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TOWARDS A PURE GAUGE ORIGIN OF THE FUNDAMENTAL FORCES: UNITY THROUGH PREONS[1]

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Abstract

The recent success of the conventional approach to grand unification as regards the meeting of the coupling constants is summarized. Its shortcomings as regards the arbitrariness in the Higgs sector are noted and a case is made for an alternative approach to grand unification based on a purely gauge origin of the fundamental forces. Within such an approach, the Higgs sector arises only effectively at a composite level. Bearing in mind the difficulties of technicolor, it is suggested that the idea of a composite Higgs is best realized by combining the notion of local supersymmetry with that of preons, which proposes that Higgs bosons are composite, but so also are quarks and leptons.

The familiar hurdles of composite models posed by (a) the smallness of the masses of the quarks and the leptons compared to their inverse sizes and (b) the inter-family mass-hierarchy are noted. Recent works showing mechanisms which help overcome these hurdles, by utilizing certain pecularities in the dynamics of massless SUSY gauge theories, are also presented.

The advantages of a recently developed preonic approach based on these results are discussed. These include economy and viability as well as an understanding of the origins of (i) diverse mass-scales, (ii) family-replication and (iii) inter-family mass-hierarchy. The model naturally yields results such as $m_W \sim m_t \sim 100$ GeV, while $m_e \leq 1$ MeV. In short, it provides a reason for the large hierarchies $(m_e/m_t) \sim 10^{-5}$ as well as $(m_W/M_{Pl}) \sim 10^{-17}$.

Experimental predictions of the model, are listed. One *crucial prediction*, tied to an understanding of the origin of masses of quarks and leptons, is that there must exist two complete vector-like families with masses of order 1 TeV. These can not, of course, be probed unless facilities like the SSC and/or the LHC are built. The model also predicts certain flavor-changing processes with observable strengths such as $t \to Zc$, $D - \overline{D}$ mixing, non-universality in tau-decay, a *correlated* small departure from 3 in neutrino-counting at LEP, and prominent $\nu_\mu - \nu_\tau$ oscillations.

Finally, a recent work exhibiting that the unity of forces may well occur at the level of preons is presented and a comparison is drawn between the conventional and the preonic approaches to grand unification.

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leptons and simultaneously for their hypercharge assignments, such that the charges of the electron and the proton are equal and opposite.

It should also provide a relationship between the weak, the electromagnetic and the strong forces, as though they are aspects of one unified force.

The $SU(2)_L \times U(1)_Y$-theory possesses much arbitrariness in the Higgs sector as well. This includes the choice of the Higgs mass, the Higgs quartic coupling and the widely-varying Yukawa couplings which determine the fermion masses and mixings. Altogether the SM possesses some ***nineteen arbitrary parameters*** comprising the three gauge couplings (g_1, g_2, g_3), the nine fermion masses $(m_e, m_d, m_u, m_\mu, m_s, m_c, m_\tau, m_b$ and $m_t)$, the two masses m_W and m_ϕ, the three CKM angles $\theta_{1,2,3}$, the CP phase δ and the angle $\overline{\theta} = \theta_{QCD} - \theta_{WEAK}$ associated with strong CP violation. The Yukawa couplings vary widely by as much as the ratio $(m_e/m_t) \approx 10^{-5}$.

Believing that a fundamental theory must be devoid of such arbitrariness, one is led to believe that there must exist new physics beyond the standard model which would serve to remove these shortcomings. I list below a few suggestions which have been made in this regard and which seem promising in removing at least some (and possibly all) of these drawbacks.

(1) Grand Unification: The idea of grand unification proposes that quarks and leptons are members of one family and that the weak, the electromagnetic and the strong forces are components of just one force, which is generated by gauging the symmetry group of this family[3, 4, 5]. The differences which one sees between quarks and leptons and between the three forces are then viewed as low-energy phenomena, brought about by spontaneous breaking of the grand unification symmetry. Since gauge interactions are universal, this idea succeeds in removing fully the arbitrariness of the SM in the gauge sector. *Thus, one is inclined to believe that the central idea of grand unification might well be a step in the right direction.* But, by itself, it does not remove the arbitrariness in the Higgs sector. Furthermore, it does not account for the origins of the three families and of the large hierarchies in the mass scales reflected by the small numbers such as $(m_W/M_U) \simeq 10^{-14\pm1}$ and $(m_W/M_{p\ell}) \simeq 10^{-17}$, where M_U and $M_{P\ell}$ denote the grand unification and the Planck-scales respectively. This last puzzle pertaining to mass-hierarchies includes the so-called gauge hierarchy problem.

(2) Supersymmetry: This is the idea that there exists an underlying symmetry which relates fermions and bosons[6]. As a local symmetry, it implies the existence of gravity, and is thus expected to be relevant in the unification of gravity with the other forces. Supersymmetry has the additional virtue that it removes quadratic divergences in self energies of bosons and thereby helps maintain a large hierarchy in mass-ratios such as $(m_\phi/M_U) \sim 10^{-14}$ and $(m_\phi/M_{p\ell}) \sim 10^{-17}$, without the need for fine tuning, provided, however, such ratios are put in by hand. Thus it provides a technical resolution of the gauge hierarchy problem. *But by itself, it does not explain*

the origin of the large hierarchies, nor does it help to reduce the parameters of the SM.

(3) Compositeness: There are *two inherently distinct suggestions* as regards compositeness of at least some of the particles of the SM.

First, there is the idea of technicolor[7], which proposes that the Higgs bosons are composite but quarks, leptons and techniquarks are elementary. This idea is excluded, at least in its simpler versions, owing to constraints from the flavor changing neutral current processes as well as oblique corrections represented by the S and T parameters[8].

On the other hand, the *idea* of preonic compositeness that not just the Higgs bosons but also the quarks and the leptons are composites of a common set of constituents called "Preons" has evolved in the last few years into a form[9, 10, 11] which is not only economical in its field content and parameters but also is viable. Most important, combined with the idea of local supersymmetry, it provides simple explanations for the origins of family-replication, inter-family hierarchy and diverse mass scales.

(4) Superstrings: Last but not least, the idea of superstrings[12] proposes that the elementary entities are not truly pointlike but are extended stringlike objects with sizes $\sim (M_{Planck})^{-1} \sim 10^{-33}$ cm. This idea appears to be most promising in providing a unified theory of all the forces of nature including gravity and yielding a well-behaved quantum theory of gravity. In principle, a suitable superstring theory could also account for the origin of the three families and for all the parameters of the SM. But in practice, this has not happened. Some of the stumbling blocks are associated with the problems of a (i) choice of the ground state (the vacuum) from among the many solutions and (ii) supersymmetry breaking.

The ideas listed above are, of course, not mutually exclusive. In fact the superstring theories already comprise local supersymmetry and the central idea of grand unification. It remains to be seen whether they give rise, in accord with the standard belief, to elementary quarks and leptons, or alternatively to a set of substructure fields – the preons, contrary to common belief. I will return to these two alternative possibilities in discussing the future perspective. First I recall the status of conventional grand unification, which regards quarks, leptons and Higgs bosons as elementary.

2 Alternative Routes to Grand Unification

What Can Neutrinos tell us about Embedding? The SM symmetry $SU(2)_L \times U(1)_Y \times SU(3)^C$ may be embedded in $SU(5)$ with members of a family assigned to $\overline{5} + 10$[4]. If $SU(5)$ is fundamental (rather than descending from $SO(10)$), there

would be no compelling reason for the existence of ν_R and, therefore, no strong reason why neutrinos should be massive. With only ν_L's and Higgs doublets ϕ, higher dimensional operators of the form $\nu_L\nu_L < \phi >< \phi > /M$which violate lepton number by two units, can still give rise to a Majorana mass to ν_L[13]. If these operators are induced by Planck scale physics, one might expect that $M \sim M_{P\ell}$. This would lead to $m(\nu_L) \sim 10^{-5}$ eV, which could be relevant to the solar neutrino puzzle through the vacuum-oscillation idea, but is too small to be relevant to the MSW solution for the solar neutrino puzzle which requires $\Delta m^2 \equiv |m^2_{\nu_e} - m^2_{\nu_{\mu,\tau,s}}| \approx (3-10) \times 10^{-6}$ eV^2 and a mixing angle $\sin^2 2\theta \approx 10^{-2}$[14]. Choosing $M \sim 10^{16}$ to 10^{17} GeV (for reasons that are unclear), one may get $m(\nu_L) \sim 10^{-3}$ eV, but getting $(\nu_e - \nu_\mu)$ or $(\nu_e - \nu_\tau)$ masses and mixings in accord with the MSW solution for either choice of M will need unexplained fine tuning in the choice of parameters. In short, if the MSW solution for the solar neutrino problem is established, it seems that that would at least be a strong hint against the conventional $SU(5)$, with or without SUSY, being fundamental.

Alternatively, the SM gauge symmetry may be embedded within a higher symmetry containing SU(4)-color, which unites quarks and leptons by assuming that lepton number represents the fourth color[3]. This naturally *requires* the existence of ν_R as the fourth color partner of the u_R's. The minimal gauge symmetry which contains SU(4)-color and ensures quantization of electric charge is[3]

$$\mathcal{G}_0 = SU(2)_L \times SU(2)_R \times SU(4)^c$$

The representations of the left and the right-handed fermions of the electron-family with respect to the symmetry group $\mathcal{G}_o$ are shown below:

$$F^e_L = \begin{pmatrix} u_r & u_y & u_b & u_\ell & = & \nu^e \\ d_r & d_y & d_b & d_\ell & = & e^- \end{pmatrix}_L = (2,1,4)$$

$$F^e_R = \begin{pmatrix} u_r & u_y & u_b & u_\ell & = & \nu^e \\ d_r & d_y & d_b & d_\ell & = & e^- \end{pmatrix}_R = (1,2,4)$$

The μ and τ-family fermions have identical representations. The symmetry $\mathcal{G}_0$ naturally suggests that the basic laws of nature are chiral and yet left-right symmetric (parity conserving), and that parity violation is a low-energy phenomenon brought about by spontaneous symmetry breaking which makes $m_{W_R} \gg m_{W_L}$[15].

The minimal symmetry $\mathcal{G}_0$ can, of course, be embedded further within simple groups such as SO(10), E_6 and SU(16)[17], which ensure one gauge coupling constant. Viewed as a part of such a bigger symmetry or even otherwise, $\mathcal{G}_0$ is assumed to break spontaneously into the SM symmetry $SU(2)_L \times U(1)_Y \times SU(3)^C$ at a scale $M_0 \gg 1$ TeV, where $Y = I_{3R} + \frac{B-L}{2}$. A particularly desirable Higgs multiplet, which implements this breaking is $\underline{126}$ of SO(10) which contains the multiplet $\Delta_R \sim (1, 3_R, 10^C)$ of $\mathcal{G}_0$. The VEV of $< \Delta_R >= v_R = M_0 \gg 1$ TeV not only makes W_R's and the

leptoquark gauge bosons heavy, but it gives a heavy Majorana mass $M_R = h_M v_R$ to ν_R's which breaks L and $B-L$ by two units. Here, h_m denotes the relevant Yukawa coupling. This heavy Majorana mass, combined with the much lighter Dirac masses of the neutrinos m_D^i, which are family-dependent, leads to the light left-handed neutrinos via the standard see-saw mechanism[18]

$$m(\nu_L^i) \sim (m_D^i)^2/M_R \ll m_D^i$$

Now, a number of symmetry breaking patterns, e.g. two-step breaking of SO(10), leads via RGE[19], to $v_R \simeq 10^{12}$ GeV, and thus $M_R \approx 10^{12\pm1}$ GeV for $h_M = 1/10$ to 10. This in turn leads to:

$$m(\nu_L^e) \sim 10^{-8}\text{ eV},\ m(\nu_L^\mu) \sim 10^{-3}\text{ eV},\ \text{and } m(\nu_L^\tau) \sim 10\text{ eV},$$

corresponding to $m_D^i \approx 2$ MeV, 500 MeV and 50 GeV for ν_e, ν_μ and ν_τ respectively. This mass pattern and the associated mixings for the $(\nu_e - \nu_\mu)$ combination matches well the MSW solution[14] for a resolution of the solar neutrino puzzle. Furthermore, the mass of ν_τ has the right magnitude for ν_τ to serve as hot dark matter, which also seems to be needed, together with about a 70% mixture of cold dark matter, to account for the COBE anisotropy and structure formation[20]. In other words, any higher symmetry containing $\mathcal{G}_0$ as a subgroup and breaking in two steps via $\mathcal{G}_0$ to the SM symmetry *or any underlying theory (see discussions later) in which $\mathcal{G}_0$ breaks at about $10^{11}-10^{12}$ GeV to the SM via $<\Delta_R>$ yields a pattern for neutrino masses and mixings which go well with the MSW solution and the COBE data together with models for structure formation.* Thus, if the MSW solution and the current interpretation of the COBE data are reconfirmed, they would together provide a strong motivation for the existence of new physics at an intermediate scale of order 10^{11} GeV and also a hint for left-right symmetry.

The planned sharpening of the solar neutrino studies and of the COBE data can thus turn out to be most revealing.

Advantages of $\mathcal{G}_0 = \mathrm{SU(2)_L} \times \mathrm{SU(2)_R} \times \mathrm{SU(4)^C}$: To summarize, the symmetry group $\mathcal{G}_0$ *even without being embedded in a simple group*, brings in a number of attractive features which are worth noting:

(i) quark-lepton unification through SU(4)-color.

(ii) Quantization of electric charge leading to $Q_p + Q_{e^-} = 0$.

(iii) Left-right symmetry, with the associated concept of spontaneous violation of parity.

(iv) Naturally massive neutrinos, with the right masses and mixings which may be needed for a resolution of the solar neutrino puzzle and also to provide hot dark matter.

(v) Finally, $B-L$ as a local gauge symmetry. Following the old arguments given by Lee and Yang, based on the Eötvos-type experiments, it follows that the massless

gauge particle coupled to $B-L$ must acquire a mass through SSB and, thereby, $B-L$ must be violated spontaneously (e.g. $<\Delta_R>$ violates L and $B-L$ by two units). Such $B-L$ violation may well be necessary to implement baryogenesis in the presence of electroweak effects which erase $B-L$ conserving baryon-excess generated at high temperatures[21].

Because of these special and most desirable features, I believe that the symmetry group $\mathcal{G}_0$ is likely to be part of a fundamental theory. ***In particular, the new concepts (i)-(v), brought in by it, are likely to survive one way or another.*** Any higher symmetry such as SO(10) or E_6 or SU(16) which contains $\mathcal{G}_0$ as a subgroup would, of course, naturally retain all the advantages of $\mathcal{G}_0$ listed above. It turns out that even the preonic approach to unification (to be presented here) relies heavily on the symmetry group $\mathcal{G}_0$ and thus enjoys the same benefits.

3 Unity Within the Conventional Approach: Proton Decay and $\sin^2\hat{\theta}_W$:

By "conventional" approach to grand unification, I mean the view that the unity of the electroweak and the strong forces occur at some ultrahigh momentum scale $M_U \sim 10^{15\pm1}$ GeV (say), where the quarks and the leptons exhibit their unity as well[3, 4, 5]. This amounts to assuming, of course, that quarks and leptons are elementary.

It has been known for sometime that both the dedicated proton decay searches especially at the IMB and the Kamiokande detectors[22], and more recently the precision measurements of the SM coupling constants (in particular $\sin^2\hat{\theta}_W$) at LEP[1], put severe constraints on grand unification models without supersymmetry. Owing to such constraints, the non-SUSY minimal SU(5) and, for similar reasons, the one-step breaking non-SUSY SO(10)-model, as well, are now excluded beyond a shadow of doubt.

But the idea of the union of the coupling constants g_1, g_2, and g_3 can well materialize in accord with the LEP data, if one either invokes supersymmetry[23, 24] into minimal SU(5) (or SO(10)) or assumes a two-step breaking of a higher symmetry like SO(10) into the SM, with or without SUSY. See Fig. 1, which shows the *impressive meeting* of the three coupling constants of the minimal supersymmetric standard model (MSSM) with an assumed SUSY-threshold around 1 TeV. Such a model can, of course, be embedded within a minimal SUSY SU(5) or SO(10) model, which would provide the rationale for the meeting of the coupling constants at a scale $M_U \approx 10^{16}$ GeV. In SUSY SU(5) or SO(10), dimension 5 operators do in general pose problems for proton decay. But the relevant parameters can be arranged to avoid conflict with experiments. This, together with the requirement that the relic neutralino density be consistent with cosmology, turns out to restrict severely the SUSY-parameter space and thereby leads to predictions for the mass-spectrum of the SUSY particles, which can provide a test of the idea[25].

The SUSY-extensions of $SU(5)$ or $SO(10)$ typically lead to prominent strange particle decay modes, e.g. $p \to \bar{\nu}K^+$ and $n \to \bar{\nu}K^0$, while a 2-step breaking of non-SUSY $SO(10)$ via the intermediate symmetry $\mathcal{G}_0$ leads to partial lifetimes for the canonical $e^+\pi^0$ mode (induced via gauge-boson exchanges) of order 10^{31} to few $\times 10^{34}$ years,[19]. Such a two-step breaking of $SO(10)$ can also lead to prominent $\Delta(B-L) = -2$ decay modes of the nucleon via Higgs exchanges such as $p \to e^-\pi^+\pi^+$ and $n \to e^-\pi^+$[26] and even $n \to e^-e^+\nu_e$ etc.[27].

It is encouraging that the super-Kamiokande (to be completed in April 1996) is expected to be sensitive to the $e^+\pi^0$ mode up to partial lifetimes of few $\times 10^{34}$ years, to the $\bar{\nu}K^+$ and $\bar{\nu}K^0$ modes with partial lifetimes $\leq$ few $\times 10^{33}$ years and to the non-canonical $n \to e^-e^+\nu_e$ and $p \to e^-\pi^+\pi^+$ modes with partial lifetimes $< 10^{33}$ years. Thus the super-Kamiokande with a fiducial mass of 22,000 tons of water, together with other forthcoming facilities, in particular, ICARUS with a sensitive mass of 4700 tons of liquid argon per module (three to be constructed), provide a *big ray of hope* that first of all one will be able to probe much deeper into neutrino physics in the near future and second proton-decay may even be discovered within the twentieth century, following the completion of these detectors.

4 A Perspective: Unity with Quarks or Preons?

Talking of a perspective of the field in the future, it is good to focus attention on the meeting of the coupling constants for the minimal SUSY SU(5) or SO(10) models, as exhibited in Fig. 1. The relevant question is: *Is this meeting a reflection of the "truth" or is it somehow deceptive?*

On the one hand, the manner in which the union occurs is certainly impressive and has prompted some to express the opinion that this union confirms, though indirectly, that both SUSY and grand unification have been discovered. On the other hand, many, myself included, feel that such a view is not warranted in part because the meeting of the coupling constants can occur in alternate ways in accord with the LEP data and τ_p. I shall give one such example at the end. The main reason why I feel that such a view is premature at present is because I believe that *a fundamental theory should exhibit not only a unity of the basic particles and of their forces but also should be devoid of arbitrariness in the Higgs sector*, if the Higgs bosons are elementary.

In this sense, neither minimal SUSY SU(5) nor SUSY SO(10) is likely to constitute a fundamental theory *by itself*, because in either scheme, the lagrangian contains two parts:

$$\mathcal{L}((SU(5) \text{ or } SO(10)) = \mathcal{L}_{gauge} + \mathcal{L}_{non-gauge}(m_i^2, h_{ab}^i, \lambda_{ij})$$

While the gauge-part is governed by a single universal gauge coupling, the parameters of the non-gauge part consisting of the scalar masses m_i^2, the Yukawa couplings h_{ab}^i and the quartic self couplings of the scalars λ_{ij} are arbitrary. In short, the unity in

the context of these theories is only *partial*, comprising just the gauge forces, but leaving out the forces mediated by the Higgs scalars.

Furthermore, neither SUSY SU(5) nor SUSY SO(10) by itself has the scope of explaining the origins of (a) the three chiral families, (b) inter-family mass-hierarchy and (c) the hierarchical mass-scales which span from M_{Planck} to m_ν. One might, of course, hope that one of the two schemes – i.e. the minimal $SUSY\ SU(5)$ or the $SO(10)$-model with the desired spectrum – emerges from one of the superstring theories[12, 28], which could account for the widely varying parameters of the Higgs sector in just the right way and thereby remove the arbitrariness. This would, of course, be the best of all worlds. But so far, the superstring theories are rather far from doing so.

To be more specific, there is a plethora of classically allowed solutions for the four-dimensional ground state or the vacuum of the superstring theories corresponding to the Calabi-Yau, orbifold and four-dimensional constructions and one is not yet in a position to (a) choose between them, (b) understand the breaking of supersymmetry and (c) generate a mass for the dilaton. Notwithstanding these fundamental difficulties, which would need a handling of the non-perturbative string dynamics, *there does not seem to be even a single solution among the vast set of solutions mentioned above which resembles or nearly resembles the known world.* In particular, there is not even a vague indication so far of a minimal $SUSYSU(5)$ or $SO(10)$-model with the desired spectrum emerging from a superstring theory[29]. If this persists, believing that the "final picture" should not only exhibit a meeting of the coupling constants but also should (a) explain the three puzzles and (b) remove the arbitrariness in the choice of parameters mentioned above, it seems to me that the union of the coupling constants in the context of the minimal $SUSY$ grand unification model(s)[24] may well be fortuitous. It should at least be taken with some caution because there are in fact alternative ways (see remarks below) by which such a meeting may occur. This brings me to present a new approach to unification based on the idea of preons.

5 Composite Higgs: Technicolor Versus Preons

Since it is the Higgs-sector which is the major source of the drawbacks noted above, it seems appropriate to explore an alternative approach to unification in which all the forces of nature have a purely gauge-origin and the Higgs-sector is dispensed with at the elementary level. In this case, the Higgs-force should arise effectively only at a composite level. Notwithstanding the goal of unification, the technicolor idea which treats the Higgs bosons as composite, but quarks and leptons as elementary, is in fact an attempt precisely in this direction. But this idea encounters several difficulties which are first of all practical in nature, because of conflicts with flavor-changing processes and oblique electroweak parameters. Second, the difficulties of technicolor are also aesthetic in nature because, as a generic feature, it needs excessive prolifer-

ation in elementary constituents but does not produce any accompanying benefits as regards an understanding of the basic issues such as family-replication or inter-family mass-hierarcy. This second difficulty remains even within the variant of walking technicolor. I therefore believe that if the Higgs bosons are composite, quarks and leptons must also be composites of a *common* set of constituents – generically called "preons".

Given that (a) there is such a big gap in energy between the Planck scale and the electroweak scale, where quarks and leptons appear elementary and that (b) the assumption of elementary quarks and leptons emerging from the superstring theories has not led as yet to any promising picture as regards resolution of the issues which arise at low energies, it seems to be in order to at least question the assumption of ultimate elementarity of quarks and leptons. If quarks and leptons are composite, the elementary objects emerging from the appropriate superstring theory may represent preonic substructures which ultimately bind, utilizing a metacolor gauge force, to give composite quarks, leptons and Higgs bosons. Apriori, this picture has some advantages but also some major hurdles, which I list below.

One prima facie *advantage* of the preonic idea compared to that of technicolor is obvious economy in the building blocks. Because quarks, leptons and Higgs bosons possess common constituents, there is no need for technifermions and extended technicolor in a preonic theory. Also, the difficulty of standard technicolor as regards the oblique electroweak parameters can be avoided neatly within the class of preonic theories to be presented here. That with regard to flavor-changing processes can be softened considerably, and perhaps even resolved, within the same class of theories (see discussions below). One major attraction of the preonic idea is that it can be built as a *pure gauge theory* (like QCD with massless quarks), so that there are no non-gauge mass, quartic and Yukawa coupling parameters of scalars at the preon level[9]. This leads to real economy in the parameters as well.

Inspite of these advantages, it is well known that the preonic idea brings with it new major hurdles, which need to be overcome if the idea has to get off the ground. First, one needs to find a mechanism which would adequately protect the masses of composite quarks and leptons compared to their compositeness scale. Together with this, one must ensure that the anomalies of the preonic theory match those of the composite one, since this is a necessary condition, in this case[30]. Second, one needs to understand family-replication. Third, considering that all three families are presumably made of the same type of constituents, bound by the same force, one needs to understand why there is such a large hierarchy between the masses of the three families – in particular, why $(m_e/m_t) \sim 10^{-5}$ – in a simple and natural way.

Overcoming the Hurdles of a Preonic Theory:
Problems of the type noted above, have plagued composite models from the time the idea was initiated in 1973-74[31]. If at all they may be resolved, they would need some novel features in the dynamics.

Precisely such novel features seem to emerge[32, 9], however, by combining the ideas of local supersymmetry with that of preons and by recognizing that a dynamical breaking of supersymmetry is forbidden in a class of theories due to the Witten index theorem[33], except for the presence of gravity. Thus SUSY-breaking is induced in this class of theories, if at all, only by the team-effort of the strong non-perturbative metacolor force *and* the weak perturbative gravitational force. Now for the case of massless preons, the preonic fermion condensates $< \overline{\psi}\psi >$ (see notation below) as well as the metagaugino condensate $< \lambda \cdot \lambda >$ break SUSY. As a result, assuming that these condensates form, each of them must be damped by one (or higher) power of $(\Lambda_M/M_{p\ell})$, corresponding to the effect of one (or multiple) graviton exchange, where Λ_M denotes the scale-parameter of the metacolor force. Barring unexpected vanishing of the leading term, we thus expect $\langle\overline{\psi}^a\psi^a\rangle = a_{\psi_a}\Lambda_M^3(\Lambda_M/M_{P\ell})$, $\langle\lambda\cdot\lambda\rangle = a_\lambda\Lambda_M^3(\Lambda_M/M_{P\ell})$. Here a_{ψ_a} and a_λ denote dimensionless numbers of order unity and the subscript a denotes preon flavor or color-index (see later). We expect a_{ψ_a} to be typically smaller than a_λ by factors of 5 to 10 because ψ's are in the fundamental and λ's in the adjoint representation of the metacolor gauge symmetry.

A number of independent consistency arguments, based on (a) the idea of the unity of forces (see remarks below), (b) the value of m_W, and (c) the masses of the light neutrinos suggest that $\Lambda_M \sim 10^{11}$ GeV[9].

The $< \lambda\cdot\lambda >$ and $< \overline{\psi}\psi >$-condensates thus induce SUSY-breaking mass-splittings δm_S of order $a_\lambda\Lambda_M(\Lambda_M/M_{P\ell}) \sim 1$ TeV $\ll \Lambda_M$. Furthermore, since $< \overline{\psi}\psi >$ is responsible for breaking $SU(2)_L \times U(1)_Y$ as well as for giving masses to the composite quarks and leptons, one naturally obtains[32, 9]:

$$(m_W, m_Z) \sim (1/10)\Lambda_M(\Lambda_M/M_{P\ell}) \sim 100 \text{ GeV};$$

$$(m_q, m_\ell) \leq (1/10)\Lambda_M(\Lambda_M/M_{P\ell}) \sim 100 \text{ GeV}.$$

The factor of (1/10) arises on dynamical ground, where use has been made of the fact that we expect a_ψ to be of order (1/5 to 1/10) of a_λ. Thus, one sees the reason why quark and lepton masses are *necessarily* protected compared to their inverse size Λ_M and also why the mass-scales span over such a wide range: from $m_{P\ell}$ to Λ_M to m_W. As observed by 't Hooft[30], corresponding to such a protection, anomalies of the unbroken chiral symmetry at the preon-level must match those at the composite level. This condition is satisfied trivially in the model because the unbroken chiral symmetry is no more than a subgroup of the anomaly-free $SU(2)_L \times SU(2)_R \times SU(4)^C$ symmetry[9].

To see, how families replicate and how the scales descend from m_W to m_e to m_ν one needs to enter, at least briefly, into the details of the model.

6 A Model with a Unification of Scales – From M_{Pl} to m_ν

The model[9] assumes that the effective lagrangian just below the Planck scale posseses $N = 1$ local supersymmetry and a gauge symmetry of the form $G_M \times G_{fc}$. Here $G_M = SU(N)_M$ (or $SO(N)_M$) generates an asymptotically free metacolor gauge force which binds preons and G_{fc} denotes the flavor-color gauge symmetry, which is assumed to be either $\mathcal{G}_0 = SU(2)_L \times SU(2)_R \times SU(4)^c$[8], or a subgroup of $\mathcal{G}_0$ containing $SU(2)_L \times U(1)_Y \times SU(3)^c$. The gauge symmetry $G_M \times G_{fc}$ operates on a set of six positive and six negative *massless* chiral preonic superfields $\Phi^{a,\sigma}_{\pm} = (\varphi, \psi, F)^{a,\sigma}_{L,R}$, each beloning to the fundamental representation N of SU(N). Thus "a" runs over six values: $(x, y); (r, y, b, \ell)$, where (x, y) denote the two basic flavor-attributes (u, d) and (r, y, b, ℓ) the four basic color-attributes of a quark-lepton family[3]. The index σ runs over metacolor quantum numbers. The metacolor gauge multiplet is made of v_μ, λ and D, which denote the metagluon, the metagaugino and the auxiliary component respectively. Likewise the gauge multiplets of the other groups. The representation content of the preonic superfields under the gauge symmetry is shown below:

		$SU(2)_L \times$	$SU(2)_R \times$	$SU(4)^C_{L+R} \times$	$SU(N)_{L+R}$
$\Phi^{f,\sigma}_{+} = (\varphi^f_L, \psi^f_L, F^f_L)^\sigma$	$\sim$	2_L,	1,	1,	N
$\Phi^{f,\sigma}_{-} = (\varphi^f_R, \psi^f_R, F^f_R)^\sigma$	$\sim$	1,	2_R,	1,	N
$\Phi^{c,\sigma}_{+} = (\varphi^c_L, \psi^c_L, F^c_L)^\sigma$	$\sim$	1,	1,	4_c,	N
$\Phi^{c,\sigma}_{-} = (\varphi^c_R, \psi^c_R, F^c_R)^\sigma$	$\sim$	1,	1,	4_c,	N

Here f stands for (x and y) which denote up and down flavors, while c denotes four colors (r, y, b, and ℓ). Since quarks and leptons carry flavor and color, they must be metacolor singlet composites consisting of at least two preons, one carrying flavor and the other carrying color[31].

We see that the preon content presented above is indeed the *minimum*, providing the attributes of just one family. *In particular, note that there is no repetition of any entity at the preonic level unlike the case of the quark-lepton families.* One then asks: Are there natural reasons within this minimal system for the origins of (a) family replication and (b) mass-hierarchy?

Before entering into this discussion, we note that the effective lagrangian of this model turns out to possess, in accord with the motivations mentioned earlier, only gauge and gravitational interactions. No mass, no non-gauge Yukawa and quartic couplings are even allowed in the model, as long as we impose the gauge symmetry specified above, supersymmetry *and* the non-anomalous R-symmetry $U(1)_X$. As a result, the model possesses *at most only three or four parameters* (see below) corresponding to the coupling constants of the gauge symmetry $G_M \times G_{fc}$. Even these few would merge into one near the Planck scale if there is an underlying unity of forces-in particular through superstrings (see remarks later).

Such a model has not yet been derived from a superstring theory, although there

does not appear to be any bar, in principle, in this regard especially in the context of a four-dimensional construction[28]. Even without such a derivation, however, if one introduces the preon-picture mentioned above through an effective lagrangian just below the Planck scale, the model is already most economical and one is able to derive a number of advantages. These include:

(i) **Origin of Diverse Mass Scales:** The model provides a reason[9] for the origin of all the diverse scales – from M_{Planck} to m_ν – and thereby of the small numbers such as $(m_W/M_{pl}) \sim (m_t/M_{pl}) \sim 10^{-17}, (m_c/M_{pl}) \sim 10^{-19}, (m_e/M_{pl}) \sim 10^{-22}$, and $(m_\nu/M_{pl}) < 10^{-27}$ – *by introducing just one fundamental input parameter:* the coupling constant α_M associated with the metacolor force. Briefly speaking, this comes about as follows. Corresponding to an input value $\overline{\alpha}_M \approx 1/27$ to $1/32$ at $M_{Pl}/10$, which incidentally is suggested independently by the idea of the unity of forces (see remarks below), the metacolor force generated by $SU(N)_M$ becomes strong at a scale $\Lambda_M \approx 10^{11} GeV$ for N=5 to 6. Thus the first big step in the hierarchical ladder leading to the small number $(\Lambda_M/M_{Pl}) \sim 10^{-8}$ arises naturally through renormalization group equations due to the slow logarithmic growth of $\overline{\alpha}_M$ and its perturbative input value at $M_{Pl}/10$.

Before discussing the origin of the TeV-scale which is the next step in the hierarchy, let me first mention about an important step in symmetry-breaking which is presumed to happen at the metacolor scale itself. It is assumed[9] that when the metacolor force becomes strong, it not only makes a set of metacolor-singlet composites like the quark-lepton families and their SUSY-partners, but also a set of metacolor-singlet condensates of scale Λ_M which preserve SUSY, but break certain gauge and global symmetries, such that *the effective symmetry below Λ_M is just the gauge symmetry of the standard model $G_{213} = SU(2)_L \times U(1)_Y \times SU(3)^c$, without any residual global symmetry*[34]. In particular, it is assumed that non-perturbatively a SUSY-preserving preon-condensate Δ_R transforming as (1,3,10) of $G_{224} = SU(2)_L \times SU(2)_R \times SU(4)^c$, acquires a VEV of order Λ_M, while the "mirror image" Δ_L transforming as (3,1,10) does not acquire a VEV[35]. This breaks G_{224} to G_{213}. It thereby breaks $L - R$ symmetry (parity) and $B - L$ and gives heavy Majorana masses to the right-chiral neutrinos ν_R^i's of three chiral families, *which are naturally all of the same order $\Lambda_M \sim 10^{11}$ GeV.*

The next step arises due to the Witten-index theorem[33] which, as mentioned above, leads to a damping of SUSY-breaking condensates by the factor (Λ_M/M_{Pl}). This provides a reason why $\delta m_S \sim \Lambda_M(\Lambda_M/M_{Pl}) \sim 1$ TeV and $m_W \sim m_t \sim (1/10)\Lambda_M(\Lambda_M/M_{Pl}) \sim 100$ GeV $\ll \Lambda_M \ll M_{Pl}$. One special feature of the model is that, while $m_t \sim 100$ GeV, it naturally provides extra symmetries in the fermion mass-matrix (see below) which protect $m_{u,d,e}$, barring corrections of order 1 MeV. There is also a good reason why the masses of the fermions belonging to the muon-

family are intermediate between those belonging to the e and the τ-families. Finally, the familiar see-saw mechanism for neutrinos with $m(\nu_R^i) \sim \Lambda_M \sim 10^{11}$ GeV and $m(\nu^i)_{Dirac} \propto \Lambda_M(\Lambda_M/M_{Pl})$ yields $m(\nu_L^i) \leq 10^{-3}M_{Pl}(\Lambda_M/M_{Pl})^3 \sim 10^{-27}M_{Pl}$. In this way, the model provides a *common origin* of all the diverse scales – from M_{Pl} to m_ν, as desired. Supersymmetry and compositeness play an essential role in achieving this result.

Note that electroweak symmetry breaking in the preon-picture is dynamical, like technicolor. ***But unlike technicolor, there is no strong force at the TeV-scale.*** The intrinsic scale of the new dynamics, responsible for electroweak symmetry-breaking, is the metacolor scale of order 10^{11} GeV. This scale incidentally goes well not only with the see-saw neutrino masses that are needed for the MSW solution of the solar neutrino puzzle but also with the desired scale for a breaking of the Peccei-Quinn symmetry[34].

(ii) **Family Replication**: Although a two-body metacolor singlet fermion-boson composite of the form $\psi^a\phi^{b*}$ can yield the desired quantum numbers of quarks and leptons[31], given that the masses of quarks and leptons are protected for reasons mentioned above, one can argue plausibly that such a "massless" spin-1/2 composite made of a "massless" spin-1/2 and a spin-0 constituent is dynamically inconsistent unless it consists of at least one additional third ingredient, which is necessarily neutral with respect to flavor and color. Thus, this third constituent is the metagluon (v). In short, the minimum dimensional composite operator representing quarks and leptons corresponds to a three-body composite of the form $\psi\phi^* v$ and its SUSY-transforms.

Recognizing that in a SUSY theory, fermionic constituents can be interchanged by their boson partners (i.e. $\psi \leftrightarrow \varphi$ and $v_\mu \leftrightarrow \lambda$ or $\overline{\lambda}$ etc.), there exist several alternative three-particle combinations with identical quantum numbers, which can make a left-chiral $SU(2)_L$-doublet family q_L^i – e.g. (i) $\sigma_{\mu\nu}\psi_L^f\varphi_R^{c^*}v_{\mu\nu}$, (ii) $\sigma^{\mu\nu}\varphi_L^f\psi_R^{c^*}v_{\mu\nu}$, (iii) $\psi_L^f\psi_R^{c^*}\lambda$ and (iv) $\varphi_L^f(\sigma^\mu\overline{\lambda})\partial_\mu\varphi_R^{c^*}$. Here $f = x$ or y corresponds to up or down flavors and $c = (r, y, b)$ or ℓ corresponds to the four colors. ***The plurality of these combinations, which stems because of SUSY, is in essence the origin of family-replication.*** By constructing composite superfields, it is found[10], curiously enough, that at the level of minimum dimensional composite operators (somewhat analogous to qqq rather than $qqqq\overline{q}$ for QCD) there are just three linearly independent chiral families $q_{L,R}^i$, and, in addition, two *vector-like families* $Q_{L,R}$ and $Q'_{L,R}$, which couple vectorially to W_L's and W_R's respectively. Each of these composite families is, of course, accompanied by its scalar superpartners. To sum up, we see that owing to fermion-boson pairing in SUSY, the model provides a good reason for replication (i.e. number of chiral families being more than one) and at least some rationale, subject to the assumption of saturation at the level of minimum dimensional composite operators, as to why the number of chiral families is three. Clearly this last assumption needs further justifi-

cation. Pending such a justification, however, it turns out, as noted below, that the mass-matrix of the fermions belonging to this system of *five families* – three chiral and two vector-like-provides a compelling reason for inter-family hierarchy.

(iii) **Inter-family Mass-Hierarchy:** First note that for the purposes of quantum numbers, the chiral and vector-like families can be represented by $q_L \sim$ "$\psi_L^f \varphi_R^{c^*} v$", $q_R \sim$ "$\psi_R^f \varphi_L^{c^*} v$", $Q_L \sim$ "$\psi_L^f \varphi_L^{c^*} v$", $Q_R \sim$ "$\varphi_L^f \psi_L^{c^*} v$", $Q'_L \sim$ "$\varphi_R^f \psi_R^{c^*} v$" and $Q'_R \sim$ "$\psi_R^f \varphi_R^{c^*} v$". Utilizing these compositions, one can see that the vector-families $Q_{L,R}$ and $Q'_{L,R}$ acquire relatively heavy masses through the metagaugino condensate $< \vec{\lambda} \cdot \vec{\lambda} >$ of order $\Lambda_M(\Lambda_M/M_{Pl}) \sim 1$ TeV, which are otherwise protected by the $U(1)_X$ quantum number of the SUSY theory.

Now in a SUSY-theory, chirality is carried by both fermions and bosons. As a result, direct mass-terms $m^{(o)}(q_L^i \rightarrow q_R^i)$ of chiral families requiring transitions, for example, of $\psi_L^f, \varphi_R^{c^*} v$ to $\psi_R^f \varphi_L^{c^*} v$ (as well as the $Q - Q'$ mixing) cannot be induced through either $< \vec{\lambda} \cdot \vec{\lambda} >$ or $< \bar{\psi}\psi >$. These, therefore, receive small contributions at most of order (1/10-1) MeV from products of $< \bar{\psi}_R \psi_L >$ and $< \varphi_R^* \varphi_L >$ condensates, each of which is damped by (Λ_M/M_{Pl}). The chiral families $q_{L,R}^i$ acquire masses, however, primarily through their mixings with the vector-like families $Q_{L,R}$ and $Q'_{L,R}$ which are induced by $< \bar{\psi}^a \psi^a >$. Thus, dropping the direct mass-terms of chiral families and $Q - Q'$ mixing mass-terms, and ignoring QCD corrections for the quarks for a moment, the Dirac-mass matrices of the five families for all four sectors - i.e., q_u, q_d, ℓ and ν - have the form[9, 11]:

$$M_{f,c}^{(o)} = \begin{array}{c} \\ \bar{q}_R^i \\ \bar{Q}_R \\ \bar{Q}'_R \end{array} \begin{array}{c} \begin{array}{ccc} q_L^i & Q_L & Q'_L \end{array} \\ \begin{pmatrix} O & X\kappa_f & Y\kappa_c \\ Y'^\dagger \kappa_c & \kappa_\lambda & O \\ X'^\dagger \kappa_f & O & \kappa_\lambda \end{pmatrix}_{f=(u,d);c=(r,y,b) \text{ or } \ell} \end{array} \tag{1}$$

Note that by varying the flavor-index $f = (u \text{ or } d)$, which are the same as $(x \text{ or } y)$, and the color-index $c = (r, y, b)$ or ℓ, one spans over all four sectors. For example, up-quarks q_u correspond to the choice $f = u$ *and* $c = (r, y \text{ or } b)$, while charged leptons ℓ correspond to the choice $f = d$ *and* $c = \ell$. The index i runs over the three chiral families. The entities X, Y, X' and Y' are column matrices in the family-space having entries which are apriori of order unity. In the above, κ_λ, κ_f and κ_c are induced respectively by $< \lambda \cdot \lambda >, < \overline{\psi}^f \psi^f >_{f=u,d}$ and $< \overline{\psi}^c \psi^c >_{c=(r,y,b) \text{ or } \ell}$. Thus, apriori, one expects $\kappa_\lambda = O(\Lambda_M(\Lambda_M/M_{Pl})) = O(1 \text{ TeV})$, while κ_f and κ_c are expected to be smaller than κ_λ by factors of 5-10 (say), because ψ's are in the fundamental and λ's in the adjoint representation of $SU(N)$. *In short, the* 5×5 *mass matrix for each of the four sectors has a natural see-saw structure.*

In the absence of electroweak corrections, which are typically of order 5-10%, one can argue that $X^T = (X')^T$ *and* $Y^T = (Y')^T$, *and that the same* X, Y *and* κ_λ

apply to all four sectors: up, down, charged leptons and neutrinos. Furthermore, ignoring electroweak corrections, one can always rotate the chiral quark or lepton fields q_R^i and q_L^i to bring the row matrices $Y^T = (Y')^T$ to the simple form $(0,0,1)$ and simultaneously $X^T = (X')^T$ to the form $(0,p,1)$, with redefined κ_f and κ_c. *Note the consequent great reduction even in effective parameters.* The 5×5 mass-matrices of the four sectors – i.e. q_u, q_d, q_ℓ and ν – which, in general could involve at least 100 parameters – are described (barring electroweak corrections and direct mass-terms $\leq$ 1 MeV) by only six effective parameters – i.e. $p, \kappa_u, \kappa_d, \kappa_\tau, \kappa_\ell$ and κ_λ. Furthermore, we know the approximate values (within a factor of ten, say) of these parameters. One can not choose them arbitrarily, unlike in the case of elementary quark-lepton-Higgs theory. Upon examining the relevant preon-diagrams, one can argue that the effective parameter p is less than one, but not very much smaller than that. A value of $p \simeq 1/3$ to $1/4$ is found to be quite natural.

Given the zeros in (1), which stem from the symmetry of the underlying SUSY preon theory, *we see that regardless of the values of the entries in X and Y and thus of p, one linear combination of the five families is guaranteed to be massless*, barring corrections of order 1 MeV, which thus can be identified with the electron-family[11]. Ignoring electroweak and multiplicative QCD corrections, one obtains the following eigenvalues[11]:

$$\begin{aligned} m^{(0)}_{u,d,e,\tilde{\nu}_e} &= 0 + O(1 \text{ MeV}) \\ m^{(0)}_{c,s,\mu,\tilde{\nu}_\mu} &\approx (\kappa_f \kappa_c/\kappa_\lambda) \cdot (p^2/2) \\ m^{(0)}_{t,b,\tau,\tilde{\nu}_\tau} &\approx 2(\kappa_f \kappa_c/\kappa_\lambda) \end{aligned}$$

$$m_U^{(0)} = m_D^{(0)} = m_{U'}^{(0)} = m_E^{(0)} = m_N^{(0)} = m_{E'}^{(0)} = m_{N'}^{(0)} = \kappa_\lambda = O(1 \text{ TeV}) \qquad (2)$$

The masses of the quark-members should be multiplied by QCD-renormalization, which turns out to be about 3.7 at 1 TeV[11, 37]. Based on these, one is led to predict[11] $m_t \sim$ (90-150) GeV, with an upper limit $m_t \leq 150$ GeV. At the same time, one understands why m_e is of order 1 MeV.

Furthermore, ignoring electroweak corrections which can be significant for the muon-family, the $\mu - \tau$ mass-ratios are given by

$$[m_{c,s,\mu}/m_{t,b,\tau}] \approx p^2/4. \qquad (3)$$

For $p \simeq 1/3$ to $1/4$, which is not too small and natural, one thus obtains a rather large $\mu - \tau$-hierarchy of $1/36$ to $1/64$, as observed. In this way, one understands naturally, without the need for invoking arbitrarily small parameters abinitio, the inter-family mass-hierarchy – i.e. $m_{u,d,e} \ll m_{c,s,\mu} \ll m_{t,b,\tau}$, with $m_e \sim \mathcal{O}$ (1 MeV) and $m_t \sim$ 100-150 GeV, and thus $(m_e/m_t) \sim 10^{-5}$. Including direct mass terms in the top-left 3×3 block which are of order 1 MeV and electroweak corrections, one also obtains hierarchical CKM mixings[11].

It needs to be stressed that all this is realized, even though the model started with no fundamental input parameters at the Planck scale, except for the three gauge couplings. The simplicity of the explanation for inter-family mass-hierarchy discussed above seems to provide support for the preonic approach. It also leads one to expect that *there ought to exist two vector-like families in the SSC/LHC-range, since they are crucial to the explanation.*

As regards intra-family mass-splittings, that between down quarks and charged leptons in a given family are accounted for primarily by QCD-corrections. The up-down mass-splittings reflected by the ratios of top versus bottom and charm versus strange quark-masses are attributed to $\kappa_u \gg \kappa_d$ which in turn is attributed to a dynamical breakdown of isospin in SUSY QCD. This latter feature needs, however, a better explanation. In particular, a study of whether an evasion of the constraints of the Vafa-Witten theorem[35] does indeed take place in SUSY QCD and a natural understanding of $(\kappa_d/\kappa_u) \approx 1/35$ are warranted. (One attractive possibility (presently only a conjecture) is that SUSY QCD pemits $\kappa_d = 0$ and $\kappa_u \neq 0$ at the "tree level" and that κ_d is induced only radiatively through $\kappa_u \neq 0$, so that $\kappa_d \approx \left(\frac{\alpha_2}{2\pi}\right) \kappa_u \ell n \frac{\Lambda}{1\text{TeV}} \sim 1/35$.)

(iv) **CP Violation:** The model provides an elegant mechanism for spontaneous CP violation, which is shown to vanish (for the observed processes), if the masses of the electron family were set to zero[11], – i.e. if the direct mass terms of the chiral families $m_{(0)}(q_L^i \rightarrow q_R^j)$ in (1) are put strictly to zero. Allowing for these direct mass-terms the model predicts $|\epsilon| \sim (m_d/m_b) \sin\xi \sim 2 \times 10^{-3}$ for a maximal CP violating phase. It also predicts an electric dipole moment for the neutron $\approx (1 \text{ to } \frac{1}{20}) \times 10^{-25} ecm$, which is observable.

(v) **Crucial Tests:** One distinguishing feature of the preon model is that it leads to several crucial predictions[11] by which it can really be falsified if it is wrong. These include:

(1) $m_t \leq 150$ GeV.

(2) $K^0 \leftrightarrow \overline{K}^0$ and $K_L \rightarrow \overline{\mu}e$ are normal as in SM, in so far as contributions from box graphs involving quarks and W's as well as those from the tree-level Z-exchange are concerned. But box diagrams containing squarks and gluinos need, as in all SUSY theories, that the squarks of different generations have to be fairly degenerate, e.g. to better than about 5% if $m_{\tilde{q}} \sim O$ (3 TeV). Such a degenerarcy in principle can arise depending upon the relative values of certain mass matrix elements, but apriori it is not guaranteed by the model.

(3) $A(\text{"}Z\text{"} \to t\bar{c}) \approx \left(\frac{g_2}{\cos\theta_W}\right)\left(\frac{\kappa_u}{\kappa_\lambda}\right)^2\left(\frac{p}{2}\right) \approx \left(\frac{g_2}{\cos\theta_W}\right)$ (1/6 to 1)%. This may allow visible single top-production at LEP 200.

(4) $A(\text{"}Z\text{"} \to c\bar{u})$ which gives $\Delta m(D-\overline{D})_{New} \approx (10-1)\times 10^{-14}$ GeV, while $\Delta m_{expt} \leq 1.3\times 10^{-13}$ GeV and $\Delta m(D-\overline{D})_{SM} \approx (1-4)\times 10^{-15}$ GeV.

(5) $A(Z \to \bar{\mu}e)$ which gives $B(\mu \to 3e) \approx (1 \text{ to } 5)\times 10^{-13}$

(6) $\tau_\tau = (\tau_\tau)_{SM}(1+\epsilon) = (\tau_\tau)_{SM}[1+(1to4)\%\,]$; N_ν (LEP) $= 3-2\epsilon = 3-(.02\text{to}.08)$. Note that corrections to τ_τ and N_ν are correlated[38]. Here $\epsilon \equiv (\kappa_u/\kappa_\lambda)^2$.

(7) Prominent $\nu_\mu - \nu_\tau$ mixing with $m(\nu_\tau) \approx (1 \text{ to } 50)$ eV, $m(\nu_\mu) \approx (10^{-3}-10^{-1})$ eV, $m(\nu_e) \approx 10^{-8}$ eV, and $\nu_\mu - \nu_e$ mixing consistent with the MSW solution.

(8) $(edm)_n \approx (10 \text{ to } 1/2)\times 10^{-26}$ ecm.

(9) Existence of SUSY partners with masses $\sim$ (100 GeV - few TeV)

(10) 2 Higgs doublets with familiar SUSY charged and neutral members corresponding to $\tan\beta \approx$ (30-40).

(11) Finally, as mentioned before, the model predicts two vector-like families, which are the hall-marks of the model. Their masses including QCD-renormalization effects, are given by[11]:

$$m_{E,E'} \approx 200-700 \text{ GeV}; \; m_{U,D,U',D'} \approx (600-3000) \text{ GeV}$$

For a variety of reasons, including renormalization group analysis, it turns out that the number of these vector-like families must be precisely two - no more, no less; one of these couples to W_L and the other to W_R. It is worthnoting that vector-like families do not contribute to the electroweak S and T parameters because their masses are $SU(2)_L \times U(1)$-symmetric. Thus, their existence, unlike the case of technicolor families, is perfectly compatible with the measurements of these parameters[38].

(vi) **Supersymmetry Breaking:** The preonic theory requires the presence of a new metacolor force in the *observable sector* which becomes strong at a superheavy scale $\Lambda_M >> 1\ TeV$. Such a force would not, however, be permissible if quarks and leptons were elementary. The existence of such a force, in the presence of gravity, allows the possibility of a dynamical breaking of supersymmetry directly in the observable sector (albeit with a damping by the Planck mass), which thus transmits efficiently into the masses of the squarks, the gluinos and the winos. This may well be an advantage over

a dynamical breaking of supersymmetry occurring entirely in the hidden sector of a superstring theory, which seems to be the only possibility in such a theory if quarks and leptons are elementary.

7 Unity of Forces at the Preon Level

Although the derivation of a preon model resembling that proposed in Ref. 9 from a superstring theory is still awaited, it is intriguing to ask whether the coupling constants g_1, g_2 and g_3 extrapolated in the context of the preon model from their measured values at low energies do indeed meet with each other as well as with g_M near the Planck scale, for any reasonable choice of the metacolor gauge symmetry G_M and the flavor-color gauge symmetry G_{fc} which operates near the Planck scale. The precise nature of G_M and G_{fc} may hopefully get determined ultimately by an underlying superstring theory if preons have their origin from such a theory. In this case, despite the non-unifying appearance of the effective symmetry $G_M \times G_{fc}$, the constraints of grand unification including the quantization of electric charge and the familiar equality of the coupling constants near the unification scale M_{SU} would still hold, especially for $k = 1$ Kac-Moody algebra, barring, of course, Planck-scale threshold effects.

Note that the extrapolation based on renormalization group equations is fully determined in regions I and II(see Fig. 2) because the spectrum and the gauge symmetry are fixed, while in region III, there is only a few discrete choices which can be made as regards the metacolor gauge symmetry G_M and the flavor-color gauge symmetry G_{fc}. The scale Λ_M is fixed at about 10^{11} GeV (within a factor of 3, say) by requiring consistency with the hierarchy of scales, in particular by the observed mass of m_W.

In a recent work, Babu and I found[39] that with the measured low-energy values of g_1, g_2 and g_3 at LEP and thus with $\sin^2\theta_W \simeq .2333, \alpha = 1/127.9$ and $\alpha_3 = .118$ at m_Z as inputs, the coupling constants including g_M, show a clear tendency to converge to a common value within a few percent of each other[40] at a scale $M_U \approx (2-5)\times 10^{18}$ GeV, for example for the choice $G_M = SU(5)_M$ and $G_{fc} = SU(2)_L \times U(1)_{I_{3R}} \times SU(4)^c$, (see Fig. 2)[41, 42]. It demonstrates that the unity of forces may well occur at the level of preons in a manner that is truly novel compared to the conventional approach of elementary quarks and leptons.

8 Concluding Remarks

To conclude, let me compare the two alternative approaches to unification: One based on the idea of elementary quarks and leptons and the other on the idea of preons.

On the negative side, the preon picture possesses a certain arbitrariness with regard to the choice in the pattern of symmetry breaking and correspondingly in the precise set of condensates which form near Λ_M. While this type of arbitrariness is present in one form or another in alternative approaches as well (compare e.g. with the needed VEVs of the scalar partners of ν_R and N in the three-generation Calabi-Yau models), it is clearly desirable to understand the dynamics of locally supersymmetric gauge theories to shed some light on these issues. Of special interest is the question *whether vectorial global symmetries such as isospin and parity can break dynamically in a SUSY QCD-type theory* to which the premises of the Vafa-Witten theorem[35] do not apply. Such a breaking has been presumed within the preonic approach. If it can be derived on dynamical grounds, one would have a compelling reason for the breakdown of isospin, parity, baryon number and perhaps other global symmetries in SUSY QCD-type theories. It also remains to be seen whether the preon-content and the gauge symmetry of the type suggested in Ref. 9 can be derived from an underlying superstring theory. On the practical side, as mentioned above, squarks of different generations have to be fairly degenerate (as in all SUSY theories) to avoid excessive flavor-changing neutral-current (FCNC) processes. Such a degeneracy could in principle arise in the model if certain mass matrix elements dominate. In this respect, the preon-model is on a better footing than standard technicolor in that it is at least not manifestly incompatible with the data. Nevertheless, a natural resolution of this issue as well as of the others mentioned above are challenges which confront the preon picture.

On the positive side, while the pattern of the condensates needs to be assumed within the preonic approach, the scales of the condensates including those with a damping by (Λ_M/M_{Pl}) are motivated on general grounds. Furthermore, even without being derived from a superstring theory as yet, the preonic approach shows many attractive features:

(a) It is economical in parameters and building blocks and thus is devoid of much of the arbitrariness that goes with the conventional approach to grand unification involving elementary quarks, leptons and Higgs bosons.

(b) It is viable with regard to all precision measurements of the electroweak parameters, unlike standard technicolor. The issue with regard to FCNC processes is, however, still open (see remarks above).

(c) The preonic approach seems capable of addressing successfully the three basic issues pertaining to the origins of (1) the diverse mass-scales from M_{Pl} to m_ν, (2) family replication and (3) inter-family mass-hierarchy. None of these issues can be addressed within the conventional approach to grand unification with elementary quarks, leptons and Higgs bosons, with or without supersymmetry. And, as I mentioned before,

the hope of addressing these issues by deriving a conventional supersymmetric grand unification model from a superstring theory seems to be marred because the existing vast set of solutions including Calabi-Yau, Orbifold and four-dimensional constructions do not show promise in this regard.

(d) The recent work of Ref. 39 opens up the possibility that the unity of forces can occur near the Planck scale through preons rather than quarks and leptons, in accord with the recent LEP data.

(e) The *real advantage* of the preonic approach, it seems to me, is that while it is capable of addressing some very basic issues, it also offers some crucial tests listed above, by which it can be excluded, if it is wrong. This is so, inspite of the fact that the compositeness scale Λ_M is found to be very high, of order 10^{11} GeV.

Thus, the preonic approach to unification seems to offer some *distinct advantages* over the conventional approach. As such it deserves further theoretical study in all its aspects involving dynamics of locally supersymmetric QCD-type theories on the one hand and a derivation of a model of the type proposed in Ref. 9 from a superstring theory on the other hand.

In this connection, it is interesting to recall that the idea of $SU(3)$-flavor as an approximate symmetry, suggested by Ikeda, Ogawa and Ohnuki; Wess; and Yamaguchi, turned out to be correct, but the identification of the fundamental triplet with the observed (p, n, and Λ) rather than with their constituents – i.e. the quarks – turned out to be wrong. Even earlier, the idea of Yang and Mills for generating strong interactions by a non-abelian gauge symmetry turned out to be right, but its association with the isospin symmetry of protons and neutrons, rather than with the color symmetry of their constituents – the quarks, also proved to be wrong. One wonders whether history is being repeated now, by adherence to the common notion that the unity of forces should occur at the level of the observed quarks and leptons. The idea of the superstring theories and therefore of the unity of forces at a fundamental level may well be right. But it remains to be seen, and here experiments of the type mentioned above can help, whether the fundamental fields, to be associated with such a unity, correspond to the observed quarks and leptons or possibly to a new layer of constituents – the preons.

By raising the alternative of preons, I am, of course, not suggesting that the search for an ultimate layer of constituents would necessarily continue for ever. Sooner or later, assuming that adequate funding of high energy experiments is not halted prematurely, we may well be able to see clear marks of such a layer and thereby also of the "final theory". I believe that this could be the case even if, on energetic grounds, one can not *directly* observe the physics at ultrahigh energies approaching the Planck scale and thereby "see" the ultimate building blocks. This is because, on the basis of concrete cases at hand discussed in the text, it seems likely that such an

ultimate theory, although defined at ultrahigh energies, coul
at low energies by which it can be probed with a reasonab
In addition to compatibility with observation, *the two criter*
for deciding whether or not one has arrived at such an "ultima
should be able to provide simple answers to all the basic questi
be capable of raising and (b) it should somehow be singled out b
thus by its lack of arbitrary parameters.

The question is: Have we arrived at such a theory already? I believe that we have not. I say this because there are still many loose ends and gaps. Among others, we do not yet have (i) a principle to derive a superstring theory, (ii) a reason for the four-dimensional nature of space-time in which we live, (iii) an insight into the non-perturbative aspect of the string theories so as to *understand* the choice of the ground state and supersymmetry breaking and (iv) a good reason for the exact or the approximate vanishing of the cosmological constant. However, optimistically speaking, there are reasons to believe that we may not be far from an "ultimate theory" in that quite a few of its major ingredients are in. The basic premises of the superstring theories and thereby of grand unification in a broader perspective are very likely among these.

However, using the criteria mentioned above, I believe that the common view in this regard that quarks and leptons are the ultimate building blocks is likely to be false. As mentioned above, the main reason why I prefer the alternative of the supersymmetric preonic theory over that of elementary quarks, leptons and Higgs bosons is that the former dictates one to write the fundamental lagrangian as a *pure gauge theory* in terms of massless fields with no non-gauge couplings.

Fortunately, a choice between the preonic theory (as discussed here) and the elementary quark-lepton theory can be made on empirical grounds through measurements which are not far from our reach. To be specific, the collection of pre-SSC *and* the post-SSC/LHC-experiments, pertaining to neutrino-physics on the one hand, and searches for (a) $e - \mu - \tau$ non-universality, (b) rare processes including $t \to Zc$, (c) proton decay, (d) Higgs particles of the neutral and the charged variety, (e) supersymmetry, and in particular, *(f) complete vector-like families*, on the other hand, would be able to resolve at least some of the basic issues, including that of a choice between the quark-lepton versus the preonic theories. Such measurements could thus provide a strong hint on the nature of the final theory. Since the fate of the SSC is in question at the time of writing this manuscript, however, I am prompted to say that much as we may dream of a final theory[44], unless facilities like the SSC and/or the LHC are made available, it will be hard (perhaps impossible) to turn any such dream into a reality. In particular, the SSC and/or the LHC are needed to explore some important fundamental ideas including those of electroweak symmetry breaking, supersymmetry and, as discussed here, the origin of inter-family mass-hierarchy. Each of these ideas proposes a new type of matter at the Fermi scale – i.e. the Higgs

n(s), SUSY partners and the vector-like families. No doubt it would be worthy our civilization to enrich itself with a knowledge of these aspects of Nature, likely they are to lie around the corner.

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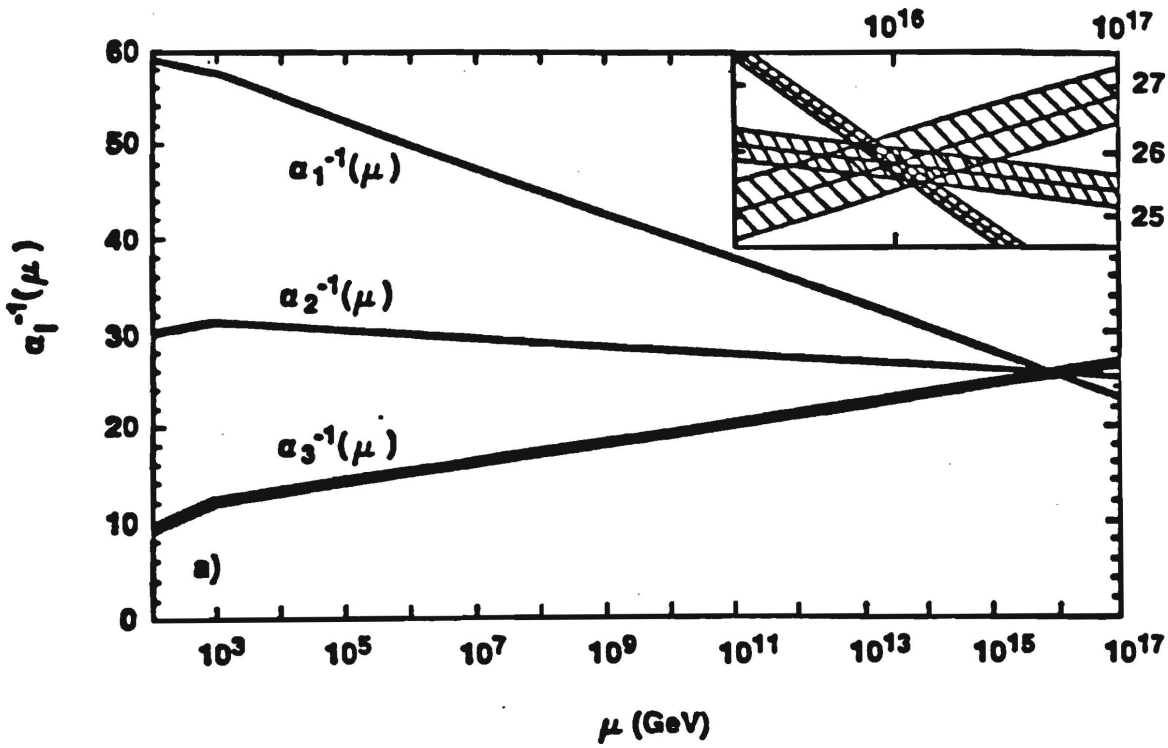

Figure 1: Running of coupling constants in SUSY minimal $SU(5)$ (Ref. 24).

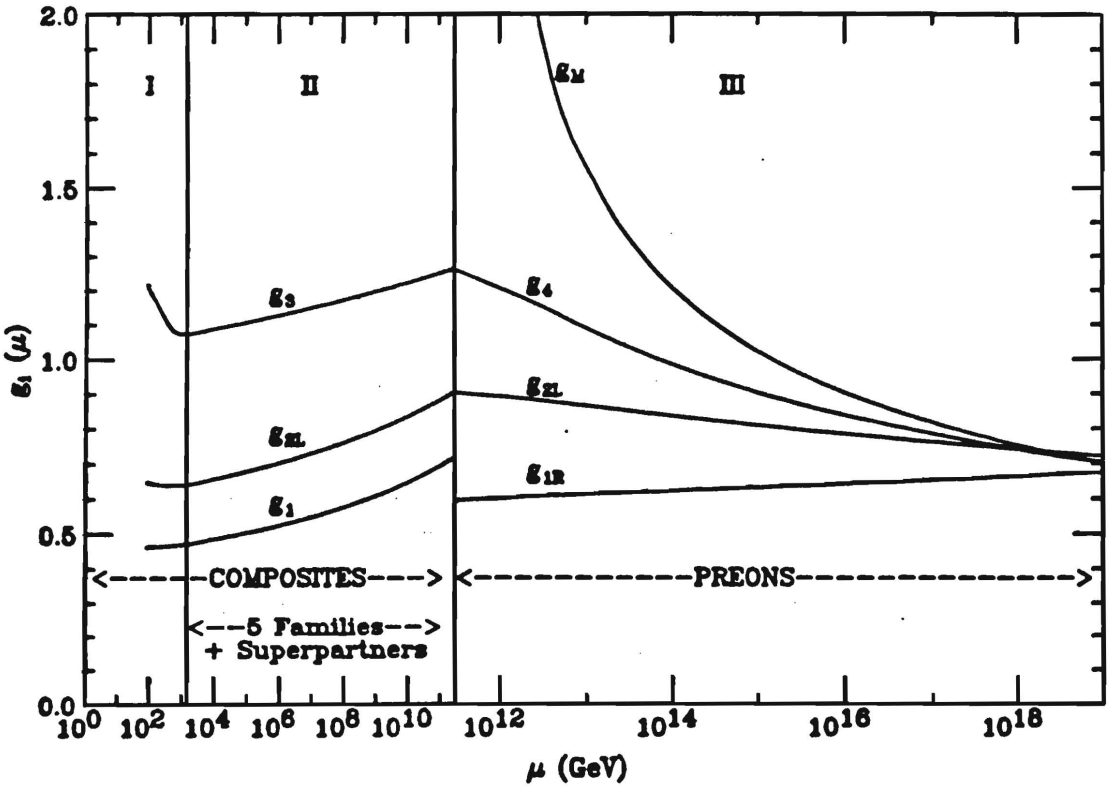

Figure 2: Running of coupling constants in the preon model (see text and Ref. 39).