Some Questions of Flavor in Supersymmetry

Michael Dine

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064

Abstract

We consider certain naturalness questions in supersymmetric theories. Various suggestions which give rise to squark degeneracies are reviewed. A stringy scenario, discussed by Kaplunovsky and Louis, is the only one which leads to complete degeneracy of squarks and sleptons at the high scale. Alternatives include the possible existence of a gauged non-Abelian horizontal symmetry, broken at some scale, and theories in which the “messengers” of supersymmetry breaking are gauge interactions. A model of the latter type is described, in which supersymmetry is dynamically broken at TeV energies. Models of this type can solve many of the naturalness problems of supersymmetric theories, and predict a rich phenomenology at SSC energies.
1. Introduction

The hierarchy problem suggests that there is new physics at TeV energy scales. The candidates which we know for this physics are supersymmetry and technicolor, though we should keep in mind that there may be something else (we have no good ideas for understanding the vanishing of the cosmological constant, for example). These are very attractive ideas, but both face potentially serious difficulties associated with problems of flavor.

It is usually said that technicolor theories fail when they confront the issue of flavor changing neutral currents. (For recent efforts to solve this problem, see ref. 1.) It is also often said that supersymmetry does not suffer from such difficulties. In particular, if squarks of different flavors are approximately degenerate, then the contribution of diagrams containing new supersymmetric particles are small. The degree of degeneracy required is quite severe, however. If the scale of supersymmetry breaking is, say, 300 GeV, then from the real part of $K$--$\overline{K}$ mixing one has

$$\frac{\delta m^2}{m_{\text{SUSY}}^2} < 10^{-2}.$$ (1.1)

As one increases the typical SUSY-violating mass, $m_{\text{SUSY}}$, this limit only improves linearly.

It is often argued that such a degeneracy is natural, at least at the Planck mass, $M_p$. In most considerations of the minimal supersymmetric standard model (MSSM), for example, one assumes that at the high scale, the soft breakings have the structure:

$$V_{\text{soft}} = m_{\text{SUSY}}^2 \sum |\phi_i|^2 + A\lambda_{ijk} + \ldots$$ (1.2)

(where $\lambda$ denote the cubic couplings in the superpotential). We will refer to the assumption that the $\phi\phi^*$ type mass terms are equal as the assumption of “degeneracy;” the assumption that the cubic soft-breaking terms are proportional to the corresponding terms in the superpotential we will refer to as the assumption of “proportionality.” In the framework of supergravity theories, one frequently hears the assertion that such a universality of couplings is reasonable; gravity, after all, is universal. But this argument, as it stands, is specious. In general relativity, matter couples universally to gravity as a consequence of a symmetry principle (and the fact that only the lowest dimension operators are important). In a supergravity theory, on the other hand, no symmetry that we observe at low energies requires degeneracy or proportionality. In string theory, for example, there is no reason to expect such relations to hold generically, and Ibanez and Lust have explicitly verified that they do not.\(^2\) There are other flavor problems in supersymmetry as well:
the neutron and electron electric dipole moments \( d_n \) and \( d_e \) severely constrain \( CP \)-violating phases in the soft-breaking terms.

In this talk, we will see that there are in fact a number of ways (at least three) in which an adequate degree of degeneracy and proportionality can arise at tree level in supersymmetric theories. Even before describing these, it should be stressed that the situation is not nearly so problematic as in the case of technicolor. In particular, if one assumes degeneracy and proportionality at the high scale, then ignoring the small Yukawa couplings (i.e., all but those of the \( t \) and perhaps the \( b \) quarks) there \( is \) a large, approximate flavor symmetry. This symmetry insures that radiative corrections to these relations are very tiny (assuming a cutoff of order \( M_p \)), and that flavor-changing processes are readily suppressed.

To understand the problem in more detail, consider a general \( N = 1 \) supergravity model, with supersymmetry broken in a hidden sector. Denote the hidden sector fields by \( z \), and the visible sector fields by \( y \). The general supergravity lagrangian (up to terms with two derivatives) is specified by three functions: the Kahler potential, \( K(\phi, \phi^*) \), the superpotential, \( W(\phi) \), and a function \( f(\phi) \) which describes the gauge couplings. In general, we can write, after suitable rescalings of the fields,

\[
K = k(z, z^*) + \sum_i y_i^* y_i + \ell_{ij}(z, z^*) y_i y_j^* + \ldots
\]  

If one writes the general potential in terms of \( K \) and \( W \), one sees that the condition for degeneracy and proportionality is that \( \ell_{ij} \propto \delta_{ij} \). As we have noted, no symmetry enforces this, and there is no reason, in general, to expect degeneracy. This condition is certainly not satisfied in any generic sense in string theory\(^[2]\). If we think in terms of ‘t Hooft’s naturalness criterion,\(^[3]\) it is clear that we do not expect degeneracy between squarks and sleptons to hold to better than \( O(\alpha/\pi) \), and between squarks of different flavors than to better than order Yukawa couplings.

I know, however, of four situations which can give rise to a significant degree of degeneracy and proportionality:

1. Kaplunovsky and Louis\(^[4]\) have recently pointed out that given certain assumptions about SUSY breaking, string theory can give rise to a significant level of degeneracy. In particular, if the auxiliary field associated with the dilaton supermultiplet, \( F_S \), is much larger than that associated with other moduli, \( F_M \), then all squarks and sleptons are indeed degenerate at tree level. These authors argue that it is hard to understand how this could come about, but I would suggest that given how little we understand about SUSY
breaking in string theory* this may be a significant clue to string dynamics. The phenomenology of this scenario has been considered in ref. 5.

2. If at the high scale the scalars are very light compared to the gauginos, some degree of degeneracy results.\[6\]

3. Perhaps there really is a flavor symmetry at the high scale. It must be broken in such a way that there are large non-degeneracies among fermions, yet a high degree of degeneracy among scalars. In the next section, I will focus on the possibility that these horizontal symmetries are non-abelian.\[7\] Since I gave this talk, the possibility of achieving this result with Abelian symmetries has been explored.\[8\]

4. Perhaps supersymmetry is broken at a rather low scale, and supersymmetry breaking is fed to ordinary fields through gauge interactions. In that case; squarks with a given set of gauge quantum numbers will be approximately degenerate. Recently, models of this type where supersymmetry breaking arises dynamically have been constructed.\[9\] These models will be reviewed briefly in section 3.

Only the first of these approaches leads to a MSSM phenomenology of the type which has been so widely explored recently. In the flavor symmetry scheme, one does not expect much degeneracy between squarks or sleptons with different gauge quantum numbers, nor between particles in the first two and the third generations. In the case that supersymmetry breaking is fed by gauge interactions, one expects masses to be roughly proportional to appropriate gauge couplings. All of this suggests that we should be open to a broad range of possibilities. The rest of this talk will focus on the third and fourth approaches to solving the degeneracy problem.

\* Indeed, one can well argue that there may be no sensible breaking of susy in string theory at weak coupling; certainly, none of the scenarios which have been proposed satisfy all of the conditions enumerated in ref. 4.
2. Non-Abelian Flavor Symmetries and Squark Degeneracy

An obvious solution to the problem of squark degeneracy is to suppose that there is an underlying, gauged non-Abelian flavor symmetry. Equally obvious is that this symmetry must be badly broken in order to account for the fermion mass matrix, $m_F$. The issue is how much degeneracy is possible with a realistic $m_F$. We will adopt a rather simple-minded approach, and will not attempt to explain $m_F$. We will follow two basic rules:

1. The horizontal symmetry will be a gauge symmetry. (More definitely, we will require that any continuous horizontal symmetry be a gauge symmetry.) This is consistent with the dogma that the only exact continuous symmetries should be gauge symmetries.

2. We will impose ’t Hooft’s naturalness criterion. We will insist that couplings (or sets of couplings) are only small if the theory becomes more symmetric in the limit that those couplings go to zero. This works two ways: new supersymmetric couplings can only be small if the theory becomes more symmetric in that limit; some of them must be small if one is to understand the smallness of corresponding Yukawa couplings.

The first question we must address is the scale of flavor symmetry breaking. Here I will assume that the breaking scale is near (in fact slightly below) $M_p$. Obviously it is of interest to explore breaking at much lower scales. The high energy scenario can be motivated in a stringy way. It is well-known that as one explores the moduli space of string compactifications, one frequently finds points of enhanced symmetry (e.g., the SU(3) symmetry of the simple $Z_3$ orbifold). Suppose that the horizontal symmetry is of this type. Then at this point there are moduli, i.e., fields with no potential, which transform under the symmetry. We will denote these fields generically by $\Phi$. The vev’s of these fields break flavor. They might also break $CP$ spontaneously. Their natural values are 0 (corresponding to unbroken symmetry) or $M_p$. In what follows we will suppose

$$\langle \Phi \rangle \sim \frac{1}{10} - \frac{1}{10^2}. \quad (2.1)$$

Such values are certainly plausible. For example, in string theory, where Fayet-Iliopoulos terms are frequently generated at one loop, the $\Phi$ vev’s might be expected to be of order $\alpha$.\[11\]

As an example, suppose that one has an SU(2) flavor symmetry, and that the light quarks and leptons lie in doublets. In particular, suppose that there are left-handed and right-handed doublets $Q^a, \bar{u}^a, \bar{d}^a$ and singlets $Q_s, \bar{u}_s, \bar{d}_s$. The
ordinary Higgs particles are assumed to be singlets of \( SU(2)_H \), while the moduli are assumed to be a set of \( N \) doublets, \( \Phi^a_i, i = 1 \ldots N \). Consider first how the fermion mass matrix arises in this framework. The superpotential just below \( M_p \) contains dimension-four terms:

\[
W_q = \lambda_1 \epsilon_{ab} Q_a \bar{d}_b H_1 + \lambda_2 \epsilon_{ab} Q_a \bar{u}_b H_2 + \lambda_3 Q_s \bar{d}_s H_1 + \lambda_4 Q_s \bar{u}_s H_2 .
\] (2.2)

These give rise to \( SU(2)_H \)-symmetric terms in the mass matrix. Clearly we need to assume that \( \lambda_1 \) and \( \lambda_2 \) are small in order that the \( u \) and \( d \) quarks be sufficiently light (this might be arranged by means of a discrete symmetry). \( SU(2)_H \)-violating terms arise at the level of dimension five and dimension six operators:

\[
\frac{1}{M_p} (\lambda_i^a \epsilon_{ab} \Phi^i_a \bar{Q}_b \bar{d}_s H_1 + \lambda_i^i \epsilon_{ab} \Phi^i_a \bar{Q}_b \bar{H}_1) + \frac{1}{M_p^2} (\lambda_i^j \epsilon_{cd} \Phi^i_a \Phi^j_c \bar{Q}_b \bar{H}_1 + ....) .
\] (2.3)

Note that the charmed-quark mass must arise from these operators, and is thus of order \( \Phi/M_p \)², so \( \Phi/M_p \) can’t be much smaller than 0.1.

Now consider soft-breaking terms. The breaking of the squark degeneracy can also be understood in terms of the effective action at scales slightly below \( M_p \). This lagrangian contains terms dimension-four, soft-breaking terms which give \( SU(2)_H \)-symmetric contributions to the squark mass matrices:

\[
V_{soft} = m_1^2 |Q_a|^2 + m_2^2 |Q_s|^2 + m_3^2 |\bar{u}_a|^2 + m_4^2 |\bar{u}_s|^2 + ...
\]

\[+ A_1 \lambda_1 Q \bar{d} H_1 + A_2 \lambda_2 Q \bar{u} H_1 + .... + h.c., \] (2.4)

Here, \( m_\Phi \) and \( A_i \) are of order \( m_{\text{SUSY}} \). Breaking of the symmetry will arise through terms of the type

\[
\delta V^2_{soft} = \frac{m_{\text{SUSY}}^2 \gamma_1 Q \bar{Q}^*}{M_p} + \frac{m_{\text{SUSY}}^2 \gamma'_1 Q \Phi_2 Q^*}{M_p} \] (2.5)

and

\[
\delta V^3_{soft} = \frac{m_{\text{SUSY}}^3 \gamma_{1.5} Q \bar{d} H_1 \eta_1 + \eta_2 \Phi_2 + \eta_3 \Phi_2^*}{M_p} + \frac{m_{\text{SUSY}}^3 \gamma_{1.5} Q \bar{d} H_1 \eta_1^*}{M_p} \] (2.6)

We have omitted \( SU(2)_H \) indices on \( Q, \bar{u}, \bar{d} \), but terms with all possible contractions should be understood. Here \( \gamma, \gamma', \eta \) and \( \eta' \) are dimensionless numbers.
By 't Hooft’s naturalness criterion, many of these couplings should not be much less than one; the theory does not become any more symmetric if these quantities vanish. As a result, the generic symmetry-violating terms in the first two generations are of order $(\Phi/M_{p})^{2} \sim 10^{-2}$. This is by itself just barely enough to adequately suppress the real part of $K-\bar{K}$ mixing. Many of the couplings here, however, can (and should!) be small by 't Hooft’s criterion, particularly off-diagonal couplings. (One might imagine suppressing these by imposing further discrete symmetries.) As a result, there is no difficulty with flavor-changing neutral currents.

If the phase of $\Phi^{a}$ is the origin of $CP$-violation, many of the new supersymmetric contributions to $d_{n}$ and $d_{c}$ are automatically suppressed. Complex terms in the gluino mass matrix must arise from terms in the function $f$ involving $\Phi^{a}$; by gauge invariance, these terms are at least quadratic in $\Phi$, and thus suppressed by two orders of magnitude. Similar remarks apply to the $A$ parameter. However, in the present framework, complex, off-diagonal terms can also arise in the squark mass matrices, and one must make sure that these are adequately suppressed. This poses no more difficulty than for the $K-\bar{K}$ system.

Clearly we have only scratched the surface of this subject. Most importantly, one would like to consider this problem in a framework which addresses the origin of quark and lepton masses, for example as in the work of ref. 12. In any case, certain predictions seem likely to emerge from any framework using non-abelian horizontal symmetries to solve the squark degeneracy problem. Because the top quark mass is so much larger than the others, one expects to encounter some sort of SU(2)-type structure. So one expects that left and right-handed squarks will lie in nearly degenerate doublets; there will be no degeneracy between the first two generations and the third, or between left and right.

3. Dynamical Supersymmetry Breaking at Low Energies

Dynamical supersymmetry breaking (DSB), needless to say, has the potential to address a set of naturalness issues which go well beyond the squark degeneracy problem. It has the potential to explain the hierarchy in terms of small, $e^{-c/g^{2}}$ effects. In addition, soft breakings and other effects should be calculable. In this section, I will briefly describe a model with

1. DSB (at a scale of order 100’s of TeV).
2. SUSY breaking fed down to ordinary particles by gauge interactions (leading to sufficient degeneracy and proportionality for FCNC’s).
3. Natural SU(2) $\times$ U(1) breaking; the low energy particle content, however, is necessarily different from that of the MSSM.
While these features are certainly wonderful, the model does have certain drawbacks:

1. It is complicated, and won’t win any beauty contests.

2. The model possesses one potentially dangerous “axion.” Provided a certain condition on couplings is satisfied, the mass of this axion can be $\sim 100 \text{ MeV}$.

Neither of these problems is in any obvious sense generic. Hopefully, they reflect the fact that we have not yet been clever enough, and someone will soon construct more attractive models with all of the good features listed above. In any case, these theories certainly provide an “existence proof,” and a framework in which to study the phenomenology of such low energy breaking. I believe that such a scheme provides an interesting alternative to that of the usual MSSM.

I do not have space here to fully review the issues involved in DSB, or to describe the model in detail, so instead I would like to just focus on some important features. The problem of DSB was first clearly posed by Witten.\textsuperscript{13} He pointed out that because of the non-renormalization theorems, supersymmetry breaking is necessarily non-perturbative and small at weak coupling. He elucidated several conditions for DSB to occur. First, one requires a massless fermion to play the role of the Goldstone fermion. In many instances, he argued, the issue is to show that a superpotential is generated for the light fields. Second, the “Witten index” must vanish; For several interesting theories, he could compute the index and showed that it was non-zero.

Subsequently, it was shown that superpotentials are generated in many theories.\textsuperscript{14} An example is provided by an SU(2) gauge theory with a single quark flavor (corresponding to two chiral doublets, $Q$ and $\bar{Q}$). Classically, such a theory has a set of degenerate vacua, with

$$Q = \begin{pmatrix} v \\ 0 \end{pmatrix} = \bar{Q}.$$  \hspace{1cm} (3.1)

For large values of $v$, the gauge symmetry is completely broken and the theory is weakly coupled. There is one light field in the vacuum; it can be written as $\Phi = \bar{Q}Q$, where it is understood that the fields are to be expanded in small fluctuations about their vacuum expectation values. A straightforward instanton calculation shows that a superpotential is generated for $\Phi$,

$$W_{np} = \frac{\Lambda^5}{\Phi}$$

where $\Lambda$ is the usual renormalization group invariant scale parameter of the theory.
While this example illustrates the non-perturbative breakdown of the non-renormalization theorems, it does not lead to a phenomenologically acceptable model, since the potential tends to zero for large $v$. If one adds a mass term, one finds that there are two supersymmetric ground states (consistent with the index).

These features turn out to be generic. In order to obtain DSB with a “nice” vacuum, one finds that one must satisfy two conditions (the “Seiberg criteria”):

1. The classical theory must have no flat directions
2. The theory must possess a spontaneously broken global symmetry.

It is easy to understand these criteria: if SUSY is unbroken, the Goldstone boson has a scalar partner, which parameterizes a set of flat directions; by assumption these don’t exist. This criterion is admittedly heuristic, but it works in all known examples.

If one wants to do phenomenology with such models, there are two approaches one might consider.

1. One might use such theories as hidden sectors for supergravity (or superstring) theories. The main problems with such schemes lie in obtaining gaugino masses\footnote{15}, and in trying to solve the other naturalness problems of supersymmetric theories. (Of course, one might try to solve these using flavor symmetries such as described in the previous section.) In the case of superstrings, one encounters the usual dilaton problem: any potential generated for the dilaton will tend to zero at weak coupling.\footnote{16}

2. Alternatively, one can consider low energy breaking.\footnote{17} In this case, one tries to gauge a global symmetry of the model, and identify it with the standard model gauge group. Then gauge loops will give rise to squark, slepton and gaugino masses. This has the desirable feature that to a very good approximation, squark and slepton masses depend only on gauge quantum numbers, and there is great suppression of flavor-changing processes. However, model building along these lines runs into a variety of serious problems. First, the simplest models exhibiting DSB with a large enough flavor symmetry possess very large gauge groups, and as a result, QCD is violently non-asymptotically free. Also, because of the presence of spontaneously broken global symmetries, there are typically unacceptable axions and Goldstone bosons.

Here I would like to describe a solution to these problems. The idea is simply to interpose an extra set of interactions between the sector of the theory which breaks DSB and the ordinary fields. In other words, there is a set of fields which are responsible for breaking DSB; we will refer to the associated gauge interactions as “supercolor.” Some of these fields carry an additional (gauged) quantum number
called “R-color.” There are a second set of fields, which I will refer to as “straddlers,” which carry both R-color and ordinary SU(3) × SU(2) × U(1) quantum numbers. Finally, there are the usual matter fields. The “straddlers” gain mass as a consequence of R-color interactions. Superpartners of ordinary fields gain mass by emitting SU(3) × SU(2) × U(1) gauge fields, which couple to the straddlers.

This approach is able to solve both of the problems listed above. First, because the R-color group need not be so large, the contribution of the straddlers to the QCD beta function need not spoil asymptotic freedom (in fact, in the model of ref. 9, it is possible to achieve the usual unification of couplings). Second, provided the R-color interactions are sufficiently strong, they can give a sufficiently large mass to the axion which arises from the DSB sector.

There is not space here to review the model of ref. 9 in detail. In that paper, a model is analyzed with

1. A sector whose full non-perturbative potential possesses a (local) minimum with DSB.
2. At this minimum, there is an unbroken SU(3) (which plays the role of R-color) and a broken SU(3), under which the straddlers transform.
3. At one loop, the straddlers obtain supersymmetry-breaking masses. These masses are negative, but analysis of the potential shows that SU(3) × SU(2) × U(1) is unbroken for a range of parameters. R-color is unbroken as well; because all of the straddlers gain mass at this stage, R-color can quickly become strong, giving mass to a dangerous axion which arose at the first stage of symmetry breaking.
4. Below the scale of the straddler masses, it is necessary to integrate out these fields. In principle, one must compute three loop graphs to obtain the masses of ordinary squarks and sleptons. However, these masses are proportional to a log of the supercolor scale over the straddler mass. This logarithmic term is easily isolated. One finds that its coefficient is positive, and that squark and lepton masses are given by an expression of the form:

\[ \tilde{m}_2 = \sum_i C_F^{(i)} \frac{\alpha_i^2}{\pi} m_{\text{SUSY}}^2 \]  

(3.2)

where \( m_{\text{SUSY}}^2 \) is a common mass parameter, and the sum is over the standard model gauge groups.
5. Gaugino masses are proportional to \( (\alpha_i/\pi)m_{\text{SUSY}} \) (with a non-universal coefficient).
6. SU(2) × U(1) breaking requires additional fields in the theory. The problem is that global discrete symmetries of the model forbid an $H_1 H_2$ term in the potential. Thus one must at least add a gauge singlet. However, if this is all one adds, only the Higgs field which couples to the top quark can gain a negative mass-squared, and the model necessarily contains an unacceptably light Higgs. This problem can be solved by adding an additional set of mirror fields, with sufficiently large couplings to the singlet. In this case, the singlet obtains a large vev, giving rise to large masses for the mirrors. The parameter space of the resulting theory is large, and it is easy to find an acceptable spectrum.

Again, I must refer the reader to ref. 9 for a complete treatment of this model. Let me close this section by summarizing its virtues (I have already stressed its drawbacks):

1. DSB
2. SU(2) × U(1) can be broken in an acceptable way; achieving this requires additional fields, and the simplest possibility we have listed above may be nearly the only one.
3. The model gives adequate squark and slepton degeneracies.
4. There are no new sources of $CP$ violation in the low energy theory, and thus no problem with $d_n$ or $d_e$.
5. There are no dangerous axions or goldstone bosons.
6. All couplings are small to high energies.
7. One can unify SU(3) × SU(2) × U(1) (at least in principle).
8. The superpotential is the most general one allowed by the gauge symmetries and a set of discrete symmetries.

There is a great deal of room for further work on these models. One would certainly like to construct examples which are less baroque and with a smaller degree of fine tuning. One might also like to find examples in which the supersymmetry-breaking minimum is the global minimum. Even within this model, one would like to further explore the parameter space, particularly with regards to the question of SU(2) × U(1) breaking. Finally, there are a number of cosmological issues one would like to examine. For example, the gravitino mass is 10’s of eV. This may pose problems for nucleosynthesis, unless they are diluted by decays of neutralinos. There are domain walls, though in the particular example of ref. 9, they disappear by the mechanism of ref. 18. Finally, the model contains massive, long-lived particles.
4. Conclusions

There are, as we noted earlier, four known ways to understand the problem of squark degeneracy. Only one, the dilaton-driven scenario in string theory, leads to assumptions precisely like those usually made in the MSSM. Two others have been explored here: the possibility of non-Abelian, gauged flavor symmetries, and DSB at low energies. Both of these offer alternatives to what has become the MSSM ideology; there is still much work to be done in exploring their phenomenology.

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