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TWENTY YEARS LATER: WHY I STILL BELIEVE IN SU(4)-COLOR

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Abstract

Following some preliminary remarks of a historical nature, 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 unification based on a purely gauge origin of the fundamental forces. This seems to call for the ideas of local supersymmetry and preons. Preonic ideas in turn seem to require SU(4)-color symmetry. The advantages of the marriage of these ideas in understanding the origins of (a) diverse mass-scales, (b) family-replication and (c) inter-family mass-hierarchy are discussed.

1. Preliminary Remarks

Professor Abdus Salam is a great scientist, a humanitarian and a symbol for the third world. I wish to dedicate this talk with pleasure and gratitude to him on the occasion of his sixty-seventh birthday.

Before I enter into the scientific part of my talk, I thought I would say a few words, befitting the occasion of this meeting, first about some rare qualities of Professor Salam and then about the way in which our collaboration started and grew.

It hardly needs to be said that Professor Salam has made some landmark contributions to physics, spanning more than three decades. This in itself is rather unusual. But I believe his unique and most valuable contribution to science and humanity, one that is perhaps unparalleled in the world, is the sacrifice he has made of his time, energy, and personal comfort in promoting the cause of science in different corners of the globe, in particular the third world. It literally pains Professor Salam to see that talented young people in the third world simply do not get opportunities to pursue the path of science to the best of their abilities. The efforts he made to resolve this problem has led to the creation of many new research centres throughout the world.

A symbol of his efforts is the creation of the International Centre, in this beautiful city of Trieste. The Centre stands as a monument of learning providing opportunities

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for the East to meet the West and the North to meet the South. The two goals which I believe the Centre has achieved remarkably well is the production of high-quality science on the one hand and the provision of meaningful opportunities to the third-world scientists for exposure to frontier developments in science on the other hand. As a frequent visitor and organizer of many activities at the Centre, I have always been impressed by (a) the total number of visitors whom the Centre invites per year from different countries in the third world; (b) the high quality of the symposia and the workshops which the Centre arranges throughout the year for the benefit of these visitors, and above all (c) the fruitful research which evolves owing to interactions between the visitors and the lecturers for the workshops. The success of each of these phases is in large part due to the insistence by Professor Salam on high quality. I have also often been touched by the extreme generosity of Professor Salam in dealing with the problems of each individual visitor. His door is always open to one and all.

As a passing remark, I should add that if the Centre has been a success, it owes this both to the dedicated efforts of Professor Salam and to the whole-hearted support and a true appreciation of the goals of the Centre by the Government of Italy, the people of Italy and the city of Trieste. In this sense, I believe that the Centre has been fortunate to have the best of both worlds: The most able leader and the most receptive country. It has thereby emerged as an example for other individuals and countries to follow.

I will now like to talk about my collaboration with Professor Salam.

2. The Strength in Our Collaboration

My collaboration with Professor Salam started in the summer of 1972. It lasted for over a decade and involved many exciting and memorable episodes. During this period, I used to come to Trieste for about two months every summer. The Adriatic Sea, the surrounding small mountains and the daily view of the setting sun have always been a source of inspiration to me. In part because of this but especially because of the warmth which I received from Professor Salam as well as from all the people at the Centre I have always loved to come back here again and again.

During the first six years, which was the most intense phase of our collaboration, Professor Salam also used to visit the University of Maryland during the academic year, often twice a year, for about a week each time. During these visits, the two of us would hide in the hotel room run by the University's Center for Adult Education, so that we would not be disturbed. There, we would spend the first few days in discussing physics and the last few days in writing papers. This was indeed a very productive period of our collaboration, marked with the joy of creativity and mutual appreciation.

During our collaboration there have been many letters, arguments, and even heated exchanges about taste and judgement in physics, but always in a good-natured

spirit.

My great respect for Professor Salam is, of course, natural, in part because of his pre-eminence, but in part also because of our common Eastern tradition, which teaches us to respect the older, who is automatically taken to be the wiser. Because of this tradition, I still address him as "Professor Salam" rather than by his first name "Abdus". But what has touched me immensely over the years is that he also treated me throughout our collaboration with respect and affection[1]. This served to establish a mutural bond between us which has lasted until today.

In our conversations, Professor Salam had some favorite phrases. For example, he would sometimes come up with an idea and if I expressed that I did not particularly like it for such and such reason, he would get impatient and say to me: "My Dear Sir, what do you want: Blood?" I would smile and say "No Professor Salam! I would like something better".

Just as he would sometimes become impatient with me, there would be occasions when I would also get impatient with him and even say to him "Professor Salam! You just don't understand!" But, whether I was right or wrong, he never took it ill. In fact, because of these free exchanges, our collaboration became all the more strong.

3. The Origin of SU(4)-Color

Due to lack of time, I cannot possibly cover the many episodes and the different stages of our collaboration. Let me therefore focus only on its initial phase: how it started and how it evolved in the first month, leading to the idea of SU(4)-color. This will allow me to illustrate a rare quality of Professor Salam, that is bringing out the best in a collaboration.

I met Professor Salam first as a student-participant in the Colorado Summer School of 1959 where he lectured on "Symmetries and Group Theory". But my close association with him began only in the summer of 1972, here at Trieste. Just before coming to Trieste that summer, I had spent six months at Delhi University, while I was on sabbatical leave from the University of Maryland. During those six months, I got somehow out of phase with the developments which were taking place in the USA and Europe. When I reached Trieste in May 1972, I found that everyone was talking about 't Hooft's proof of renormalizability of spontaneously broken gauge theories and the SU(2) $\times$ U(1) electroweak model[2]. Many papers appeared in 1972 which tried to build variants of the SU(2) $\times$ U(1) model. For example, there was a model proposed by Georgi and Glashow[3] which got rid of the neutral current weak interactions altogether because experiments were hinting that they may be absent. Then, there was the model of Bars, Halpern and Yoshimura[4] which proposed a gauge theory of the electroweak and the strong forces, but the idea underlying the model is very different from what prevails today. I realized that I had a lot to catch up on.

However, as I was trying to do this, I felt that something basic was missing from the main thrust of activities. It appeared to me that the heart of the matter lay not in building variants of the SU(2) $\times$ U(1) model but in removing the arbitrariness of the model first in the gauge sector and then in the Higgs sector, involving the scalar mass, the quartic and the Yukawa coupling parameters of the Higgs boson.

One aspect of the gauge-sector of the model that bothered me from the beginning was the assignment of the abelian weak hypercharge to the different SU(2)-doublets and the singlets. These assignments did not follow from an underlying principle and thus did not have an *apriori* meaning. They were simply put in by hand to fit the known charges.

Moreover, it seemed unsatisfactory that quarks and leptons are introduced in the model without a rationale for their co-existence and for the asymmetry that is built in between these two kinds of matter. A third ingredient that was also bothersome was the disparity with which the model treated the left and the right chiral fermions. This amounted to putting in non-conservation of parity by hand. Short of a compelling reason why (in Pauli's words) God should be weakly left-handed, it seemed that the introduction of such a disparity is arbitrary and thus unaesthetic.

Last but not least, it appeared that if the weak and the electromagnetic interactions are generated by a gauge principle, the fundamental strong interactions must also have their origin in the same principle. For these reasons, I felt then that the SU(2) $\times$ U(1) model, even it were to be eventually borne out by experiments, which it was, can not constitute a fundamental theory by itself. It must emerge from within a bigger structure which should remove these shortcomings.

In those days, there used to be a tradition at the Centre of having an informal seminar once a week, followed by a tea. In one of those tea gatherings, I casually mentioned to Professor Salam that there ought be a *compelling reason* for the way the weak hypercharge is assigned to the various fields in the SU(2) $\times$ U(1) model – as compelling as the eigenvalues of I_3 in an SU(2) symmetry and those of I_3 and F_8 in an SU(3)-symmetry. An underlying theory should also provide a reason for the co-existence of quarks and leptons and simultaneously for their hypercharge assignments, such that the charges of the electron and the proton are equal and opposite. I mentioned that in order to implement these features, one would need to put quarks and leptons in one common multiplet of a higher gauge symmetry group, which must be spontaneously broken at a high energy scale to account for the observed disparity between quarks and leptons.

Now, the idea of putting quarks and leptons in the same multiplet was rather unconventional at that time. Rather than expressing any reservation about it, as some others did, Professor Salam responded immediately by saying "That seems like an excellent idea! Let us develop it together". It is this sort of spontaneous appreciation and encouragement – a quality that is rare – that has helped to enrich our collaboration at every step. Given the high esteem that I had for him, I, of course,

welcomed wholeheartedly his participation. Thus, from that tea conversation began our collaboration.

After a few days, Professor Salam made the important remark that if one could understand why the electron and the proton have equal and opposite charges, one would then have an answer to Feynman's question as to why the electron and the proton, rather than the positron and the proton, exhibit the same sign of longitudinal polarization in β-decay. This made the search for such an answer even more pressing.

Over the next two weeks, we had many discussions at the blackboard and several false starts. One Sunday afternoon, as I was working in my apartment in Sistiana (a sea-side resort near Trieste), it suddently appeared as as a flash that quarks and leptons can be united in a very elegant manner by using the symmetry SU(4)-color. With SU(4)-color the whole spectrum of quarks and leptons fitted beautifully into a 4×4-structure of a symmetry group $SU(4)^{\text{flavor}} \times SU(4)^{\text{color}}$ operating on four flavors (u, d, c, s) and four colors (r, y, b, ℓ)[5]. Such a structure accounted naturally for the vanishing of the sum of the quark and the lepton charges and thereby for the vanishing of $(Q_{e^-} + Q_p)$. Within it, the neutrino and the electron are interpreted simply as the up and the down quarks of lepton color.

I was naturally elated by the picture which had thus emerged and called Professor Salam over the phone to convey my feelings. As usual, he was working at his desk and asked me to come over to the Centre. I caught a bus and reached the Centre in late afternoon. As I described the incomplete idea, it became clear to both of us that a gauging of SU(4)-color would provide a compelling reason, based on the requirement of renormalizability of the full set of interactions, for why the weak interactions must utilize the flavor degree of freedom including isospin in the first place any why *they must be universal with respect to quarks and leptons.* Because of these features, we both felt that SU(4)-color may well turn out to be fundamental. Professor Salam stressed to me that we must now find the right Higgs system which would break the relevant gauge symmetry appropriately. That Sunday afternoon thus marked the origin of SU(4)-color.

It became clear to us in the next few days that if quarks and leptons have to be united in SU(4)-color, *one important by-product of such a unification is that the known strong interactions must be generated entirely by the SU(3)-color gauge symmetry,* so that the effective gauge symmetry at low energies must be $SU(2)_L \times U(1)_Y \times SU(3)^c$[6, 7]. This became known eventually as the standard model symmetry.

We wrote up this aspect of our thinking in a short draft which we submitted to J.D. Bjorken for presentation at the 1972 Batavia Conference and then in a paper which appeared in the Physical Review[7]. In this paper, we initiated the concepts of quark-lepton unification in terms of SU(4)-color as well as the idea of unification of forces in terms of a single gauge coupling constant, without exhibiting explicitly a symmetry to implement this idea. In detail, we stressed in this paper the desirability of the combined gauge symmetry $SU(2)_L \times SU(1)_Y \times SU(3)^c$ as an effective low-energy

symmetry and left the development of suitable Higgs system, for more extended symmetries including SU(4)-color, to two later papers[8]. The discovery of asymptotic freedom, which took place about a year later in May 1973[9], gave a final boost to such a gauge structure, in particular to $SU(3)^c$.

The idea of SU(4)-color in turn generated within the next year and a half other ideas such as those of (i) the gauge symmetry $SU(2)_L \times SU(2)_R \times SU(4)^C$[8], (ii) left-right symmetry and right-handed neutrinos implying $m_\nu \neq 0$[8, 10], (iii) non-conservations of baryon and/or lepton numbers, owing to spontaneous breaking of the gauged generator B-L, leading to phenomena such as proton decay which has emerged as one of the hall marks of quark-lepton unification[8, 11], (iv) explicit construction of grand unification models such as those of SU(5)[11], SO(10), $[SU(4)]^4$ E_6 and SU(16)[12]. These finally led to the demonstration of the meeting of the coupling constants with a prediction for $\sin^2\theta_W$ in the context of such models.[13] All of these ideas, except for minimal non-supersymmetric SU(5), are very much alive today.

I now turn to the scientific part of my talk, where I explain why, twenty years later, I still believe in SU(4)-color. In this context, I discuss (i) the advantages of the symmetry group $SU(2)_L \times SU(2)_R \times SU(4)^c$ as a stepping stone to higher unification and (ii) the current status of the conventional approach to grand unification, in particular its recent success with the meeting of the coupling constants, as well as its shortcomings as regards the arbitrariness in the Higgs sector. A case is made for an alternative approach to unification based on *a purely gauge-origin* of the fundamental forces and thus for a theory which is devoid of the Higgs sector at a fundamental level. It is suggested that this idea is best realized by combining the idea of local supersymmetry with that of preons. The advantages of a recently developed preonic approach[14] with regard to achieving economy in the building blocks and the parameters, as well as an understanding of (i) the origin of diverse mass scales, (ii) family replication[15] and (iii) inter-family mass-hierarchy[16] are presented. It is stressed that the preonic approach lends itself to many tests by which it can be falsified. Finally, a recent work which demonstrates that the unity of forces may well occur at the level of the preons, rather than quarks and leptons, is presented[17]. As it turns out, the preonic approach needs and thus preserves intact the idea of SU(4)-color.

4. SU(4)-Color and Higher Symmetries

Standard model 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[7]. 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[8]

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

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:

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

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

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 $m_{W_R} \gg m_{W_L}$[8, 10].

The minimal symmetry $\mathcal{G}_0$ can, of course, be embedded further within simple groups such as SO(10), E_6 and SU(16)[12], 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, 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[19] 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.[21]

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

Advantages of $\mathcal{G}_0 = \mathbf{SU(2)_L \times SU(2)_R \times SU(4)^C}$: 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[22].

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 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.

5. 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[7, 8, 11, 13]. 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, and more recently the precision measurements of the SM coupling constants (in particular $\sin^2\hat{\theta}_W$) at LEP, 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.

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 $\overline{\nu}K^+$ and $\overline{\nu}K^0$ 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.

6. 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. The superstring theories, despite the multitude of solutions, do not seem to be capable of yielding a conventional grand unification model like SUSY SU(5) or SUSY SO(10), with the desired spectrum and parameters (even nearly), and thereby removing the arbitrariness of such a model in the Higgs sector.

Towards a Pure Gauge Origin of the Fundamenal Forces: 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 proliferation in elementary constituents but does not produce any accompanying benefits as regards a synthesis or an understanding of the basic issues. 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".

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 share common constituents, there is no need for technifermions and extended tech-

nicolor in a preonic theory. Also, the familiar difficulties of technicolor as regards flavor-changing processes and the oblique electroweak parameters can be avoided at least within a class of preonic theories (the model to be presented here is in fact one of this nature). Furthermore, one major attraction of the preonic idea, which incidentally has kept me occupied in the development of this idea well over a decade, 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.[14] 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. 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:

Problems of the type noted above, have plagued composite models from the time the idea was initiated in 1973-74[25]. If at all they may be resolved, they would need some novel features in the dynamics.

Precisely such novel features seem to emerge[26, 14], 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[27], 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 (Λ_M/M_{pl}), 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 $\langle\overline{\psi}^a\psi^a\rangle = a_{\psi_a}\Lambda_M^3(\Lambda_M/M_{Pl})$, $\langle\lambda\cdot\lambda\rangle = a_\lambda\Lambda_M^3(\Lambda_M/M_{Pl})$. 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[14].

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[14]:

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

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

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[28], 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.

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.

7. A Model with a Unification of Scales – From $M_{P\ell}$ to m_ν

The model[14] 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[8]. 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 two flavors (x and y), 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[25].

We see that the preonic 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 by the gauge symmetry, 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 four-dimensional construction[29]. 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[14] 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 $M_{Pl}/10$.

The next step arises due to the Witten-index theorem[27] which, as mentioned above, leads to a damping of SUSY-breaking condensates by the factor $(\Lambda_M/M_{P\ell})$. This provides a reason why $\delta m_S \sim \Lambda_M(\Lambda_M/M_{P\ell}) \sim 1$ TeV and $m_W \sim m_t \sim (1/10)\Lambda_M(\Lambda_M/M_{P\ell}) \sim 100$ GeV $\ll \Lambda_M \ll M_{P\ell}$. 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.

(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[25], 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[15] 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 justification. 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**: Owing to symmetries of the underlying theory and the quantum numbers of the composites, it turns out[14, 16] that the 5×5 mass-matrix of the three chiral and two vector-like families acquire relatively heavy masses through the metagaugino condensate of order $\Lambda_M(\Lambda_M/M_{Pl}) \sim 1$ TeV, but the direct mass-terms of the three chiral families vanish barring corrections of order (at most) 1 MeV. The latter acquire masses primarily through their mixings with the two vector-like families. Such mixings are induced through the preonic $\langle\overline{\psi}\psi\rangle$-condensates. Although all three chiral families are on a par in that their mixings with the two vector-like families are comparable to each other, *the rank of such a 5×5 see-saw type mass-matrix automatically guarantees one linear combination of the chiral families to be massless*, apart from corrections of order 1 MeV. This combination may be identified with the electron family. At the same time, the heaviest fermion (top) acquires a mass of order 100-150 GeV and the members of the muon-family acquire masses which are naturally intermediate between those of the electron and the tau family.

In this way, one obtains a simple reason for the inter-family mass-hierarchy – i.e. why $m_{u,d,e} \ll m_{c,s,\mu} \ll m_{t,b,\tau}$[16]. In particular, one understands both why $m_e \sim O(1 \text{ MeV})$ and the heaviest chiral quark (top) is around 100-150 GeV, so that $(m_e/m_t) \sim 10^{-5}$. It needs to be stressed that all this is realized, even though the model started with no fundamental input parameters except for the three gauge couplings. The simplicity of this explanation 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.*

The intra-family mass-splittings between quarks and leptons 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 a dynamical breakdown of isospin in SUSY QCD[16]. This latter feature needs, however, a beter explanation. In particular a study of whether an evasion of the constraints of the Vafa-Witten theorem[30] does indeed take place in SUSY QCD is warranted.

(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[16], – i.e. if the direct mass terms of the chiral families

$m_{(0)}(q_L^i \to q_R^j)$ 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 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[16] 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 $K_L \to \overline{\mu}e$ 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) $A(\text{“}Z'' \to t\overline{c}) \approx \left(\frac{g_2}{\cos\theta_W}\right)$ (1/6 to 1)%

(4) $A(\text{“}Z'' \to c\overline{u})$ 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) $A(Z \to \overline{\mu}e)$ which gives $B(\mu \to 3e) \approx$ (1 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[31].

(7) Prominent $\nu_\mu - \nu_\tau$ mixing with $m(\nu_\tau) \approx$ (1 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 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[16]:

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

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.

(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.

8. Unity of Forces at the Preon Level

Although the derivation of a preon model resembling that proposed in Ref. 14 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[29].

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[17] 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[32] at a scale $M_U \approx (2-5)\times 10^{18}$ GeV, for example for the choice $G_M = SU(5)_M$ and $G_{fc} = SU(2)_L \times U(1)_{I3R} \times SU(4)^c$, (see Fig. 2)[33]. 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.

9. 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[29] 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. 14 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 somewhat 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. 17 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. 14 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, could well cast clear shadows at low energies by which it can be probed with a reasonable degree of confidence. In addition to compatibility with observation, *the two criteria which one may use for deciding whether or not one has arrived at such an "ultimate theory" are: (a) it should be able to provide simple answers to all the basic questions which one would be capable of raising and (b) it should somehow be singled out by its uniqueness and thus by its lack of arbitrary parameters.*

The question is: Have we arrived at such a theory already? My answer is 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. Optimistically, speaking, however, 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, the two alternatives can be distinguished from each other by pre-SSC and especially post-SSC/LHC experiments of the type mentioned here. If, on the basis of these experiments, preonic ideas turn out to be right, what would that

mean for the idea of SU(4)-color? The above discussion shows that this symmetry has played a crucial role even in the preonic approach. In fact, if ν_R's are relevant, I can not think of any elegant way to construct a composite model without this symmetry. This is why, twenty years later, I still believe in SU(4)-color.

Finally, I must say that I feel especially fortunate to have had the privilege of a most intense and fruitful collaboration with Professor Salam, marked by many moments of shared joy and happiness. For this and for the warmth and friendship which he has extended to me, I wish to express once again my deepest gratitude, together with my very best wishes for the future.

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[1] To illustrate this, I digress for a moment. I come from the state of Orissa lying in the east coast of India – about 200 miles to the south of Calcutta. Orissa possesses one of finest temples in India, called Konarak, built about 800 years ago, with superb sculpture, engaraved on the stone. Professor Salam visited this temple and was much impressed by its beauty. He described it to me as the Taj Mahal of the Hindus. In the early stages of our collaboration, he once told me "Jogesh: since you come from the land of the Konarak, I expect nothing less than a Konarak in physics from you". This remark, coming from him, has always been a source of inspiration for me.

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[5] Recall that in 1972 there was no need to consider more than four flavors. Effectively, such a 4×4-structure is to be viewed as a merger of two families, each being a 2×4. In reality, one must, of course gauge a suitable chiral counterpart of $SU(4)^{flavor}$ together with $SU(4)^{color}$, which could be vectorial or chiral. This is

what we did by gauging $SU(2)_L \times SU(2)_R \times SU(4)^c$ or $[SU(4)]^4$ with mirrors (see later). But for the purposes of classification and assignment of electric charge, which is vectorial, it suffices to use the non-abelian vectorial $SU(4)^f \times SU(4)^c$.

[6] To clarify the background of this suggestion, the idea of $SU(3)^c$ as a global symmetry was introduced implicitly through paraquarks by O.W. Greenberg, *Phys. Rev. Lett.* **13**, 598 (1964). M. Han and Y. Nambu (*Phys. Rev.* **139**, B1006 (1965)) introduced the same symmetry explicity and made the important suggestion of gauging $SU(3)^c$, but in a manner that violated $SU(3)^c$ explicitly through the coupling of the photon to integer charge quarks (icq). This spoilt the renormalizability of the theory. They also introduced medium strong interactions utilizing flavor symmetry. These two shortcomings were removed and the advantages of the combined gauge structure $SU(2)_L \times SU(1)_Y \times SU(3)^c$ were noted in two papers by Salam and myself starting with a contribution to the 1972 Batavia Conference (Ref. 7). H. Fritzsch and M. Gell-Mann also promoted $SU(3)^c$ gauging at the same conference. They, and many others, favored the alternative of the fractionally charged quarks (fcq) with confinement. To Salam and myself, this was only an alternative along with the one of liberated gauged icq; the two alternatives arise within the same theory depending upon the nature of SSB. We therefore proposed, over the next few years, some key experiments which could help distinguish between the two alternatives. Eventually, by the mid 1980's the two-photon experiments seemed to favor clearly fcq over gauged icq. The two central ideas of quark-lepton unification and the consequent non-conservations of baryon and lepton numbers, introduced in Refs. 7 and 8, are of course, independent of the nature of quark-charges.

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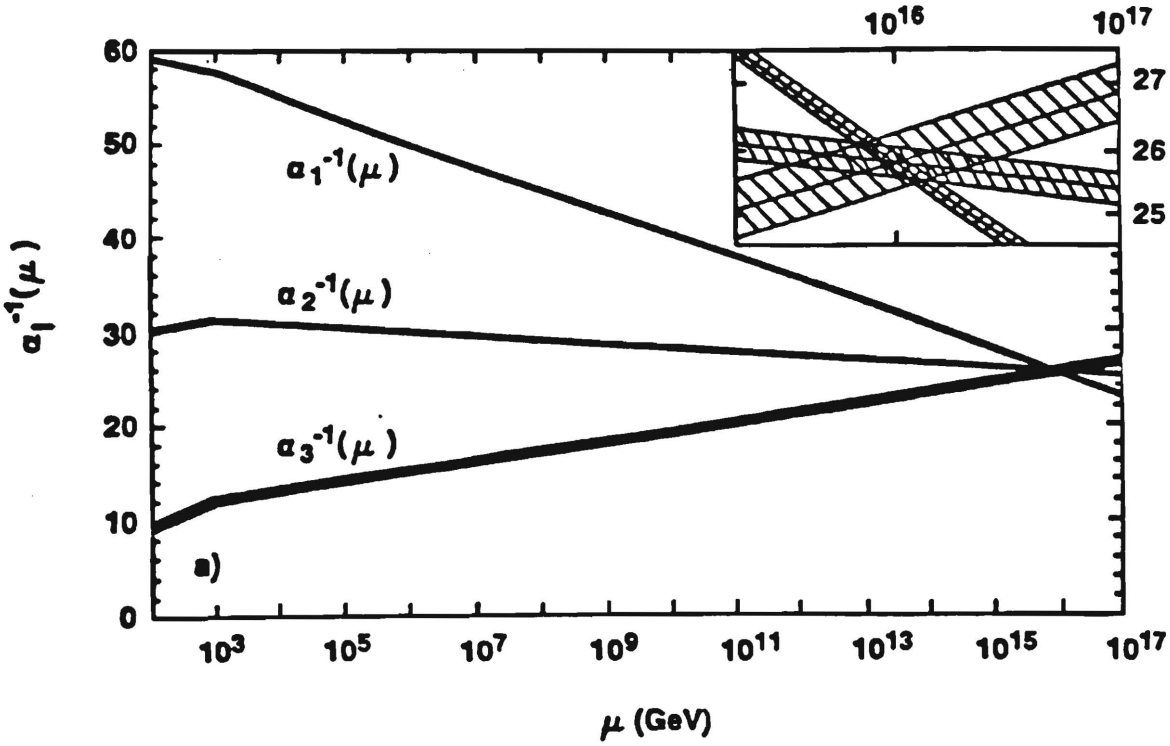

Figure 1: Running of coupling constants in SUSY minimal $SU(5)$ (Ref. 24).

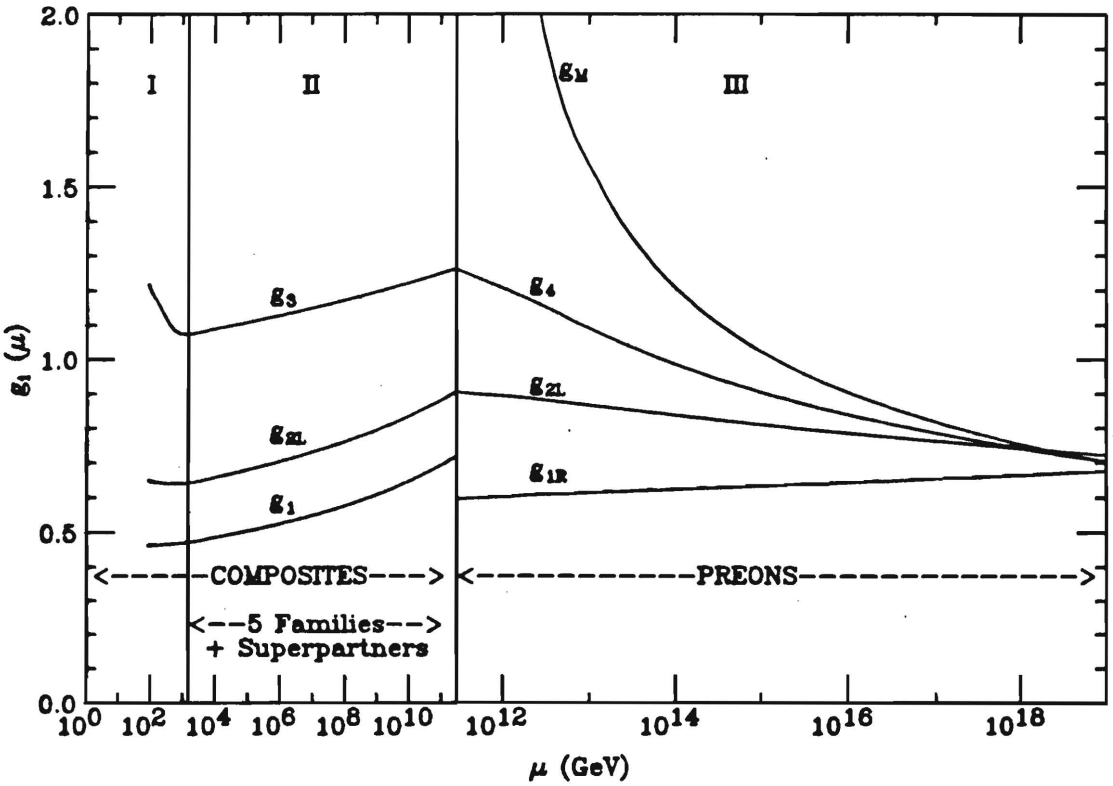

Figure 2: Running of coupling constants in the preon model (see text and Ref. 17).