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A GRAND UNIFIED THEORY OBTAINED FROM BROKEN SUPERGRAVITY

John Ellis
CERN -- Geneva

Mary K. Gaillard
LAPP-Annecy-le-Vieux

Bruno Zumino
CERN -- Geneva

*To our friend Jacques Prentki
on the occasion of his
60th birthday*

ABSTRACT

We examine the possibility that the "fundamental" particles appearing in grand unified theories are a subset of the $SU(8)$ bound states of preons belonging to the $SO(8)$ extended supergravity, selected by the requirement that they form a renormalizable gauge theory. Analysis of the $SU(8)$ Higgs potential given by supersymmetry suggests that the maximal grand unification symmetry is $SU(5)$. A maximal subset of fermions free of $SU(5)$ anomalies, and hence renormalizable, contains three generations of $\underline{5} + \underline{10}$ left-handed helicity states. The unbroken $SU(5)$ theory may also contain $\underline{5}$ and $\underline{24}$ Higgs fields which are massless at the tree level.

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At present there are two main approaches to the problem of unifying all particle interactions: grand unified theories (GUTs)^{1),2)} and extended supergravities³⁾. On the one hand, interactions between "fundamental" particles of matter are often thought to be described by a renormalizable grand unified gauge theory. These GUTs have some phenomenological successes such as calculations^{4),5),6)} of $\sin^2 \theta_w$ and the mass of the bottom quark^{5),6),7)}, while also being sufficiently flexible to accommodate the full spectrum of fermions and interactions observed at low energies. The bottom quark mass calculation furnishes a phenomenological suggestion^{6),7)} that there are only three generations (u,d,e,ν_e) , (c,s,μ,ν_μ) , (t,b,τ,ν_τ) of "light" fermions with masses $\ll$ the grand unification mass of order 10^{15} GeV. A key problem⁸⁾ with GUTs is to understand the hierarchy of scales of symmetry breaking and masses, which apparently requires the unnatural fine-tuning of at least one^{6),9)} parameter in the Higgs potential. In fact these so-called "grand" unified theories have many ugly free parameters, mostly associated with their untidy Higgs systems. They are also grossly incomplete in that, although they become exact symmetries only at energies within about four orders of magnitude of the Planck mass, they do not attempt to include gravity. Extended supergravities³⁾ attempt to provide a viable theory of the coupling of matter fields to gravity without¹⁰⁾ many (all?) of the loop divergences usually encountered. Unfortunately there is so far no phenomenological evidence for supersymmetry, let alone supergravity. The observed "light" particles have no obvious supersymmetric partners¹¹⁾ and the largest known extended supergravity has an $SO(8)$ internal symmetry group which is too small¹²⁾ to contain the smallest GUT based²⁾ on the group $SU(5)$. Furthermore, it is not known whether the internal symmetry group of $SO(8)$ extended supergravity can be gauged.

A possible solution to these last two problems was discovered by Cremmer and Julia¹³⁾ who pointed out that each extended supergravity theory contained a concealed local unitary symmetry ($SU(8)$ in the case of $SO(8)$ supergravity, $U(4,5,6)$ for $SO(4,5,6)$ supergravity) associated with composite fields. They conjectured¹³⁾ that some unknown dynamical mechanism might cause the composite adjoint vector fields of this symmetry to become physical, propagating gauge bosons¹⁴⁾. We have further conjectured with Maiani¹⁵⁾ that the supersymmetric partners of these vector fields might also become dynamical, with some of them being the fermions and Higgs bosons "observed" at low energies. Thus the fields appearing explicitly in a supergravity theory would be preons of which all the "fundamental" particles of GUTs, but not the graviton, are composites. Unfortunately, this program runs into two essential problems¹⁵⁾. The gauge currents have

anomalies which would prevent the construction of a renormalizable theory, and conventional methods are unable to give masses to all unwanted fermionic states due to the lack of the necessary helicity partners with identical symmetry properties under the exact gauge subgroup $SU(3)_{\text{colour}} \times U(1)_{\text{e.m.}}$. These two problems arise from the essential chirality of the composite supermultiplet. We want some chirality in the theory to explain the left-handedness of weak currents and the low (zero?) masses of the neutrinos, but one can have too much of a good thing.

In this paper we propose a solution to the problem of embedding GUTs in supergravity, based on an unpublished argument of Veltman¹⁶⁾ which we understand as follows. If composite states are to have masses much smaller than their inverse size and to have effective interactions described by perturbation theory at energy scales much less than their inverse size, then their interactions must be renormalizable. Otherwise singularities would arise in the computation of vertex functions for which the only cut-off is the inverse size, which would result either in masses of order the inverse size for those states which have non-renormalizable couplings, or a breakdown of perturbation theory for their effective interactions.

Examples of this "theorem" are provided by the pseudo-Goldstone bosons (PGBs) of exact gauge symmetries broken dynamically, such as colour and technicolour¹⁷⁾. In these theories there are low-mass bound states (pions, technipions) whose masses would be zero in the absence of explicit chiral symmetry breaking in the Lagrangian. At energy scales much less than their inverse sizes $((1 \text{ fermi})^{-1}, 1 \text{ TeV})$, the interactions of these PGBs are described by an effective, renormalizable low-energy gauge theory $(U(1)_{\text{e.m.}}, SU(3)_{\text{colour}} \times SU(2)_L \times U(1))$. The strong or extra-strong non-renormalizable interactions of these PGB's are suppressed by powers of (E/f) at low energies E , where f is of order $(1 \text{ fermi})^{-1}$ for pions and 250 GeV for technipions.

On the basis of Veltman's "theorem" we conjecture that some unknown dynamical mechanism causes the symmetries of extended supergravity to break down at or near the Planck mass, giving rise to an effective lower energy GUT which is renormalizable and realized by some subset of the supermultiplet containing the composite gauge fields found by Cremmer and Julia¹³⁾. The most general renormalizable theory contains an anomaly-free representation of spin 1/2 fermions and fundamental scalar fields, as well as gauge vector bosons. Therefore the invocation of Veltman's "theorem" circumvents the two problems found¹⁵⁾ in our previous analysis with Maiani. This new philosophy gives us constraints on the symmetries, particle content and couplings of GUTs, and we obtain the following results.

The only supergravity theory large enough to contain a realistic GUT is based on $SO(8)$ and its composite symmetry $SU(8)$, while the only GUT that it contains is based on the $SU(5)$ group of Georgi and Glashow²⁾. Two arguments then indicate that a direct breakdown of $SU(8)$ to $SU(5)$ is plausible. Preliminary studies of the $SU(8)$ scalar field potential suggest that it may break the symmetry down at or near the Planck mass to a symmetry which cannot be larger than $SU(5)$. Analysis of the anomalies associated with the $SU(8)$ gauge group reveals that it must have anomalies, and that the only possible anomaly-free sub-theories based on the $SU(7)$ and $SU(6)$ subgroups which are vector-like with respect to $SU(3)_{\text{colour}} \times U(1)$ are actually completely vector-like. By contrast, the basic composite supermultiplet contains a maximal subset which is free of $SU(5)$ anomalies and has left-handed spin 1/2 fields in the following reducible representation:

$$(45 + \bar{45}) + 4(24) + 9(\underline{10} + \bar{\underline{10}}) + 3(\underline{5} + \bar{\underline{5}}) + 3(\bar{\underline{5}} + \underline{10}) + 9(\underline{1}) \quad (1)$$

Most of the spectrum (1) is vector-like, and these particles can acquire masses of order 10^{15} GeV to 10^{19} GeV. However, the spectrum (1) is slightly chiral, containing three generations of $SU(5)$ left-handed $\bar{\underline{5}} + \underline{10}$ fermions.

We find that if some components of the traceless scalar fields develop a vacuum expectation value, then the maximal residual symmetry is $SU(5)$. One appealing pattern breaks $SU(8)$ down to $SU(5)$ in such a way that the unbroken $SU(5)$ theory contains at least some $(\underline{5} + \bar{\underline{5}})$ and adjoint $\underline{24}$ representations of scalar fields, which are massless at the tree level and may be suitable for generating the successive lower energy spontaneous breakdowns of $SU(5) \rightarrow SU(3)_{\text{colour}} \times SU(2)_L \times U(1) \rightarrow SU(3)_{\text{colour}} \times U(1)$ through radiative corrections^{9),18)}.

In a normal pattern of spontaneous symmetry breakdown the massless $(\underline{5} + \bar{\underline{5}})$ scalars would have been "eaten" by $SU(8)$ vector bosons in a prior breakdown to $SU(5)$. However, in our scenario the $SU(8)/SU(5)$ gauge bosons could already have acquired masses through dynamical effects associated with anomalies, so that the $(\underline{5} + \bar{\underline{5}})$ scalars may survive to lower energies as pseudo-Goldstone bosons instead of being "eaten" at the Planck mass as Higgs fields.

We now describe the derivation of the results outlined above. The minimal GUT is based²⁾ on the group $SU(5)$ with rank 4. The candidate effective gauge group G_E from supergravity should be at least as large as this, and should in fact presumably contain a non-trivial generation group G_G at least as large as $SU(2)$:

$$G_E \supseteq SU(5) \times G_G \quad (2)$$

Only the largest supergravity based on $SO(8)$ has a $G_E = SU(8)$ large enough to satisfy the condition (2). The rank of $SU(8)$ is 7 and one might imagine that it could contain a GUT larger than $SU(5)$, but this is not the case. The only^{5),19)} realistic GUT group of rank 5 is $SO(10)$, and this is not a subgroup of $SU(8)$. The decomposition $SU(8)/SU(2)$ does not contain a suitable²⁰⁾ rank 6 GUT such as E_6 .

To proceed further we need the supermultiplet of composite fields containing the gauge fields of G_E . Arguments based on $N = 1$ and 2 supermultiplets and on superconformal theories have led us¹⁵⁾ to expect the generic structure indicated in the Table.

Table

A composite supermultiplet from $SO(N)$ supergravity

Helicity	$\frac{3}{2}$	1	$\frac{1}{2}$	0	---	$\frac{4-N}{2}$	$\frac{3-N}{2}$	+ TCP conjugates
Tensor Representation	J^A	V_B^A	$F_{[BC]}^A$	$S_{[BCD]}^A$	---	$R_{[BCD...F]}^A$	$\tilde{R}^A$	

where the lower indices are totally antisymmetrized 1,2,3...(N-1) times. The representations listed in the Table are reducible; they contain a traceless part and traces such as $S_{[ACD]}^A$ etc. In the case of $N = 8$ supergravity the V_A^A field does not correspond to a gauge symmetry of the theory, whereas it does in the cases of $N = 4,5,6$. In the case of $N = 6$ supergravity the helicity $\pm 1/2$ fermions appear in the representations (trace representations are shown in parentheses)

$$\left. \begin{aligned} +\frac{1}{2} &: \quad \underline{84} \quad (+\underline{6}) = \underline{45} + \underline{24} + \underline{10} + \underline{5} \quad (+\underline{5} + \underline{1}) \\ -\frac{1}{2} &: \quad \underline{70} \quad (+\underline{20}) = \underline{40} + \underline{15} + \underline{5} + \underline{10} \quad (+\underline{10} + \underline{10}) \end{aligned} \right\} \quad (3)$$

where we have also indicated $SU(5)$ decompositions. Adding the TCP conjugates of the $-1/2$ fermions to the $+1/2$ fermions we get a total set of left-handed fermions

$$\left. \begin{aligned} +\frac{1}{2} &: \quad \underline{84} + \underline{70} \quad (+\underline{6} + \underline{20}) = \underline{45} + \underline{40} + \underline{24} + \underline{15} + 2\underline{10} + 2\underline{5} \\ &\quad (+\underline{10} + \underline{10} + \underline{5} + \underline{1}) \end{aligned} \right\} \quad (4)$$

which is not sufficiently large to contain the "observed" spectrum of $SU(5)$ fermions whether or not we include the trace representations. The same is true a fortiori for the $N = 5$ case. We see again that we are forced to consider^{*} $N = 8$, whose spin 1/2 fields have the $SU(5) \times SU(3)$ decompositions:

$$\begin{aligned} +\frac{1}{2}: \quad \frac{216}{(+8)} &= (\overline{45}, 1) + (24, \underline{3}) + (10, \overline{3}) + (\underline{5}, \overline{3}) + (\underline{5}, \underline{8}) \\ &\quad + (\underline{5}, 1) + (\underline{1}, \underline{6}) + (\underline{1}, 3) \quad (+(\underline{5}, 1) + (\underline{1}, \underline{3})) \end{aligned} \quad \left. \vphantom{\frac{216}{(+8)}} \right\} (5)$$

$$\begin{aligned} -\frac{1}{2}: \quad \frac{504}{(+56)} &= (\overline{45}, \overline{3}) + (\overline{40}, \underline{3}) + (\underline{24}, 1) + (\overline{15}, 1) + (\overline{10}, \underline{8}) + (\underline{10}, \underline{6}) \\ &\quad + (\underline{10}, \underline{3}) + (\underline{10}, 1) + (\underline{5}, \underline{3}) + (\underline{5}, \overline{3}) \quad (+(\underline{10}, \overline{3}) + (\underline{10}, 1) + (\underline{5}, \overline{3}) + (\underline{1}, 1)) \end{aligned}$$

which are clearly sufficient to accommodate the "observed" quarks and leptons. Since the composite spin 1 trace field V_A^A is not a gauge field of $SO(8)$, it seems possible that none of the trace fields shown in parentheses in (5) actually become dynamical at low energies.

Before looking for anomaly-free subsets of the fermions (5) which Veltman's "theorem" suggests are candidates for low energy effective gauge theories, we first analyze the breakdown of $SU(8)$ by the scalar fields $S_{[BCD]}^A$ of the Table and their conjugates. They have the $SU(7)$ decomposition

$$0: \quad \frac{420}{(+28)} = \underline{224} + \underline{140} + \underline{35} + \underline{21} \quad (+\underline{21} + \underline{7}) \quad (6)$$

which contains no $SU(7)$ singlet. Therefore, if any component of $S_{[BCD]}^A$ can acquire a vacuum expectation value, $SU(7)$ must be broken. Continuing to the $SU(6)$ decomposition

$$0: \quad \frac{420}{(+28)} = \underline{105} + 2 \underline{84} + \underline{35} + 2 \underline{20} + 4 \underline{15} + 2 \underline{6} \quad (+\underline{15} + 2 \underline{6} + \underline{1}) \quad (7)$$

we also find no $SU(6)$ singlet in the untraced representation. From our hypothesis that the $SU(8)$ supermultiplet trace fields are not dynamical at low energies, it follows that $SU(6)$ must also be broken. Finally, we have the $SU(5)$ decomposition

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^{*}) The supergravity theories for $N = 7$ and $N = 8$ are almost certainly identical with both having an $SU(8)$ gauge symmetry.

$$0: \begin{array}{l} \underline{420} \\ (+28) \end{array} = 3 \underline{45} + \underline{40} + 3 \underline{24} + 9 \underline{10} + 3 \underline{10} + 9 \underline{5} + \underline{5} + 3 \underline{1} \quad (8)$$

$$(+10 + 35 + 31)$$

in which a singlet appears in the untraced representation for the first time. This means that group theory allows SU(5) as a maximal unbroken subgroup of SU(8).

We therefore focus on the SU(5) subgroup of SU(8), which is now the largest group about whose anomalies we need worry. There are many subsets of the fermions (5) which are free of SU(5) anomalies. Low energy phenomenology requires an $SU(3)_{\text{colour}} \times U(1)_{\text{e.m.}}$ subgroup of SU(5) to be vector-like. With this constraint there is a unique subset of (5) which has the maximum number of left-handed fermions: lumping $+1/2$ fermions and TCP conjugates of the $-1/2$ fermions together it is that displayed in Eq. (1). Perturbative symmetry breaking by radiative corrections may favour^{9),18)} the choice of a representation with the largest possible number of fermions. The sight of three chiral generations of $(\underline{10} + \bar{\underline{5}})$ fermions in (1) fills us with joy.

If we step back and try to find a subset of the fermions (5) which has no SU(6) anomalies and has a vector-like $SU(3)_{\text{colour}} \times U(1)$ subgroup, then the only solutions are completely vector-like. Furthermore, the "maximal" such theory which has the fermion content

$$(\underline{84} + \bar{\underline{84}}) + 2 \underline{35} + 4 \underline{20} + 2(\underline{15} + \bar{\underline{15}}) + (\underline{6} + \bar{\underline{6}}) \quad (9)$$

clearly has fewer fermions than the "maximal" SU(5) theory (1). Conversely, if we try to embed the SU(5) representation (1) in an SU(6) representation of fermions it will automatically have SU(6) anomalies. Thus the combined requirements of chirality, a vector-like $SU(3)_{\text{colour}} \times U(1)$ and maximality strongly favour the SU(5) anomaly-free representation (1), and strongly suggest that the SU(6) subgroup of SU(8) is broken down by anomalies.

It is in principle possible to go further in the analysis of symmetry breaking by analyzing the scalar field Lagrangian using supersymmetry constraints²¹⁾ which can determine a subset of couplings, namely

$$\mathcal{L} \left((\underline{420})^4 \right) + \mathcal{L} \left((\underline{216})^2 \times \underline{420} \right) + \mathcal{L} \left(\underline{216} \times \underline{504} \times \underline{420} \right)$$

One might hope that despite the dynamical breaking of supersymmetry, some or all of these constraints may remain valid at high momentum scale at or near the Planck mass^{*)}. They would then provide boundary conditions for computing the evolution of the coupling constants down to lower momenta using the renormalization group. It seems likely that the supersymmetric scalar field Lagrangian may provide a breakdown of SU(8) to SU(5) at or near the Planck mass. This could either be directly through the presence of a term quadratic in the $\underline{420}$ fields $S_{[BCD]}^A$ or indirectly through the presence of a zero in the quartic term $((\underline{420})^4)$ for some field direction $S_{[BCD]}^A$ which could then be exploited by radiative corrections to give $\langle 0 | S_{[BCD]}^A | \rangle \neq 0$.

One possibility suggested by preliminary studies of the scalar field potential is that some components $S_{[iCD]}^i$, where the upper index is identical with one of the lower indices, may develop non-zero values. These v.e.v.'s have components in the following representations of the SU(6) subgroup of SU(8):

$$\left\{ \langle 0 | S_{[iCD]}^i | 0 \rangle \right\} \in \underline{105}, \underline{84}, \underline{35}, \underline{15}, \underline{6} \quad (11)$$

if $\langle 0 | S_{[iCD]}^i | 0 \rangle \neq 0$ for just one pair $[C,D]$ then the symmetry breaking would be through an adjoint representation of some SU(6) subgroup of SU(8). The $\underline{35}$ and the $\underline{6}$ in (11) contain singlets of SU(5) which are what is needed if scalar fields are to break SU(8) down to SU(5) at or near the Planck mass.

In achieving this Higgs breaking, the scalar field potential would necessarily generate some zero mass fields which would normally be eaten by the corresponding SU(8)/SU(5) vector fields thereby giving them a mass. However, in our framework these vectors are supposed to have already acquired masses because of the dynamical symmetry breaking due to anomalies. They no longer have any appetite left, and the would-be massless Higgses are left as physical states. Presumably they need only be massless at the tree level as there is no reason to expect the loop

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*) This would be analogous to using SU(5) symmetric initial conditions to calculate $\sin^2 \theta_w$ from the measured values of α and α_s if we knew the renormalization group equations but did not know about the Higgs mechanism for spontaneous symmetry breaking.

corrections to the $SU(8)$ scalar field potential to respect all the $SU(8)$ supersymmetry. Since when an $SU(8)$ adjoint representation is decomposed with respect to $SU(5)$:

$$\underline{63} = \underline{24} + 3(\underline{5} + \bar{\underline{5}}) + 9 \underline{1} \quad (12)$$

one encounters three $(\underline{5} + \bar{\underline{5}})$ representations, it seems that the uneaten "pseudo-Higgses" may include several fields suitable for subsequent stages of $SU(5)$ symmetry breaking through radiative corrections¹⁸⁾. In order for a complete scenario⁹⁾ of $SU(5)$ symmetry breaking by radiative corrections to be valid, one also needs at least one $\underline{24}$ of scalar fields massless at least at the tree level, to take care of the first stage of $SU(5)$ symmetry breaking. Preliminary analysis of the $SU(6) \times (N = 2 \text{ supersymmetry})$ constraints on the couplings of $SU(6)$ adjoint scalars in (11) suggests that an $SU(5)$ adjoint $\underline{24}$ subset of scalars may indeed be massless at the tree level, though this requires further analysis. Having $\underline{24}$ and $\underline{5}$ Higgses massless at the tree level in the manner discussed here would be sufficient to evade theorems²²⁾ about sequential breaking of symmetries through radiative corrections. It remains to be seen whether this will in fact be possible.

There are clearly very many other questions about the program we have outlined. They are all in principle answerable, since our approach has no free parameters in the absence of topological effects. Answering these questions may in practice prove non-trivial.

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