THE ROLE OF GRAVITY IN DETERMINING PHYSICS AT HIGH AS WELL AS LOW ENERGIES[†]

Jogesh C. Pati

Institute for Advanced Study
Princeton, NJ 08540 USA
and
Department of Physics, University of Maryland[*]
College Park, MD 20742 USA

Abstract

It is noted that in the context of a supersymmetric preonic approach to unification, gravity, though weak, can play an essential role in determining some crucial aspects of low-energy physics. These include: (i) SUSY-breaking, (ii) electroweak symmetry-breaking, (iii) generation of masses of quarks and leptons, all of which would vanish if we turn off gravity. Such a role of gravity has its roots in the Witten index theorem which would forbid SUSY-breaking, within the class of theories under consideration, in the absence of gravity.

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[*] Address after July 1, 1995. E-mail: "pati@umdhep.umd.edu"

I.   A Prelude

That gravity should play a major role in determining the nature of physics near the Planck scale (which is the subject of this meeting) is of course to be expected because at that scale quantum gravity becomes supremely dominant. But traditionally gravity is regarded as too weak to be relevant to our understanding of microscopic physics at sub-Planck energies $Q \lesssim M_{Planck}/100$, say) – that is at distance scales $\gtrsim 10^{-31} cm$. One main purpose of this talk is to show that in the context of a supersymmetric preonic approach to unification, which has recently evolved into a viable and economical form [1,2,3,4], gravity plays an *essential role* in determining some important aspects of low-energy physics as well. These include (i) supersymmetry breaking, (ii) electroweak symmetry breaking, and (iii) generation of masses of quarks and leptons.

Gravity enters into the game at low energies in this approach as follows. The supersymmetric preonic metacolor force becomes strong at an intermediate scale $\Lambda_M \sim 10^{11}$ GeV. Owing to the constraints of the Witten index theorem [5] which forbids SUSY-breaking in the absence of gravity, the metacolor force by itself can not break supersymmetry. It *needs* the collaboration of gravity to induce SUSY-breaking. At such "low" energies ($Q \sim 10^{11}$ GeV), gravity is of course weak and perturbative. Even then it induces a negative $(\text{mass})^2$ proportional to Newton's constant for certain composite scalars which would otherwise be massless in the limit of SUSY, and thereby induces a VeV for such scalars and in turn SUSY-breaking. As a result, the square root of the gravitational coupling – i.e., the inverse of M_{Planck} – enters into the SUSY-breaking preonic condensates such as $\langle \bar{\psi}\psi \rangle$. These condensates induce mass-splittings (δm_s) between SUSY-partners and even electroweak symmetry breaking (and thereby m_W) as well as m_q, all of which thus become proportional to the much lower scale – i.e., $\Lambda_M(\Lambda_M/M_{Pl}) \sim 1 \, TeV \ll \Lambda_M$ [2]. *In this way, gravity plays the role of a major actor [32], not just that of a spectator, in determining some crucial elements of low-energy physics.* Furthermore, it turns out that the damping by M_{Planck} (noted above) relative to Λ_M, together with symmetries of the preonic theory, naturally explains not only why δm_s, m_W and m_t are so much smaller than M_{Planck} but also why m_e and even m_ν are smaller still by many orders of magnitude compared to m_t [4,1]. In short, the interplay of the metacolor force and gravity and the symmetries of the SUSY preonic theory turn out to explain the entire panorama of scales from M_{Planck} to $m_t \sim m_W$ to m_e to m_ν.

To bring out this role of gravity and to provide motivations for the underlying preonic approach, I need to say a few words about the puzzles in particle physics which confront us in the context of the standard model and the unifying ideas which have been proposed to resolve some of these puzzles.

II.   Going Beyond the Standard Model

The standard model of particle physics comprising electroweak and QCD components has brought a good deal of synthesis in our understanding of the basic forces of nature, especially in comparison to its predecessors, and has turned out to be brilliantly successful in terms of its agreement with experiments. Yet, as recognized

for some time [1], it falls short as a fundamental theory because it introduces some 19 parameters. And it does not explain (i) family replication; (ii) the coexistence of the two kinds of matter: quarks *and* leptons; (iii) the coexistence of the electroweak *and* the QCD forces with their hierarchical strengths $g_1 \ll g_2 \ll g_3$, as observed at low energies; (iv) quantization of electric charge; (v) inter and intrafamily mass-hierarchies - *i.e.*, $m_{u,d,e} \ll m_{c,s,\mu} \ll m_{t,b,\tau}$ and $m_b \ll m_t$, etc. - reflected by ratios such as $(m_u/m_t) \sim 10^{-4}$, $(m_c/m_t) \sim 10^{-2}$ and $(m_b/m_t) \sim \frac{1}{35}$; and (vi) the origin of diverse mass scales that span over more than 27 orders of magnitude from M_{Planck} to m_W to m_e to m_ν, whose ratios involve very small numbers such as $(m_W/M_{Pl}) \sim 10^{-17}$, $(m_e/M_{Pl}) \sim 10^{-22}$ and $(m_\nu/M_{Pl}) < 10^{-27}$. There are in addition the two most basic questions: (vii) how does gravity fit into the whole scheme, especially in the context of a good quantum theory?, and (viii) why is the cosmological constant so small or zero? Furthermore, turning to issues in cosmology, it is still a challenge to obtain a satisfactory particle-physics derived model for both inflation and baryogenesis.

These issues constitute at present some of the major puzzles of particle physics and provide motivations for contemplating new physics beyond the standard model which should shed light on them. The ideas which have been proposed and which do show promise to resolve at least some of these puzzles include the following hypotheses:

(1) **Grand Unification**: The hypothesis of grand unification, which proposes an underlying unity of the fundamental particles and their forces [6,7,8], appears attractive because it explains at once (i) the quantization of electric charge, (ii) the existence of quarks *and* leptons with $Q_e = -Q_p$, and (iii) the existence of the strong, the electromagnetic and the weak forces with $g_3 \gg g_2 \gg g_1$ at low energies, but $g_3 = g_2 = g_1$ at high energies. These are among the puzzles listed above and grand unification resolves all three. *Therefore I believe that the central concept of grand unification is, very likely, a step in the right direction.* By itself, it does not address, however, the remaining puzzles listed above, including the issues of family replication and origin of mass-hierarchies.

(2) **Supersymmetry**: As mentioned before, this is the symmetry that relates fermions to bosons [9]. As a local symmetry, it is attractive because it implies the existence of gravity. It has the additional virtue that it helps maintain a large hierarchy in mass-ratios such as $(m_\phi/M_U) \sim 10^{-14}$ and $(m_\phi/M_{Pl}) \sim 10^{-17}$, 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 does not explain the origin of the large hierarchies.*

(3) **Compositeness**: Here there are *two distinct suggestions*:

(a) Technicolor: The idea of technicolor [10] proposes that the Higgs bosons are composite but quarks and leptons are still elementary. Despite the attractive feature of dynamical symmetry breaking which eliminates elementary Higgs bosons and thereby the arbitrary parameters which go with them, this idea is excluded, at least in its simpler versions, owing to conflicts with flavor-changing neutral current processes

and oblique electroweak corrections. The so-called walking technicolor models may be arranged to avoid some of these conflicts at the expense, however, of excessive proliferation in elementary constituents. Furthermore, as a generic feature, none of these models seem capable of addressing any of the basic issues listed above, including those of family replication and fermion mass-hierarchies. Nor do they go well with the hypothesis of a unity of the basic forces.

(b) Preons: By contrast, the idea of preonic compositeness which proposes that not just the Higgs bosons but also the quarks and the leptons are composites of a *common* set of constituents called "preons" seems much more promising. Utilizing supersymmetry to its advantage, the preonic approach has evolved over the last few years to acquire a form [1-4] which is (a) far more economical in field-content and especially in parameters than either the technicolor or the conventional grand unification models, and, (b) is viable. Most important, utilizing primarily the symmetries of the theory (rather than detailed dynamics) and the peculiarities of SUSY QCD as regards forbiddeness of SUSY-breaking, in the absence of gravity, the preonic approach provides simple explanations for the desired protection of composite quark-lepton masses and at the same time for the origins of family-replication, inter-family mass-hierarchy and diverse mass scales. It also provides several testable predictions. In this sense, though still unconventional, the preonic approach shows promise in being able to address certain fundamental issues. I will return to it shortly.

(4) **Superstrings**:   Last but not least, the idea of superstrings [11] proposes that the elementary entities are not truly pointlike but are extended stringlike objects with sizes $\sim (M_{Planck})^{-1} \sim 10^{-33}$ cm. Strings as a rule smoothe out singularities of point-paritcle field theories. These theories (which may ultimately be just one) appear to be most promising in providing a unified theory of all matter (spins 0, 1/2, 1, 3/2, 2, ...) and all the forces of nature including gravity. Furthermore, by smoothing out singularities, as mentioned above, they seem capable of yielding a well-behaved quantum theory of gravity. In principle, assuming that quarks, leptons and Higgs bosons are elementary, a suitable superstring theory could also account for the origin of the three families and the Higgs bosons at the string unification scale, as well as explain all the parameters of the standard model. But in practice, this has not happened as yet. Some general stumbling blocks of string theories are associated with the problems of (i) a choice of the ground state (the vacuum) from among the many solutions and (ii) understanding supersymmetry breaking.

The ideas listed above are, of course, not mutually exclusive. In fact the superstring theories already comprise the idea of local supersymmetry and the central idea of grand unification. It remains to be seen, however, 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. In the following, I first recall the status of conventional grand unification, and then provide a perspective as well as motivations for an alternative approach to grand unification, based on the idea of preons. In this case, I discuss the origin of diverse mass-scales – from M_{Planck} to m_ν – through the interplay of the metacolor and gravitational forces. This brings out the role of grav-

ity in determining some crucial parameters of low-energy physics which is the main purpose of this talk. In the last section, I provide a summary and a perspective.

III. Grand Unification in the Conventional Approach and Supersymmetry

By "Conventional approach" to grand unification I mean the one in which quarks and leptons – and traditionally the Higgs bosons as well – are assumed to be elementary [6,7,8]. Within this approach, there are two distinct routes to higher unification: (i) the SU(4)-color route [6] and (ii) SU(5) [7]. Insisting on a compelling reason for charge – quantization, the former naturally introduces the left-right symmetric gauge structure $G_{224} = SU(2)_L \times SU(2)_R \times SU(4)^C_{L+R}$ [6], which in turn may be embedded in anomaly-free simple groups like SO(10) or E_6 [12].

It has been known for sometime that the dedicated proton decay searches at the IMB and the Kamiokande detectors [13], and more recently the precision measurements of the standard model coupling constants (in particular $\sin^2 \hat{\theta}_W$) at LEP [14] 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 invokes supersymmetry [15,16,17] into minimal SU(5) or SO(10). 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 $M_U \approx 2 \times 10^{16}$ GeV, and for their staying together beyond that scale.

The fact that the coupling constants meet in the context of these models is reflected by the excellent agreement of their predicted value of $[\sin^2 \hat{\theta}_W(m_z)_{theory} = .2325 \pm .005$ (using $\alpha_s(m_z) = \cdot 12 \pm \cdot 01$) with that determined at LEP: $[\sin^2 \hat{\theta}_W(m_z)]_{expt.} = .2316 \pm .0003$. In SUSY SU(5) or SO(10), dimension 5 operators do in general pose problems for proton decay. But the relevant parameters of the SUSY-space can be arranged to avoid conflict with experiments [18]. 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 SO(10) via the intermediate symmetry G_{224} 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 $n \to e^- \pi^+$ and even $n \to e^- e^+ \nu_e$, etc. in addition to the canonical $e^+ \pi^0$-mode [19].

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 $\leq 10^{34}$ 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, together with other forthcoming facilities, in particular, ICARUS,

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.

Questioning the Conventional Approach

Focusing attention on the meeting of the coupling constants (Fig. 1), the question arises: To what extent does this meeting reflect the "truth" or is it somehow deceptive? There are two reasons why such a question is in order.

(1)   First, the unity of forces reflected by the meeting of the coupling constants in SUSY SU(5) or SO(10) is truly incomplete, because it comprises only the gauge forces, but not the Higgs-exchange forces. *The latter are still governed by many arbitrary parameters – i.e., the masses, the quartic and the Yukawa couplings of the Higgs bosons – and are thus ununified.* Such arbitrariness goes against the central spirit of grand unification and has been the main reason in my mind since the 1970's (barring an important caveat due to the growth of superstring theories in the 1980's, see below) to consider seriously the possibility that the Higgses as well as the quarks and the leptons are composite. Furthermore, neither SUSY SU(5) nor SUSY SO(10), by itself, has the scope of explaining the origins of (a) the three families, (b) inter- and intra-family mass-splittings and (c) the hierarchical mass-scales: from M_{Planck} to m_ν.

(2)   The second reason for questioning the conventional approach is this: one might have hoped that one of the two schemes – i.e., the minimal SUSY SU(5) or the SUSY SO(10)-model, or a broken "grand unified" symmetry with relations between its gauge couplings near the string scale, would emerge from one of the solutions of the superstring theories [11,20], which would yield not only the desired spectrum of quarks, leptons and Higgs bosons but also just the right parameters for the Higgs masses as well as their quartic and Yukawa couplings. While it seems highly nontrivial that so many widely varying parameters should come out in just the right way simply from topological and other constraints of string theories, it would of course be most remarkable if that did happen. *But so far it has not.* There are in fact a very large number of classically allowed degenerate 4D solutions of the superstring theories (Calabi-Yau, orbifold and free fermionic, etc.), although one is not yet able to choose between them. Notwithstanding this general difficulty of a choice, it is interesting that there are at least some three-family solutions. However, not a single one of these has yielded *either* a SUSY SU(5) or an SO(10)-symmetry, *or* a broken "grand unified" symmetry involving direct product of groups, with the desired spectrum *and* Higgs-sector parameters, so as to explain the bizarre pattern of fermion masses and mixings of the three families [21]. Note that for a string theory to yield elementary quarks, leptons and Higgs bosons, either the *entire package* of calculable Higgs-sector parameters, which describe the masses of all the fermions and their mixings (subject to perturbative renormalization), should come out just right, or else the corresponding solution must be discarded. This no doubt is a *heavy burden.* For the case of the broken grand unified models, there is the additional difficulty that the grand unification scale of $2 \times 10^{16}\ GeV$ obtained from low-energy extrapolation

6

does not match the string unification scale of about 4×10^{17} GeV [22].

Thus, even if a certain superstring theory is the right starting point, and I believe it is, it is not at all clear, especially in view of the difficulties mentioned above, that it makes contact with the low-energy world by yielding elementary quarks, leptons and Higgs bosons. In this sense, it seems prudent to keep open the possibility that the meeting of the coupling constants in the context of conventional grand unification, which after all corresponds to predicting just one number – i.e., $sin^2\theta_W$ – correctly, may be fortuitous. Such a meeting should at least be viewed with caution as regards inferring the extent to which it reflects the "truth" because there are in fact alternative ways by which such a meeting can occur (see discussions below).

IV. The Preonic Approach to Unification and Supersymmetry

This brings me to consider an alternative approach to unification based on the ideas of preons and local supersymmetry [1-4]. Although the general idea of preons is old [23], the particular approach [1-4] which I am about to present has evolved in the last few years. It is still unconventional, despite its promising features. Its lagrangian introduces only six positive and six negative chiral preonic superfields which define the two flavor and four color attributes of a quark-lepton family and possess only *the minimal gauge interactions* corresponding to flavor-color and metacolor gauge symmetries [6]. But the lagrangian *is devoid altogether of the Higgs sector since its superpotential is zero owing to gauge and non-anomalous R-symmetry.* Therefore, it is free from all the arbitrary Higgs-mass, quartic and Yukawa coupling parameters which arise in the conventional approach to grand unification. This brings *real economy. In fact, the preon model possesses just three (or four) gauge coupling parameters which are the only parameters of the model and even these few would merge into one near the Planck scale if there is an underlying unity of forces as we envisage* [24]. By contrast, the standard model has 19 and conventional SUSY grand unification models have over 15 parameters. As mentioned in the introductory chapter, in addition to economy, the main motivations for pursuing the preonic approach are that it provides simple explanations for (a) the protection of the masses of the composite quarks and leptons [2], (b) family replication [3], (c) inter-family mass-hierarchy ($m_{u,d,e} \ll m_{c,s,\mu} \ll m_{t,b,\pi}$) [4], and (d) diverse mass-scales [1]. At the same time, it is viable with respect to observed processes including flavor-changing neutral current processes (see remarks later) and oblique electroweak corrections.

Fermion-boson partnership in a SUSY theory, (i.e. $\psi \leftrightarrow \varphi$ and $v_\mu \leftrightarrow \lambda$ or $\overline{\lambda}$ etc.), leads to 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 and c denote flavor and color quantum numbers. *The plurality of these combinations, which stems because of SUSY, is in essence the origin of family-replication.* By constructing composite superfields, Babu, Stremnitzer and I showed [3] that at the level of minimum dimensional composite operators (somewhat analogous to qqq 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 with spin-1/2 is, of course, accompanied by its scalar super-partner. *We thus see that one good answer to Rabi's famous question: "Who ordered that?", is supersymmetry and compositeness.*

Certain novel features in the dynamics of a class of SUSY QCD theories, in particular (as mentioned in the introduction) the forbidding of SUSY-breaking in the absence of gravity [5,2], and symmetries of the underlying preonic theory, play crucial roles in obtaining the other desired results – (a), (c) and (d), mentioned above. The reader is referred to the papers in Refs. 1-4 and in particular to a recent review of the preonic approach in Ref. 25 for details of the two broad dynamical assumptions [26] and the reasons underlying a derivation of these results. One attractive feature of the model, which emerges primarily through the symmetries of the underlying lagrangian, is that the two vector-like families $Q_{L,R}$ and $Q'_{L,R}$ (mentioned above) acquire masses of order 1 TeV, while the three chiral families acquire their masses primarily through their spontaneously induced mixings with the two vector-like families. This feature automatically explains why the electron family is so light compared to the tau-family and (owing to additional symmetries) why the masses of the muon-family lie inter-mediate between those of the electron and the tau-families. In particular, the model explains why $m_e \sim 1~MeV$ while $m_t \approx 100 - 180~GeV$, i.e., why $(m_e/m_t) \sim 10^{-5}$.

It is shown [1,4] that the model is capable of generating all the diverse scales – from M_{Planck} to m_ν – and thereby 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 $(m_\nu/M_{Pl}) < 10^{-27}$ – *in terms of just one fundamental input parameter*: the coupling constant α_M associated with the metacolor force. This comes about as follows. Corresponding to an input value $\overline{\alpha}_M \approx 1/27$ to $1/32$ at $M_{Pl}/10$, 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 constraint on SUSY breaking, which is forbidden [5], except for the presence of gravity. As mentioned before in section I, SUSY-breaking condensates like $\langle\lambda\lambda\rangle$ and $\langle\overline{\psi}\psi\rangle$ are thus naturally damped by (Λ_M/M_{Pl}) [2]. These induce (a) SUSY-breaking mass-splittings $\delta m_S \sim \mathcal{O}(\Lambda_M(\Lambda_M/M_{Pl})) \sim \mathcal{O}(1~TeV)$ and (b) $m_W \sim m_t \sim (1/10)\mathcal{O}(\Lambda_M(\Lambda_M/M_{Pl})) \sim \mathcal{O}(100~GeV)$. Note the natural origin of the small numbers: $(\delta m_s/M_{Pl}) \sim 10^{-16}$ and $(m_W/M_{Pl}) \sim 10^{-17}$. As also noted above, symmetries of the 5×5 fermion mass-matrix take us down to still lower scales – in particular to $m_e \sim \mathcal{O}(1~MeV)$, thus accounting for the tiny number $(m_e/M_{Pl}) \sim 10^{-22}$.

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 mass scales – from M_{Pl} to m_ν, and of the associated small numbers, as desired [1]. *This constitutes a unification of scales which is fundamentally as important as the unifica-*

tion of forces. By and by we see, as indicated in the beginning, that gravity plays an essential role in determining some crucial parameters of low-energy physicss, such as $\delta m_s, m_W, m_t, m_e$ and m_ν, all of which will vanish if we turn off gravity.

Furthermore, using the values of the standard model gauge couplings measured at LEP and the spectrum of the preon model above and below the preon-binding scale $\Lambda_M \sim 10^{11}\ GeV$, it is found (see Fig. 2) that the flavor-color gauge symmetry being $SU(2)_L \times U(1)_R \times SU(4)^c$ near the Planck scale and the metacolor gauge symmetry being either $SU(5)$ [24] or $SU(6)$ [27], the gauge couplings do tend to meet near the Planck scale. This opens up a novel possibility for grand unification at the preon level and thereby a possible new route for superstring theories to make connection with the low-energy world.

Last but not least the preon model leads to some *crucial predictions* which include the existence of the two vector-like families at the TeV-scale. [See Refs. 1,4 and 25 for a list of predictions.] These two families can be searched for at the forthcoming LHC, the e^-e^+ next linear collider (in planning) and especially at a future version of the now-extinct SSC. Their discovery or non-discovery with masses up to few TeV will clearly vindicate or exclude the preonic approach developed in Refs. 1-4.

V. Summary and a Perspective

The passage from the standard model to grand unification to supersymmetry and superstrings generates rightfully the hope for achieving an ultimate synthesis of all matter and its forces. The ideas and principles underlying this passage are those of:

- Local gauge invariance,
- Spontaneous breaking of symmetries through either elementary or composite Higgs boson,
- Supersymmetry and
- Extended string-like rather than point-like elementary entities.

Of these, the relevance of the first two ideas to nature – i.e., local gauge invariance and spontaneous symmetry breaking – is amply demonstrated by the success of the standard model comprising electroweak and QCD forces. Even then, the precise origin of electroweak symmetry breaking – i.e., whether it occurs through the vacuum expectation value of an elementary or a composite Higgs boson – is still not clear.

As explained above, although unconventional, the preonic alternative, which proposes that the Higgs bosons as well as the quarks and the leptons are composite, seems to be viable and deserves serious consideration. Its drawback at present is that it relies on two dynamical assumptions [26] as regards (a) confinement and (b) the pattern of symmetry-breaking that might occur at the preonic metacolor scale of 10^{11} GeV. While these two assumptions are not implausible, they have not yet been proven [28]. Not withstanding this drawback, the preonic approach has the clear advantage that it is the most economical model around. Furthermore, the simplicity with which it explains the origin of inter-family mass-hierarchy and of the diverse mass-scales (from M_{Planck} to m_W to m_ν) lends support to this approach. As noted above, the

preonic approach also retains the central spirit of grand unification as regards the meeting of the coupling constants. Its major strength is that it offers some crucial predictions, in particular the existence of two vector-like families at the TeV-scale (see above), by which it can be falsified or vindicated. For these reasons, it seems prudent to keep an open mind about the prospects of both the conventional as well as the preonic alternative.

Turning now to the relevance of supersymmetry to nature, although it is yet to show in experiments, just by uniting bosons and fermions it seems to play an *essential role* in every attempt at higher unification, beyond that of the standard model. These include: (i) the conventional approach to grand unification, (ii) the preonic approach, and (iii) superstrings.

Turning finally to the relevance of superstring theories to nature, motivations for these theories at present are entirely theoretical, somewhat analogous to but considerably beyond those for only supersymmetry. As mentioned before, the superstring theories provide the scope for the greatest synthesis so far in particle physics in that they seem capable of unifying *all matter* (spins 0, 1/2, 3/2, 2 and higher) as vibrational modes of the string and also *all their interactions*, which include not only the gauge forces and gravity but also the apparently non-gauge Higgs-type Yukawa and quartic couplings, within a single coherent framework. *The most attractive feature is that the superstring theories permit no dimensionless parameter at the fundamental level.* Equally important, they provide the scope for yielding a good quantum theory of gravity.

For these reasons, I believe that superstring theories possess many (or most) of the crucial ingredients of a "final theory" – "the theory of everything". *But I also believe that, as they stand, they do not constitute the whole of an ultimate theory*, because, first and foremost, in spite of the desirable feature that they constrain the gauge symmetry, the spectrum and the S-matrix elements (interactions), they are not generated by an underlying principle analogous to that of general coordinate or gauge invariance. Second, as a practical matter, they do not yet explain why we live in $3 + 1$ dimensions, and given the fact that supersymmetry does break in the real world, they do not explain why the cosmological constant is so small or zero. Third, they also do not yet provide a consistent understanding of (a) supersymmetry breaking and (b) choice of the ground state. Resolutions of some or all of these latter issues, which may well be inter-related, would clearly involve an understanding of the non-perturbative aspects and the symmetries of superstring dynamics. Recent developments which include the ideas of duality symmetries [29] and the realization that the strong-coupling limit of certain superstring theories is equivalent to the weak-coupling limit of certain other theories [30], permitting the elegant and bold conjecture [31] that there is just one superstring theory, may evolve into a form so as to achieve the lofty goal of solving superstring dynamics. It remains to be seen, however, as to how much of the resolution of the issues mentioned above could come "merely" from our understanding of the non-perturbative dynamics of the existing string theories and how much of such a resolution would involve altogether new ingredients beyond

the framework of existing string theories, which may call for some *radical changes* in our concepts at a fundamental level.

As another practical matter, for reasons mentioned in Sections III and IV, it is far from clear that the superstring theories make connections with the low-energy world by yielding elementary quarks, leptons and Higgs bosons. The preonic approach, though unconventional, provides a viable and attractive alternative to the conventional approach. It therefore remains to be seen whether the right superstring theory would yield the elementary quark-lepton-Higgs system with the entire "right package" of Higgs-sector parameters or, instead, the preonic spectrum and the associated gauge symmetry. In the latter case, the superstring theory would, of course, be relieved from yielding the right package of such Higgs sector-parameters because the Higgs-sector is simply absent in the preonic theory.

One last remark, our understanding of superstring theories is rather premature. It would clearly take some time – optimistically a decade but conservatively several decades –for us to understand (and this may be optimistic) the true nature of superstring theories and to discover the missing ingredients (alluded to above) in these theories, which together would help resolve the issues mentioned above. Meanwhile, regardless of these developments in the future, supersymmetry has clearly evolved as a great synthesizing principle. It is a common denominator and a central feature in all the attempts at higher unification which I mentioned above. *As such, it is hard to imagine how nature could have formulated her laws without the aid of supersymmetry.* Fortunately, unlike some other concepts, the relevance of supersymmetry to particle physics, as commonly conceived, can be established or falsified, depending upon whether the superpartners are discovered with masses in the range of 100 GeV to a few TeV or found to be absent in the forthcoming accelerators.

To conclude, the point of view brought forth in this talk is this: in the context of a supersymmetric preonic approach to unification, weak perturbative gravity, in collaboration with the preonic metacolor force, can play an *active role* in determining some crucial aspects of low-energy physics. Such an interplay between these two forces would in particular permit us to resolve one of the major puzzles in particle physics pertaining to the origin of diverse mass-scales that span over more than 27 orders of magnitude – from M_{Planck} to m_W to m_e to m_ν. By linking these diverse mass scales, one obtains a unification of scales [1] which is fundamentally as important as the unification of forces. This attractive scenario that emphasizes the active role of gravity at low energies can of course be realized, as far as I can see, only in the context of supersymmetry and preons [32]. Fortunately, just like supersymmetry, the preonic approach provides some crucial tests, in particular the existence of the two vector-like families with masses of order 1 TeV, which can be searched, together with SUSY particles and the Higgses, at the LHC, e^+e^- NLC and a future version of the now-extinct SSC. It is only these experimental facilities which can ultimately free us from the present bottleneck in particle physics and hopefully tell us which of our preconceived notions about elementary particles are right, if any, and which are wrong.

11

VI.   Acknowledgements

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[27] The threshold effects at Λ_M which permit unity with metacolor symmetry being SU(6) have been considered by K.S. Babu, J.C. Pati and M. Parida (to appear).

[28] The validity of the two assumptions stated in Ref. 26 in the light of certain general results derived recently by N. Seiberg [Proc. of PASCOS '94] is not clear either way if one allows for soft SUSY-breaking scalar preon (mass)^2-terms, which are expected to be induced by a hidden sector. There are a few other relevant differences between the premises of Seiberg's work and those of the preonic approach which are noted in Ref. 25 [see especially footnote 26 of this paper].

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