GUT's. However, such a solution brings in many more particle states and it is not yet clear how really to break these higher symmetries. Experimental searches of the supersymmetric partners of the known particles have been set afoot. Results from such searches as well as the details of proton decay studies will be crucial to these ideas.

(iii) The problem of understanding the origin of the three (possibly more) generations has remained unsolved through all the stages of unification outlined above. How are the different generations related? How are their mass relations to be understood? No satisfactory answers are available yet.

BEYOND THE THIRD UNIFICATION

On the march towards unification we have met with a whole crop of fermions, gauge bosons, Higgs scalars (and possibly their supersymmetric partners). The number is so large that one can hardly believe that we have really reached the final fundamental level of physics (if there is such a final level). Several attempts are therefore afoot to look for a simpler set of elementary objects out of which the various quarks, leptons and bosons are to be constructed as composites. It is hoped that at the energy scales of several hundred TeV one may see the composite structure of quarks and leptons that are seen as elementary only at our present energy scales of several tens to hundreds of GeV. All such composite models are still in a very preliminary qualitative stage—no sufficiently realistic dynamical scheme has been proposed so far.

A serious problem facing such attempts is that it is quite possible that for a long time to come (if at all) energies high enough to probe distances much smaller than 10^{-16} cm might not be available, and our experimental science may begin to turn into speculative philosophy. In this connection we may note that, based on the present day technology, accelerator builders have formualted the scaling law: cost $\propto$ (Energy)^2, while, as 't Hooft put it in Paris, our theoretical interest $\propto$ log (Energy). So there is a widening gulf between the theoretical and the experimental fronts. Of course, surprises may yet turn up that change the picture dramatically.

In the developments described above the gravitational interaction has remained in the wings. Will there be a fourth unification that includes gravity? Sakharov has advocated the point of view that gravitation might possibly be merely an effective force resulting from the interplay of the other fundamental interactions, just as the elastic forces in a solid arise from the basic forces among the constituent atoms and molecules. In contrast is the point of view, gaining many supporters, that gravitation is the most basic of forces and therefore holds the key to a genuine unfication. The most ambitious attempt in this direction so far is the formulation of the $N=8$ supergravity (gauged supersymmetry) theory, which can be looked upon as a supergravity theory in an 11-dimensional space that has 4-non-compact dimensions identified with the ordinary space-time and 7 compactified dimensions manifesting the various internal degrees of freedom. It is far from clear yet which, if any, of the differing imaginative proposals of to-day will succeed in attaining to established status in physics. It is very interesting, all the same, that the physics of the tiniest dimension and of the largest cosmological dimension are showing signs of coming together into a fundamental unity.