IL8302832

WIS-82/60 Dec-Ph

Composite Models for Quarks and Leptons *

Haim Harari

Weizmann Institute of Science, Rehovot, Israel

Abstract

We discuss the motivation for constructing composite models for quarks and leptons, the hopes we have for a successful model and the difficulties encountered, so far, in this field. This paper corresponds to the contents of lectures given at the SLAC Summer Institute (August 1982), at the DESY Workshop on "Electroweak Interactions at High Energies" (September 1982) and at the Solvay Conference at the University of Texas, Austin, Texas (November 1982).

1. Foreword

The possibility that quarks and leptons are composite, plays a peculiar role in present-day particle physics. On one hand, it is the most natural extrapolation of the development of modern physics and the least imaginative proposition for extending our theoretical ideas beyond those of the "standard model" of electromagnetic, weak and color interactions. On the other hand, any attempt to construct an explicit composite model immediately faces serious difficulties, necessitating assumptions and ideas which are at least unusual, possibly revolutionary. Thus, we are dealing with an approach which is, paradoxically, extremely speculative and somewhat unimaginative

*Supported in part by U.S.-Israel Binational Science Foundation.

at the same time. In this lecture we review the present status of this field, emphasizing the hopes as well as the difficulties. We do not discuss specific models in any detail.

2. Compositeness and the Fundamental Interactions.

Every level of compositeness in the history of modern physics, led to a major revision of the list of fundamental forces. The understanding of atomic structure showed that Van-der-Waals forces are residual electromagnetic effects and are therefore not a separate fundamental interaction. The substructure of the nucleus revealed the existence of a new short range force (the Strong or Nuclear or Hadronic Force) and led to the identification of an even shorter-range force (the Weak force). The hadron substructure uncovered the Color force and showed that the Nuclear or Hadronic forces are residual color effects. It is almost certain that a possible substructure of quarks and leptons, if found, will reveal one or more new forces. It is also possible that it may demote one or more of the existing "fundamental interactions" into the role of a "residual interaction".

New fundamental particles may be found in the future and may have escaped detection in the past in several different ways:

(i) The production of high mass free particles requires experiments at sufficiently high energies. The W and Z bosons and the toponium bound states have presumably escaped detection in such a way.

(ii) Low mass (or even massless) particles may escape detection if they interact weakly with all visible matter. That is how the neutrino eluded experiments for several decades. We may have a variety of light neutral particles, especially Goldstone or pseudo-Goldstone-bosons escaping us now in such a way.

(iii) Confined particles, even if they have small effective masses, require experimental probes with energies far exceeding their confinement energy scale. Only such probes can reach into small distances in which the confined particle can be indirectly observed. Thus, many Gev's were needed for indirect evidence for light quarks and massless gluons, where the confinement scale is $\Lambda_C \sim 100$ MeV. If there is a second confining force with a scale Λ_H, we will need energies which substantially exceed Λ_H in order to "observe" the new confined states.

In close correspondence with these three methods, there are at least three ways of discovering a new fundamental interaction:

(i) It may be a short range interaction corresponding to distance scales and energy scales beyond those presently available. That is how the strong nuclear force remained unknown until the 1930's.

(ii) It may be an extremely weak force, not necessarily with a short range. Such a force can be uncovered only by increasing the sensitivity and accuracy of low energy experiments.

(iii) It may be a confining force, mediated by a massless boson but possessing a confinement scale beyond present energies.

Any of these possibilities may "hide" additional new interactions which could play an important role in quark and lepton compositeness. There may also be a fourth, hitherto unknown, method by which new particles and new interactions may escape detection. After all, had we discussed this subject 15 years ago, we would have listed only the first two items in the above lists of possibilities. We would not have anticipated the possiblity that an extremely strong force with massless force-carriers (Color) could have escaped detection. Today, we may be equally blind. The binding force of the constituents of quarks and leptons in perhaps eluding us in a new clever way.

3. Why Do We Wish to Go Beyond the Standard Model?

The standard model of electromagnetic, weak and color forces is based on a renormalizable local gauge theory, where $SU(3)_c xSU(2)xU(1)$ is the basic gauge group, and its spontaneous breaking via a Higgs mechanism leaves an unbroken $SU(3)_c xU(1)_{EM}$ gauge group. Ignoring temporarily the Higgs sector, the model involves massless quarks, leptons, photon, gluons and weak bosons with only three independent parameters representing the coupling constants of the three interactions. The Higgs sector induces all the necessary masses, increasing the number of arbitrary parameters to twenty or more.

There are several reasons which lead us to believe that the standard model, in spite of its elegance, self-consistency and experimental success, cannot be the final answer. Every one of these reasons is, to some degree, a matter of taste. However, the emerging overall picture convinces us that there must be some new fundamental physics beyond the standard model.

Why do we wish to go beyond the standard model?

(i) Too many parameters. It is unlikely that the laws of physics contain over twenty independent parameters and that the various Cabibbo angles and quark or lepton masses are as fundamental as the fine structure constant. A theory beyond the standard model may enable us to calculate most of these parameters, starting from a small number of constants. Such a calculation will hopefully explain the peculiar mass spectrum of the observed quarks and leptons.

(ii) Generation Puzzle. The standard model contains no clues explaining the existence of several generations of quarks and leptons. There is no good reason for having three generations (or any other specific number of generations). We do not know what distinguishes the generations from each other. A new quantum number or a new property which "labels" the generations can emerge only from theories which go beyond the standard model. Any hope of calculating the mass matrices for the quarks and leptons must involve an understanding of the distinction between fermions of different generations.

(iii) Pattern within one generations. The mysterious triplication of generations enhances the significance of another puzzle, namely- the pattern observed within one generation. The standard model does not explain why quark and lepton charges are quantized in a related way. It does not explain why the color and electric charge are correlated (integer charge always comes with color singlets; noninteger charge with color triplets). It also does not explain why the quarks and leptons possess identical SU(2) properties (left-handed doublets; right-handed singlets) and why all integer multiples of $Q=\frac{1}{3}$ between $Q=-1$ and $Q=+1$ appear but no $|Q|>1$ fermions seem to exist. All of these features would have required explanation even if we had only one generation. Since the same pattern occurs three times, there must be a particularly good reason for repeatedly having that specific pattern within the generation.

(iv) Unification. One other motivation for going beyond the standard model is the obvious hope of unifying the three interactions. We must remember that the SU(2)xU(1) gauge theory provides us with a beautiful and important connection between the electromagnetic and weak interactions but it does not fully unify them. We still have an independent coupling constant for each interaction.

(v) Hierarchy problem and fine tuning. These may count as two problems or one problem depending on one's point of view. In any way of looking at it, we have here a mismatch between different energy scales. Assuming that there is an important energy scale beyond the standard model (be it the Planck mass or a somewhat lower energy scale of some other type of new physics), it is difficult to understand how particles with masses corresponding to the low energy scales of the standard model can survive enormous self-energy corrections. Vector bosons and fermions may be protected from such corrections by a gauge symmetry or a chiral symmetry, respectively. Scalars are not protected, in general.

The above five arguments are not compelling in any rigorous sense. However, after considering them, it is difficult to avoid the conclusion that some deeper theory must lie beyond the standard model, settling at least some of the above issues.

4. Avenues Leading Beyond the Standard Model.

We have listed five reasons to go beyond the standard model: (i) Too many parameters; (ii) Generation puzzle; (iii) Pattern within one Generation; (iv) Unification; (v) Hierarchy problem and fine tunning. At least five different classes of approaches have been proposed for handling these issues. There is no one-to-one correspondence between the five problems and the five classes of models. Let us briefly review each approach:

(a) "Horizontal Symmetries": These are alleged new symmetries[1] connecting the different generations. Such symmetries cannot settle any issue except, possibly, the generation puzzle (ii). We return to some of these ideas in section 9. No convincing horizontal symmetry scheme has been proposed, so far.

(b) "Technicolor". The fine tuning problem (v) may be resolved or at least postponed, to higher energies, by postulating that the Higgs scalars are condensates of new fundamental "technifermions" bound by a new confining "technicolor" interaction[2]. This approach does not shed any light on problems (i)-(iv). In fact, it normally leads to additional particles and additional free parameters. The technicolor idea is a limited version of compositeness, in which scalars and, consequently, the longitudinal components of massive gauge bosons, are composite objects. Quarks, leptons, transverse gauge bosons and technifermions are all fundamental. In order to produce quark and lepton masses, technicolor schemes must be extended to include new gauge bosons which connect quarks to techniquarks[3]. Such bosons usually play a role similar to that of Horizontal gauge bosons, thus incorporating the Horizontal symmetry approach into the technicolor scheme. Here, again, no satisfactory model is presently available.

(c) Grand Unification. This approach satisfactorily settles points (iii) and (iv). The structure of one generation is beautifully accounted for in any scheme[4] based on O(10) or any of its candidate subgroups (SU(5) or SU(4)xSU(2)xSU(2)). The three interactions are clearly unified. However, the number of free parameters is increased beyond those of the standard model, no explanation is given to the generation puzzle and the hierarchy problem remains unanswered. In addition, we must face an energy "desert" spanning twelve orders of magnitude and the controversial possibility of heavy magnetic monopoles. Proton decay is the earliest crucial test of grand unified theories.

There are ambitious attempts[5] to combine Grand unification, technicolor and horizontal symmetries in all-encompassing schemes based on large groups such as SU(7), SO(14) etc. No convincing model has been found

(d) Supersymmetry. Supersymmetry, besides being an attractive mathematical "toy", provides a hope for settling the hierarchy problem[6]. Unfortunately, the particle spectrum is doubled, introducing alleged supersymmetric partners for all gauge bosons, quarks , leptons and scalars. Thus we have more particles and more parameters, without solving any of the problems (i)-(iv). Grand unification can be combined with supersymmetry, thus combining possible solutions to points (iii)(iv)(v), but the price is, again, a significantly more complicated spectrum of particles as well as additional theoretical problems.

(e) Composite Models. Here we assume that quarks, leptons, scalars and possibly some gauge bosons are composite objects of some new fundamental constituents. Here, again, no satisfactory model is available. In the following sections (6-12) we discuss the hopes and difficulties of such models, vis-a-vis the various reasons for going beyond the standard model.

But, before we move on to our discussion of composite models, we must discuss the question of experimental tests.

5. Experiments Beyond the Standard Model

Theories which go beyond the standard model, like all other theories in physics, must pass two types of tests: self-consistency and agreement with experiment. The requirement of theoretical self-consistency is not as simple as it sounds. We must remember that in all previous stages in the understanding of the structure of matter, from the Bohr atom to the quark model, the original version of the theory had many correct ingredients but suffered from serious theoretical inconsistencies. In all cases, experimental clues played a crucial role in the acceptance of the correct ideas. The satisfactory theoretical self-consistency came only gradually, with modifications which were partly discovered by pure reasoning and partly through new experimental facts. Our main difficulty today is the total lack of any experimental facts which might force us to go beyond the standard model. To rely entirely on arguments of theoretical self-consistency is dangerous. It is not clear that such arguments would have allowed the quark model to be developed!

We therefore believe that experimental clues are crucial. In order to review such clues we must first discuss the relationship between the hypothetical new theory which goes beyond the standard model, and the Lagrangian of the standard model. In all cases we do not wish to discard the standard model. We would like to keep it as a good aproximation of the ultimate theory, valid at energies well below the new high energy scale. Schematically, we may consider the following situation: We have a new theory at small distances and high energies. Its Lagrangian, L_{NEW} is useful for describing high energy phenomena. It hopefully corresponds to a renormalizable theory which is fully self-consistent. At lower energies we may have an effective Lagrangian L_{EFF} which, in principle, can be derived from the fundamental high energy Lagrangian. It is presumably approximately equal to the standard-model Lagrangian L_{SM}.

$$L_{NEW} \to L_{EFF} \cong L_{SM}$$

When we search for experimental tests of the new theory, we may look for two general classes of tests:

(i) Tests of L_{NEW}. These are, necessarily, high energy tests involving future high-energy accelerators. If the energy scale of L_{NEW} is Λ_H, we may look for particles of mass Λ_H (e.g. Horizontal gauge bosons in Horizontal symmetry schemes, Monopoles in grand unified theories, Technihadrons in Technicolor models, etc.). We may also look for light particles which are confined within small confinement radii corresponding to a high energy scale Λ_H (e.g. preons in some composite models, techniquarks etc).

(ii) Tests of the small difference between L_{EFF} and L_{SM}. The low-energy phenomenology of the new scheme is, presumably, almost identical to that of the standard model. The small differences between the two may actually provide us with the first clues for physics beyond the standard model. Such clues may come from a variety of terms in L_{EFF}. A few examples:

(a) L_{EFF} may contain high-dimension four-fermion operators such as $uude^-$ or $\bar{\mu}e\bar{e}e$. These must be preceded by a coefficient of order Λ_H^{-2}. Such terms induce transitions like $p \to e^+\pi^0$ or $\mu \to 3e$, respectively. These are low-energy processes which, if observed, would necessitate some physics beyond the standard model.

(b) L_{EFF} may show slight deviations from certain coupling-constant relations of the standard model. For instance, the coupling constants $g_{We\nu}$, $g_{W\mu\nu}$ which are identical in the standard model ("universality") may turn out to differ by terms of order m_ℓ/Λ_H as a result of some e-μ difference which is revealed only at the scale of Λ_H.

(c) L_{EFF} may contain weakly coupled light Goldstone bosons χ with Yukawa couplings such as $\frac{m_e}{\Lambda_H}\chi\bar{e}e$. Such bosons are difficult to detect. If they exist, they could provide hints for some new physics.

The above classes of experimental tests are relevant to any theory which goes beyond the standard model. They are also true for composite models of quarks and leptons. The right-hand side of figure 1 indicates the general orders of magnitude of the new energy scale, corresponding to various theoretical approaches beyond the standard model. On the left-hand side of the same figure we show some of the experimental bounds which are relevant to composite models of quarks and leptons. We now turn to a discussion of these bounds.

6. Experimental Constraints on Composite Models of Quarks and Leptons

Any attempt to construct a composite model for quarks and leptons, must take into account several experimental constraints:

(i) The anomalous magnetic moments of the electron and muon provide us with an (almost) model-independent constraint[7]. It has been argued that if a composite structure at a scale Λ_H leads to deviations from the QED predictions for g-2, and if the composite model has a chiral symmetry, we expect:

$$\delta(g-2)_\ell \sim 0\left(\frac{m_\ell}{\Lambda_H}\right)^2$$

In the case of the muon, present g-2 experiments yield $\Lambda_H > 500\text{GeV}$. If we relax the chiral-symmetry assumption, the bound is much more

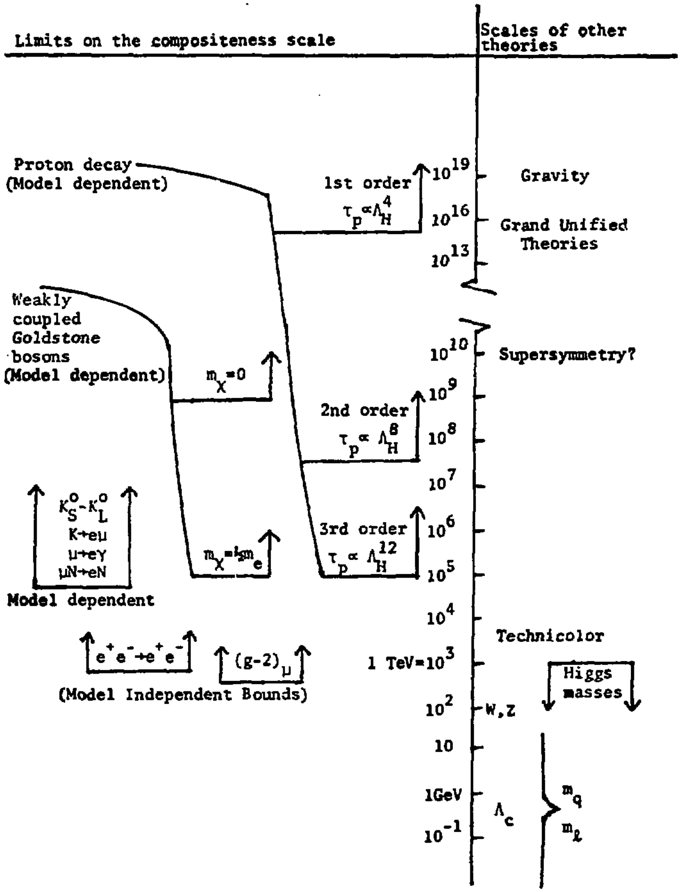

Figure 1: Experimental limits on the energy scales of theories beyond the standard model.

severe. The 500GeV bound for the muon is essentially model-independent. However, it is only an order of magnitude estimate, and factors of π could easily change it in either direction.

(ii) If electrons are composite, we expect L_{EFF} to contain a four-fermion term of the form $\bar{e}e\bar{e}e$. Such a term would contribute to the cross-section for $e^+e^- \to e^+e^-$. The present agreement between this cross-section and QED places a new model-independent bound[8)] on Λ_H. Here, again, one can only estimate the order of magnitude, obtaining $\Lambda_H > 700$GeV. Similar related estimates may be obtained for $e^+e^- \to \mu^+\mu^-$ and for neutral current neutrino reactions[8)].

(iii) The absence of the decays $\mu \to e\gamma$, $\mu \to 3e$, $K \to \mu e$, $K \to \pi\mu e$ and the reaction $\mu N \to eN$ provide us with model-dependent bounds on compositeness. If the muon and the electron are prevented from transforming into each other by some selection rule or by a strong suppression-factor which depends on their detailed internal structure, no useful bounds can be derived from the present experimental limits. However, it is possible that the muon and the electron can easily convert into each other, the transition being suppressed only by the physical dimension of the composite system. In such a case we would expect L_{EFF} to include effective four-fermion terms such as $\frac{1}{\Lambda^2}\bar{\mu}e\bar{e}e$ or $\frac{1}{\Lambda^2}\bar{s}d\bar{e}\mu$. These would enable us to derive limits of the order of $\Lambda_H \sim 10-100$TeV for various processes. We emphasize, however, that this case is very different from the previous item. No selection rule can forbid an $\bar{e}e\bar{e}e$ effective interaction, but it is perfectly reasonable to expect a small suppression factor ε based on some selection rule, appearing in an expression of the form $\frac{\varepsilon}{\Lambda^2}\bar{\mu}e\bar{e}e$. If ε is sufficiently small, the bound on Λ_H may become totally useless.

(iv) A related experimental bound follows from the well-measured K_S-K_L mass difference. The observed value can be accounted for by the standard model. A composite model for quarks might allow an effective term of the form $\frac{\varepsilon}{\Lambda^2}\bar{s}d\bar{s}d$ contributing to ΔM. Here, again, the constraints are model dependent. If ε is sufficiently small, due to a selection rule based on the different internal structure of s and d, no useful bound can be deduced. If $\varepsilon \sim O(1)$, we may obtain a very strong bound around 1000 TeV. However, it is somewhat unlikely that any composite model would allow $\varepsilon \sim O(1)$.

(v) Many composite models[9] may involve massless Goldstone bosons or extremely light pseudo-Goldstone bosons χ, whose Yakawa couplings to ordinary quarks and leptons are of order $\frac{m_\ell}{\Lambda_H}$ or $\frac{m_q}{\Lambda_H}$. Such bosons can easily escape detection in terrestrial experiments. However, the process $\gamma+e \rightarrow \chi+e$ which must occur frequently in stars places a limit[10] on the $\chi\bar{e}e$ coupling, and through it - on the compositeness scale. From the known limit on the allowed energy loss of red giant stars, we obtain: for a massless Goldstone boson - $\Lambda_H > 10^9$GeV; for $m_\chi = \frac{1}{2}m_e$, $\Lambda > 10^5$GeV; for $m_\chi = m_e$ no useful limit is obtained in this way. Thus the constraints are extremely sensitive to the boson mass.

(vi) Proton decay provides another crucial, but model-dependent, test for the compositeness scale. If no selection rules or supression factors exist, we find the usual result:

$$\tau_p \sim \frac{\Lambda_H^4}{m_p^5}$$

leading to $\Lambda_H > 10^{15}$GeV. However, proton decay is actually forbidden in some composite models. In other models it may proceed in second order[11] (giving $\Lambda_H > 10^7$ GeV) or in third order[12] (giving $\Lambda_H > 10^5$GeV)

The overall picture is the following: At present, there is no experimental evidence for quark or lepton compositeness. Model-independent bounds tell us that $\Lambda_H > 0.5$ TeV or $r < 4.10^{-17}$cm. Any specific model must be compared with a variety of model-dependent tests. For instance, anyone who wishes to suggest that quark and lepton compositeness will be revealed already at energies around, say, 10-1000 TeV, must provide strong suppression factors for proton decay, and the K_S-K_L mass difference, as well as avoid massless Goldstone bosons which couple to electrons and up and down quarks. Additional experimental tests which one must consider involve $\sin^2\theta_W$, the W-Z mass ratio, the W magnetic moment, the possible existence of "right-handed" weak bosons, etc.

7. Requirements from an Ideal Composite Model

What do we hope to achieve by constructing a successful composite model of quarks and leptons?

(i) Such a model should include a few species of fundamental objects interacting with each other through few types of fundamental interactions. The total number of parameters is presumably extremely small: several coupling constants and possibly (but not necessarily) a few mass parameters. All masses of the composite quarks and leptons should, in principle, be calculable from the parameters of the fundamental theory, in the same way that all hadronic masses and coupling constants are, in principle, calculable from the QCD coupling and a few quark masses.

(ii) The pattern of quarks and leptons within one generation should be fully explained in terms of the features of the fundamental fermions. For instance, if both quarks and leptons are composites of the same set of fundamental fermions, their charge quantization must clearly be related. The peculiar relation between electric charge and color may simply emerge from the color and charge of the fermions. The restrictions on |Q| may be related to the number of constituents within a composite quark or lepton, in the same way that the limitations on the strangeness or isospin of hadrons follow from the number of valence quarks in a hadron.

(iii) The different generations may be excitations of a composite system, similar to excited atoms, nuclei or hadrons. The type of excitation in each case must be different, however.

(iv) The scalar particles, as well as the quarks and leptons, are presumably composites of the new fundamental fermions. Hopefully, no fundamental scalar particles are necessary. The fundamental fermions may be massless or may have explicit mass terms, but need not gain masses through symmetry breaking. The problem of fine tuning may thus be avoided.

(v) Other features are left open. Color, Electromagnetism and the weak interactions may all exist in the underlying theory.

Alternatively, one or more of these interactions may turn out to be a residual force, appearing only in L_{EFF}. Additional color-like or other types of forces may be needed in order to bind the new fermions inside the quarks and leptons. The underlying theory may be left-right symmetric, with Parity being spontaneously broken at the composite level. Alternatively, the fundamental theory may already include explicit parity violation.

It is not at all clear that a composite model with all the above desired features can be constructed, but it is certainly worth exploring. So far no one has come close.

Among the various problems which face model builders, we choose to discuss four in some detail:

(a) The problem of scales. Quark and lepton masses are much smaller than any possible compositeness scale. This is the most difficult problem for all composite models, and it has several interesting aspects, which we discuss in section 8.

(b) The generation puzzle. If quarks and leptons are composite, what kind of quantum number distinguishes among generations and what kind of excitation can yield a higher-generation quark or lepton? We discuss this issue in section 9.

(c) Structure within one Generation. Can we select a simple set of fundamental constituents, such that the entire pattern within one generation will be fully accounted for in a natural way? We propose an answer in section 10.

(d) Possible Compositeness of Gauge Bosons. In addition to the quarks, leptons and scalar Higgs particles some of the gauge bosons of the standard model may be composite. If they are, the corresponding interactions become residual and do not appear in the fundamental high-energy Lagrangian. Among the various gauge bosons, the most likely candidates for compositeness are the W and Z bosons. We discuss their possible composite nature in section 11.

8. The Problem of Energy Scales

We have already explained why composite quarks and leptons must be approximately massless with respect to their compositeness scale Λ_H. Such masslessness must emerge from a symmetry principle. The simplest symmetry which may prevent a fermion from acquiring a mass is a chiral symmetry[13]. We may therefore wish to look for a composite model with a chiral symmetry.

The chiral symmetry is essentially automatic if the fundamental fermions appearing in L_{NEW} are massless. However, the existence of a chiral symmetry in the fundamental Langrangian does not necessarily guarantee its preservation at the composite level. The chiral symmetry may be broken spontaneously, leaving no reason for massless fermions at the composite level.

Thus the necessary logical sequence of assumptions is as follows:

(i) The fundamental Lagrangian contains massless fermions and therefore possesses a chiral symmetry.

(ii) The full chiral symmetry or, at least, a chiral subsymmetry remains unbroken at the composite level.

(iii) The chiral symmetry of the effective Langragian containing the composite fermions, prevents the latter from gaining a mass. We have composite massless fermions.

Three questions imediately arise:

(a) If the new fundamental fermions are massless, why don't we observe them?

(b) What is the interaction which binds the fundamental fermions inside the composite quarks and leptons?

(c) If both fundamental and composite fermions are massless, what provides us with the necessary "compositeness scale" Λ_H?

All three questions can be immediately answered by one postulate[13], if we assume a new color-like force ("hypercolor") with a scale parameter Λ_H. All fundamental fermions carry hypercolor. They are confined by hypercolor forces of characteristic scale Λ_H into hypercolor-singlet composite fermions with an effective radius $r \sim \Lambda_H^{-1}$. The confined fundamental fermions cannot be experimentally observed. The binding and the scale are provided by the hypercolor gauge force.

The above scenario is an attractive framework for the construction of a composite model. However, it is crucial that the chiral symmetry or at least a chiral subgroup must remain unbroken at the composite level. This is not apriori impossible but it differs from the observed pattern of chiral symmetry breaking in QCD. No composite massless fermions emerge in QCD. The hypercolor situation must, for some reason, be different!

We now face a dilemma which stems from the following statements:

(i) We believe that in two-flavor massless QCD, the chiral symmetry is <u>completely broken</u>. No chiral subgroup remains intact.

(ii) If we neglect all interactions except hypercolor (all other interactions are probably much weaker at the Λ_H-scale), a hypercolor model with K fundamental massless fermions is <u>isomorphic</u> to K-flavor massless QCD.

(iii) In order to have massless composite fermions, some chiral symmetry should remain <u>unbroken</u> in the hypercolor case.

(iv) In no case do we have a <u>full dynamical understanding</u> of chiral symmetry and its breaking.

It is hard to reconcile statements (i), (ii), (iii), but no negative proof can be given. What are the logical possibilities?

(a) A resonable attitude, advocated by some theorists, is simply to declare that (i), (ii) and (iii) are inconsistent. In that case one should not continue to pursue our discussion beyond this point and the hypercolor idea should be abandoned. Perhaps this is true. Perhaps not.

(b) One way out is to consider a composite model in which left- and right-handed fermions have different transformation properties under the gauge group. Such a model is not isomorphic to QCD and statement (ii) does not apply to it. In such a model an $\bar{f}f$ condensate cannot break the chiral symmetry without breaking the original gauge symmetry. Two options are open: Either there is no condensation or the gauge symmetry breaks itself into a smaller subgroup. The first possibility has been studied by various authors and no realistic model was found. The second possibility is the interesting "tumbling" approach[14]. Here, again, no realistic model was found. However, the left-right symmetric classification may still be the correct solution.

(c) It is possible that the pattern of chiral symmetry-breaking depends on the number of flavors K. This could happen at least in two ways. There may be a phase transition at some K-value, K>3, leading to a different pattern for QCD and for a hypercolor theory with K>3 flavors of fundamental fermions. It is also possible that the general $SU(K)_L \times SU(K)_R$ chiral symmetry always breaks, leaving a small conserved chiral subgroup which is trivial for K=2 but is nontrivial for large K. An example could be a discrete Z_K chiral group. A chiral Z_2 cannot protect any fermion from acquiring a mass. A chiral Z_4 or Z_6 can do it. There is no dynamical reason to expect any of these speculations to be true, but there are no complete arguments against them.

(d) Another possible speculation is that the presence of the color or electroweak interactions somehow influences the pattern of chiral symmetry breaking in a hypercolor scheme. This is the most obvious difference betweeen the hypercolor case and QCD. The simplest attitude would be to treat color and electroweak interactions as minor perturbations which cannot substantially change anything. However, subtle effects may occur. For instance, imagine a situation in which the chiral symmetry can break via $\bar{f}f$ or $\bar{f}f\bar{f}f$ condensates, the potential having two similar minima. A small perturbation could conceivably change the balance between the two minima, making the $\bar{f}f\bar{f}f$ condensate the likely one. At this point we may also add that the usual $N_c \to \infty$ argument for the breaking of chiral symmetry in QCD[15] does not necessarily remain valid if N_c/N_f is held fixed. In some composite models, such a fixed ratio may be a necessary requirement.

The above discussion can be summarized very simply: One can speculate about scenarios which provide the required pattern of chiral symmetry breaking for a composite model. All such scenarios are not supported by any decent dynamical arguments, but they cannot be ruled out.

Even if we succeed in producing a composite model with a chiral symmetry which is not completely broken, we still have to worry about the anomaly-matching condition[13], to which we now turn.

Let us assume that we have constructed a composite model of quarks and leptons based on an $SU(N)_H$ hypercolor gauge group and containing K fundamental massless fermions, all assigned to the N-dimensional representation of $SU(N)_H$. The underlying Lagrangian automatically possesses a global $SU(K)_L \times SU(K)_R \times U(1)$ symmetry. The U(1) factor is a vector charge counting the number of fermions. An additional axial U(1) factor is broken by instanton terms .

The model contains "flavor" triangle anomalies corresponding to products of three SU(K) currents or to products of two SU(K) currents and the U(1) current. Such anomalies are perfectly legitimate, since the $SU(K)_L \times SU(K)_R \times U(1)$ symmetry is not gauged. However, in the zero momentum limit, a given anomalous term can be exactly calculated both from the underlying theory and from the low-energy effective theory containing trhe composite particles. The results must be the same, thus imposing a severe constraint on the spectrum of composite particles.

If, in the underlying level, the anomaly does not vanish, the theory must produce massless composite particles[13)16)]. We may consider three logical possibilities:

(i) The chiral symmetry is not broken at all. There are composite massless fermions. Their contribution to each anomaly must be exactly equal to that of the fundamental massless fermions. Thus a severe constraint is imposed, connecting the fundamental fermions to the composite fermions. This is the famous 't Hooft condition[13)].

(ii) The chiral symmetry is completely broken. No chiral subsymmetry remains. The only massless composite particles are Goldstone bosons. Their contribution to the anomaly is equal to that of the fundamental fermions. However, since the Goldstone bosons have unknown couplings, the anomaly constraint can only be used in order to compute these couplings, leading to equations similar to the Goldberger-Trieman relations.

(iii) The chiral symmetry is broken, but a chiral subgroup remains conserved. The chiral subgroup may be continuous or discrete. In this case, massless Goldstone bosons must exist but massless fermions may also exist. The combined contributions of the massless composite bosons and fermions must balance the anomaly of the underlying theory.

The anomaly constraint is particularly powerful in case (i). It is not very useful in case (ii), but we are interested in massless composite fermions, and they do not occur in that case. Case (iii) allows composite massless fermions, and the anomaly constraint is somewhat less powerful.

We suspect that case (iii) is the most likely candidate for a realistic composite model. In particular, we may consider the interesting possibility of a continuous chiral symmetry in the original Lagrangian, broken into a discrete chiral symmetry at the composite level. Such situations arise naturally in simple unrealistic "toy" models[17].

In case (iii) the massless composite fermions are accompanied by massless Goldstone bosons. Such bosons appear in a wide variety of composite models. They may escape detection because their Yukawa couplings to quarks and leptons are of order m_q/Λ_H and m_ℓ/Λ_H, respectively. We have mentioned the resulting experimental constraint in section 7.

We have gone here through an elaborate maze of difficulties, all stemming from the fundamental mismatch between the compositeness scale Λ_H and the masses of the composite objects. If the chiral symmetry hypothesis, together with a new hypercolor force, will not solve the problem, what other options do we have? The most likely possibility is some new fundamental force with some new features, not resembling any of the known interactions. Various ideas in that direction have been considered, including magnetic monopoles [18], dimensional compactification[19], nonlocal theories[20], and quarks and leptons as massless supersymmetric Goldstone fermions[21]. It is difficult to believe that the correct theory can be found without some experimental hints.

9. The Generation Puzzle

The existence of quark and lepton generations is, perhaps, the most striking experimental fact which guides us beyond the standard model. Let us first discuss the general problem, then turn to the possible description of generations within composite models of quarks and leptons.

We have three identical generations of quarks and leptons. The standard model does not contain any quantum number which distinguishes among the generations. Yet, we suspect that such a quantum number must exist. Three classes of solutions have been considered for a generation-labelling quantum number. In all cases we are looking for a symmetry which is already spontaneously broken at the stage of creating the fermion masses. The existence of Cabibbo mixing tells us that any "generation number" cannot remain exactly conserved.

The three possibilities are:

(i) A discrete generation label. A discrete symmetry is introduced, such that each generation obtains a different eingenvalue under the symmetry operation. It is necessary that, say, e, μ and τ have different eingenvalues. It is not necessary that e and u have the same eingenvalues, although it would be more elegant if they do. The scalar particles must have well-defined transformation properties under the discrete symmetry and the allowed Yukawa couplings are severely restricted by the symmetry. The mass matrix for analogous states in different generations contains matrix elements contibuted by different scalar fields. If scalar fields with a non-vanishing generation number obtain vacuum expectation values, the discrete symmetry is broken and Cabibbo mixing is introduced. There is no real theoretical difficulty in describing the generations using a discrete symmetry. The only drawback of such an approach is the fact that all such discrete symmetries appear completely arbitrary and artificial.

(ii) A Continuous Global Symmetry. A variation on the same theme would be a continuous global symmetry under which each generation obtains a different eingenvalue. Here we face a serious difficulty: If the continuous symmetry is spontansously broken, an unwanted Goldstone boson appears. Here, again, the ad hoc nature of the symmetry is usually unattractive.

(iii) A Gauged Generation Label. A third possibility which avoids the dangerous Goldstone boson is to consider an extra "horizontal" gauge group under which different generations form a gauge multiplet. The simplest example is a U(1) gauge symmetry but larger groups can be considered. The complications are: A severe anomaly constraint; the existence of a new gauge boson (or bosons); the danger of flavor changing neutral currents associated with "horizontal" gauge bosons.

Of the three possibilities, the discrete one is the only one which leads to no great difficulties. If we could find a discrete symmetry which is "natural" in the sense that its existence is caused or guaranteed by some other feature of the overall theory, it would be a likely candidate for a generation labeling scheme.

Another important property of a generation-labeling quantum number is its space-time nature.

Let us consider an operator under which e^o, μ^o and τ^o possess the quantum numbers X_e, X_μ, X_τ. Here e^o is a massless electron appearing in the standard model Lagrangian. If the symmetry is vectorial, $X(e_L)=X(e_R)$ etc. If it is axial, $X(e_L)=-X(e_R)$ etc. In the first case a scalar field with X=0 can induce diagonal mass terms for e, μ and τ.

The necessary X-values for scalar fields which contribute to mass-matrix elements are:

$$\begin{pmatrix} 0 & X_e-X_\mu & X_e-X_\tau \\ X_\mu-X_e & 0 & X_\mu-X_\tau \\ X_\tau-X_e & X_\tau-X_\mu & 0 \end{pmatrix}$$

On the other hand, if X is an axial quantum number, the three diagonal mass-matrix elements must be contributed by three different scalar fields.

The necessary values are:

$$\begin{pmatrix} 2X_e & X_e+X_\mu & X_e+X_\tau \\ X_e+X_\mu & 2X_\mu & X_\mu+X_\tau \\ X_e+X_\tau & X_\mu+X_\tau & 2X_\tau \end{pmatrix}$$

In view of the different scales of the masses of different generations, we believe that the axial option is preferable[22]. In grand unified theories such as O(10) only axial quantum numbers are possible, since e^-_L and e^+_L belong to the same multiplet and must have the same eigenvalue for a given generation-labeling operator. Consequently, e^-_L and e^-_R must have opposite eigenvalues.

We conclude that, on quite general grounds, an attractive generation- labeling symmetry would be an axial discrete symmetry, provided that it is not artificially concocted. In composite models we do not have an arbitrary freedom for inventing such symmetries. The fundamental Lagrangian in such models is fully specified and all symmetries at the composite level must follow in one way or another from the properties of the theory.

Corresponding quarks and leptons in different generations must have the same $SU(3)_c xSU(2)xU(1)$ quantum numbers. They differ by some "generation number". All generations are approximately massless in comparison with the compositeness scale. Hence, they cannot be obtained by radial or orbital excitations of the first-generation "ground state". A possible excitation of a composite massless fermion which may lead to a different composite massless fermion is an excitation by one or more pairs of fermionic constituents. In a given composite model we should therefore investigate the possibility of constructing a system of preons and antipreons forming a scalar under the Lorentz group as well as under $SU(3)_c xSU(2)xU(1)$, but possessing a nonvanishing value of some "generation number". Such a system could be the difference between corresponding composite fermions in different generations.

An interesting possibility[23]: In hypercolor composite models with K massless constituent fermions, we have a global

$SU(K)_L x SU(K)_R x U(1)$ symmetry. An additional axial U(1) factor is broken. However, a discrete axial Z_{2K} symmetry always remain unbroken. Such a symmetry may serve as an adequate candidate for a generation number. It is an axial, discrete symmetry and it is not artificial at all. It exists in the theory, "waiting" to be used.

10. Structure Within One Generation

Each generation of quarks and leptons contains eight types of states. We list them in table 1, arranged in descending order of

	Color	Q	B-L
e^+	1	1	1
u	3	$\frac{2}{3}$	$\frac{1}{3}$
$\bar{d}$	$\bar{3}$	$\frac{1}{3}$	$-\frac{1}{3}$
ν_e	1	0	-1
$\bar{\nu}_e$	1	0	1
d	3	$-\frac{1}{3}$	$\frac{1}{3}$
$\bar{u}$	$\bar{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$
e^-	1	-1	-1

Table 1: Fermions and antifermions of the first generation

their electric charges.

An inspection of the table reveals a few features which cannot be explained within the standard model:

(i) The electric charges of the quarks and the leptons are quantized in a related way. Thus $Q(u)=\frac{2}{3}Q(e^+)$ and the hydrogen atom is exactly neutral. This is not at all guarranteed if the SU(2) and U(1) gauge interactions are unrelated.

(ii) The sum of the electric charges of all fermions vanishes. This is the famous condition for the vanishing of the triangle anomaly in SU(2)xU(1). It is the only ingredient of the standard model which explicitly connects quarks and leptons and which tells us that a model with quarks and no leptons (or vice versa) is not renormalizable. A fermion (antifermion) is defined as a left-handed doublet (singlet) of the SU(2) gauge group in the standard model.

(iii) There are certain color-charge combinations which exist (and repeat themselves in higher generations). Other combinations do not exist. We have surprising correlations. For instance, 3Q (mod 3) is identical to the color triality, although no relation between charge and color is implied by the standard model.

(iv) The electric charge is limited by $|Q|\leqslant 1$.

The above regularities cannot be accidental. They must be explained by some theoretical structure which goes beyond the standard model, either by embedding the three different gauge groups in a larger simple group or by constructing all quarks and leptons from more fundamental constituents.

In a grand unified O(10) theory all of these regularities are beautifully accounted for by the structure of the group and its 16-dimensional spinor representation. The related charge quantization of quarks and leptons is guaranteed by the relationship between the SU(2) and U(1) couplings. The absence of anomalies is automatic in O(10). The color-charge correlations are dictated by the specific way in which $SU(3)_c \times U(1)_{EM}$ is embedded in O(10). The $|Q| \leq 1$ limitation is a property of the 16-dimensional multiplet. In a SU(5) grand-unified theory all of these features are also explained.

In a composite model one would hope to explain the pattern within one generation by a set of simple rules based on the properties of the fundamental fermions. Such rules should presumably be analogous to the quark model rules which neatly explain the repeated appearance of decuplets, octets and singlets of the flavor-SU(3), with no other representation appearing.

A particularly satisfactory explanation of all features of one generation is given in the rishon model[24], based on a hypercolor SU(3)-group. There we postulate two types of fermions: The T-rishon in a $(3,3)_{1/3}$ of $SU(3)_H \times SU(3)_c \times U(1)_{EM}$ and the V-rishon in a $(3,\bar{3})_0$. The structure of one generation is given by the hypercolor-singlet lowest-color states of three rishons and three antirishons. These states are listed in Table 2.

All four features which we mentioned at the beginning of this section, can be neatly explained in such a model:

(i) All electric charges are due to the T-rishon or $\bar{T}$-antirishon. Hence, quark and lepton charges obey simple ratios. A Hydrogen atom contains $e+u+u+d \equiv 4T+4\bar{T}+2V+2\bar{V}$. Its neutrality is trivially understood.

(ii) The quarks and leptons in one generation are $3(u+d)+e+\nu_e \equiv 6(\bar{T}+T+\bar{V}+V)$ Hence, their sum of electric charges (or any other additive quantum number) vanishes, and the standard-model anomaly cancellation is simply understood.

	Color	Q	B-L	Rishon Combination
e^+	1	1	1	TTT
u	3	$\frac{2}{3}$	$\frac{1}{3}$	TTV
$\bar{d}$	$\bar{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	TVV
ν_e	1	0	-1	VVV
$\bar{\nu}_e$	1	0	1	$\bar{V}\bar{V}\bar{V}$
d	3	$-\frac{1}{3}$	$\frac{1}{3}$	$\bar{T}\bar{V}\bar{V}$
$\bar{u}$	$\bar{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$\bar{T}\bar{T}\bar{V}$
e^-	1	-1	-1	$\bar{T}\bar{T}\bar{T}$

Table 2: Rishon model assignments of first generation fermions and antifermions.

(iii) The color-charge correlation is automatic. Replacing a T by a V corresponds to $\Delta Q=-\frac{1}{3}$, Δ(triality)=-1. Hence, the equality between 3Q(mod 3) and the color triality.

(iv) All quarks and leptons are three-rishon states, all combinations appear and the fundamental charge is $\frac{1}{3}$. Hence, the observed electric charges must correspond to all integer multiples of Q ranging between Q=+1 and Q=-1. |Q|>1 values cannot be obtained from three rishons or antirishons.

The rishon model, like all other composite models, suffers from several difficulties which we have discussed in detail elsewhere[24]. Its success in accounting for the structure within one generation is, however, impressive.

11. Composite Weak Bosons and Residual Weak Interaction

In composite models of quarks and leptons we usually face at least four types of gauge bosons: Hypergluons, gluons, photon, and weak bosons.

Which of these bosons must be elementary? Can some of them be composite?

There is a certain confusion in discussing the possibility of composite gauge bosons. There are theories in which a certain fermion-antifermion pair of fields may appear to have some or all of the properties of a gauge boson. In some sense this is a composite gauge boson, but it appears in the same fundamental Lagrangian with the fermion fields and all other fields of the theory. Such a possibility is very interesting and some toy-models incorporating it have been constructed.

A different concept of a composite gauge boson is this: It does not appear at all in the fundamental Lagrangian of the theory (in the same way that other composite objects do not appear there). It does appear in the low-energy effective Lagrangian together with all other composite particles. Here we would like to study whether some of the gauge bosons may appear as composites in this sense.

In a hypercolor composite model, the hypergluon must clearly appear as a fundamental massless gauge field in the underlying Lagrangian. It will not appear at all in the low-energy Lagrangian. What about the gluon, photon and weak bosons? Consider first the massless gauge bosons (gluon and photon). If an exactly massless gauge boson appears in the low-energy effective Lagrangian, the

Lagrangian must be exactly gauge invariant under the corresponding gauge group. This gauge invariance cannot be broken by higher dimension terms which are proportional to Λ_H^{-N}(N positive). If no small corrections of any kind are allowed to break the exact gauge invariance of the effective Lagrangian, it is essentially unavoidable that the original underlying Lagrangian also possesses the same local gauge symmetry. But in that case, it would probably contain the corresponding massless gauge bosons as fundamental fields. We therefore suspect that the gluon and the photon are not composite. They have the same status as the hypergluon in the underlying Lagrangian which must now be gauge invariant at least under $SU(N)_H \times SU(3)_c \times U(1)_{EM}$.

The above argument does not necessarily apply to the massive W and Z weak bosons. The weak gauge symmetry of the effective Lagrangian could be an approximate symmetry, broken by higher dimension terms which vanish as $\Lambda_H \to \infty$. It is conceivable that this approximate gauge symmetry is not fully present at the underlying level. In fact, the longitudinal components of W and Z are "born" from the scalar fields which are probably formed as condensates of the fundamental fermions. In some sense, at least the longitudinal W and Z must be composite in such a scheme.

The possibility of composite W and Z which do not appear in the underlying Lagrangian is extremely interesting. It leads to exciting consequences but also to serious difficulties.

Let us consider a process such as neutrino-neutrino scattering, in a model in which neutrinos are composite. The neutrino carries no hypercolor, color or electric charge. However, it must contain objects which possess at least hypercolor, possibly even color. At short distances of order Λ_H^{-1}, the two scattered neutrinos must experience a short range residual hypercolor force. Even if the nature of the binding force of the constituents is different, and even if it is not a color-like interaction, we still expect a short-range residual interaction between two composite neutrions. One way of parametrizing this short-range force, is in terms of the exchange of the lightest bosonic bound states of the same fundamental constituents. If W and Z are such composite states, their exchange may control the longest-distance component of the residual short-range force. In that case, the conventional weak interactions are identified as a residual effect[25)] of the original hypercolor force (or any other fundamental binding force inside the neutrino). The weak interaction are then eliminated from the list of fundamental interactions in the same way that hadronic interactions are residual color forces.

If the photon is fundamental but W and Z are composite, how do we understand the "unified" electroweak theory of the standard model? In the standard model, the electromagnetic and weak interactions are not fully unified. Their relative strength remains an arbitrary parameter, related to $\sin^2\theta_W$. The standard model provides us with a clear mechanism for γ-Z^o mixing which could be somewhat analogous to the γ-ρ^o, γ-ω^o and γ-ϕ^o mixing of the old "vector dominance" idea. A major difference between the two situations stems from the different order of magnitude of the ρ^o and the Z^o direct couplings.

Experimentally, $g_{\gamma\rho}^2 \sim 1/300$ while $g_{\gamma Z}^2 \sim 1/4$. How can we explain such a difference?

Many authors have discussed this issue during the last year[26]. Their consensus in that there is no difficulty in obtaining a $g_{\gamma Z}$ of the correct order of magnitude, provided that the spacing between Z^0 and any higher composite boson is of the order of a TeV or so. That sets another bound or the compositeness scale Λ_H , for the case of a composite Z .

In fact, we may consider two extreme possibilities in theories with composite W and Z bosons:

(i) The compositeness energy scale is relatively low, say, between 1 TeV and 10 TeV. In such a case we may hope to observe experimental deviations from the standard model predictions for the properties of W and Z. Such a deviation could be seen in the W/Z mass ratio, W magnetic moment, small violations of universality etc. For $\Lambda_H \sim 1$ TeV, the effects could probably be detected within the next decade (but the model should cope with all the constraints of figure 1, a highly nontrivial requirement!)

(ii) The compositeness scale is $\Lambda_H \gg M_W$ (say, above 100 TeV). In such a case L_{EFF} should be extremely close to L_{SM} and no experimental effects can be observed in the near future. In that case, however, we must face a new puzzle: If $\Lambda_H \gg M_W$, what symmetry principle protects M_W and M_Z from obtaining higher order mass corrections which would lift them up to the order of magnitude of Λ_H? So far no one has proposed a convincing reason for a small mass of a composite W or Z boson. In the absence of such a reason, the possibility $\Lambda_H \gg M_W$ appears to be unlikely.

Needless to say, there is a continuum of possible Λ_H-values. The lower Λ_H is, the sooner we can detect deviations from the standard model . For smaller Λ_H it is easier to understand the value of M_W but it is more difficult to construct a model which survives all the tests of figure 1.

We therefore conclude that the possibility of composite W and Z bosons is interesting, but serious difficulties exist, especially for large Λ_H-values.

12. Summary and Outlook

We conclude with four statements:

(i) At present, there is no experimental evidence for quark or lepton compositeness. Both high energy and low energy experiments should continue to search for such evidence. Experimentalists should probably ignore specific theoretical composite models and concentrate on pushing the various experimental limits until some new effects are discovered.

(ii) There is strong circumstantial evidence for the compositeness of quarks and leptons. In view of the lack of experimental clues, it is perhaps too early to demand a serious self-consistent theoretical model.

(iii) There is no satisfactory theoretical model of composite quarks and leptons. However, the models proposed so far contain many interesting new ideas. Each of these ideas should be investigated on its own merit, regardless of the detailed model which may have led to it. Several correct ingredients of the correct theory may already be with us now.

(iv) *We have hardly began to investigate the subject of compositeness.* It is almost unavoidable that the next decade or two will bring new experiments, new theoretical ideas as well as new difficulties for quark and lepton compositeness. The subject will certainly stay with us for a long time. It is not at all clear whether by the end of the century (and the millenium) we will know whether the electron is composite.

Acknowledgement

I would like to thank Nathan Seiberg for a long and fruitful collaboration and for many helpful discussions.

References

1. See e.g. H.Harari, Proceedings of the Jerusalem Einstein Symposium, 1979.
2. S.Weinberg, Phys. Rev. D19,1272(1979); L.Susskind, Phys. Rev.D20,2619(1979).
3. For a review see e.g. E.Farhi and L.Susskind, Phys. Reports, 74C,277(1981).
4. H.Georgi and S.L.Glashow, Phys. Rev. Letters, 32,438(1974); J.C.Pati and A.Salam, Phys. Rev. D8,1240(1973); D10,275(1974).
5. See e.g. E.Farhi and L.Susskind, Phys. Rev. D20,3404(1979).
6. For a review see e.g. B.Zumino, to be published in Proceedings of the 1982 Solvay Conference, Austin, Texas, Nov. 1982.
7. G.L.Shaw, D.Silverman and R.Slansky, Phys. Letters 94B,57(1980); S.J.Brodsky and S.D.Drell, Phys. Rev. D22,2236(1980).

8. E.Eichten, private communication.

9. See e.g. H.Harari and N.Seiberg, Nuclear Phys. B204,141(1982).

10. See e.g. D.A.Dicus, E.W.Kolb, V.L.Teplitz and R.V.Wagoner, Phys. Rev. D18,1829(1978).

11. H.Harari, R.N.Mohapatra and N.Seiberg, Nuclear Phys. (in print).

12. J.C.Pati and A.Salam, Phys. Rev. D10, 275(1974).

13. G.'tHooft, Proceedings of the Cargese Summer Institute, 1979.

14. S.Raby, S.Dimopoulos and L.Susskind, Nuclear Phys. B173, 208(1980).

15. See e.g. S.Coleman and E.Witten, Phys. Rev. Letters 45,100(1980).

16. Y.Frishman, A.Schwimmer, T.Banks and S.Yankielowicz, Nuclear Phys. B177,157(1981).

17. H.Harari and N.Seiberg, Phys. Letters 115B,450(1982).

18. J.C.Pati, Phys. Letters, 98B,40(1981).

19. See e.g. E.Witten, to be published in Proceedings of the Banff Summer Institute, Banff, Alberta, Canada, August 1981.

20. See e.g. S.L.Adler, Phys. Rev. D21,2903(1980).

21. See e.g. W.A.Bardeen and V.Visnjic, Fermilab-Pub 81/49-THY, 1981.

22. See e.g. A.Davidson and K.C.Wali, Phys. Rev. Letters 25, 691(1981).

23. H.Harari and N.Seiberg, Phys. Letters 102B,263(1981).

24. H.Harari and N.Seiberg, Phys. Letters 98B,269(1981); Nuclear Phys. B204,141(1982).

25. H.Harari and N.Seiberg, ref.24; O.W.Greenberg and J.Sucher, Phys. Letters 99B,339(1981).

26. See e.g. J.J.Sakurai, Munich preprint MPI-PAE/TH 22/82; P.Chen and J.J.Sakurai, Phys. Letters 110B,481(1982); R.Barbieri and R.N.Mohapatra, CCNY - HEP - 82/14; H.Fritzsch and G.Mandelbaum, Phys. Letters 109B, 224 (1982); M.Kuroda and D.Schildknecht, CERN preprint, TH-3395; H.Fritzsch, D.Schildknecht and R.Kogerler, CERN preprint TH-3264.