BEYOND THE STANDARD MODEL: AN ANSWER AND TWENTY QUESTIONS

FRANK WILCZEK
School of Natural Sciences, Institute for Advanced Study
Princeton, NJ 08540, USA

In dedicating this school to marking the 50th anniversary of the birth of particle physics, Professor Zichichi posed a special challenge and opportunity. When we think about our subject on such a large scale, we realize just how much was accomplished in a short time. Fifty years ago pions and kaons were ‘discovered’, in the sense that one first clearly distinguished pions from muons, and there were a pair of cosmic ray events that seemed to indicate the existence of unstable, heavy, hitherto unknown particles. From today’s perspective, we can see that these discoveries were the first steps along a path leading to completely new perspectives. Fifty years ago, one had the subjects of nuclear forces and beta decay. These were rich subjects in themselves, and for applications (nuclear reactors, atomic weapons, theory of stars). But the new discoveries made it obvious that nuclear forces ultimately should not be considered a self-contained subject, that at higher energies these ‘forces’ mutated into a much richer subject involving new particles and production processes, that the subject needed a new name: the strong interaction. Similarly the new discoveries showed that beta decay was just one exemplar of a wider set of instabilities infecting other particles. Some universality in these instabilities was perceived, and beta decay evolved into the weak interaction. A third great discovery 50 years ago was the Lamb shift. The outcome of this discovery was quite different. Instead of a new theory, one discovered the unexpected, latent power of existing ideas. By taking quantum electrodynamics in full seriousness as a relativistic quantum field theory, theorists were able to account for this and other radiative corrections to the naive theory, with awesome precision.

From these first stirrings of strong and weak interaction theory, and modern quantum field theory, to their fruition in the Standard Model was about 25 years. The succeeding 25 years have seen, first of all, the consolidation of the Standard Model, after extremely extensive and rigorous testing. But in learning in great depth and detail what the Standard Model can do, we also have become acutely aware of what it can’t do. The remaining questions are especially profound, because they have eluded an extremely powerful, successful
theory. I have been asked to discuss physics beyond the Standard Model, with the time scale of 50 years. One clear lesson from the history just discussed, is that it is foolhardy to try to do this too precisely. But vague discussions are mostly useless. So what I will present are precise questions (and a few tentative answers). I hope – and suspect – that several of them will be answered, and others made to look silly, in a significantly shorter time than 50 years.

To set the stage for the questions, let us begin with a quick overview of the Standard Model. The core of the Standard Model of particle physics is easily displayed in a single Figure, here Figure 1. There are gauge groups $SU(3) \times SU(2) \times U(1)$ for the strong, weak, and electromagnetic interactions. The gauge bosons associated with these groups are minimally coupled to quarks and leptons according to the scheme depicted in the Figure. The non-abelian gauge bosons within each of the $SU(3)$ and $SU(2)$ factors also couple, in a canonical minimal form, to one another. The $SU(2) \times U(1)$ group is spontaneously broken to the $U(1)$ of electromagnetism. This breaking is parameterized in a simple and (so far) phenomenologically adequate way by including an $SU(3) \times SU(2) \times U(1)$ scalar ‘Higgs’ field which condenses, that is, has a non-vanishing expectation value in the ground state. Condensation occurs at weak coupling if the bare (mass)$^2$ associated with the Higgs doublet is negative.

The fermions fall into five separate multiplets under $SU(3) \times SU(2) \times U(1)$, as depicted in Figure 1. The color $SU(3)$ group acts horizontally; the weak $SU(2)$ vertically, and the hypercharges (equal to the average electric charge) are as indicated. Note that left- and right-handed fermions of a single type generally transform differently. This reflects parity violation. It also implies that fermion masses, which of course connect the left- and right-handed components, only arise upon spontaneous $SU(2) \times U(1)$ breaking.

Only one fermion family has been depicted in Figure 1; of course in reality there are three repetitions of this scheme. Also not represented are all the complications associated with the masses and Cabibbo-like mixing angles among the fermions. These masses and mixing angles are naturally accommodated as parameters within the Standard Model, but I think it is fair to say that they are not much related to its core ideas – more on this below.

With all these implicit understandings and discrete choices, the core of the Standard Model is specified by three numbers – the universal strengths of the strong, weak, and electromagnetic interactions. The electromagnetic sector, QED, has been established as an extraordinarily accurate and fruitful theory for several decades now. Let me now briefly describe the current status of the remainder of the Standard Model.

Some recent stringent tests of the electroweak sector of the Standard Model
Figure 1: The core of the Standard Model: the gauge groups and the quantum numbers of quarks and leptons. There are three gauge groups, and five separate fermion multiplets (one of which, $e_R$, is a singlet). Implicit in this Figure are the universal gauge couplings – exchanges of vector bosons – responsible for the classic phenomenology of the strong, weak, and electromagnetic interactions. The triadic replication of quark and leptons, and the Higgs field whose couplings and condensation are responsible for $SU(2) \times U(1)$ breaking and for fermion masses and mixings, are not indicated.

are summarized in Figure 2. In general each entry represents a very different experimental arrangement, and is meant to test a different fundamental aspect of the theory, as described in the caption. There is precisely one parameter (the mixing angle) available within the theory, to describe all these measurements. As you can see, the comparisons are generally at the level of a percent accuracy or so. Overall, the agreement appears remarkably good, especially to anyone familiar with the history of weak interactions.

Some recent stringent tests of the strong sector of the Standard Model are summarized in Figure 3. Again a wide variety of very different measurements are represented, as indicated in the caption. A central feature of the theory (QCD) is that the value of the coupling, as measured in different physical processes, will depend in a calculable way upon the characteristic energy scale of the process. The coupling was predicted – and evidently is now convincingly measured – to decrease as the inverse logarithm of the energy scale: asymptotic freedom. Again, all the experimental results must be fit with just one
Figure 2: A recent compilation of precision tests of electroweak theory, from [4], to which you are referred for details. Despite some 'interesting' details, clearly the evidence for electroweak $SU(2) \times U(1)$, with the simplest doublet-mediated symmetry breaking pattern, is overwhelming.

| Parameter | Measurement with Total Error | Systematic Error | Standard Model | Pull |
|-----------|-------------------------------|------------------|----------------|------|
| $\sin^2 \theta_W$ | 0.2320 ± 0.0010 | 0.0008 | 0.23167 | 0.3 |
| $m_W$ [GeV] | 80.356 ± 0.125 | 0.110 | 80.353 | 0.0 |
| $1 - m_b^2/m_Z^2$ (ee) | 0.2214 ± 0.0012 | 0.0036 | 0.2235 | 0.2 |
| $m_e$ [GeV] | 175 ± 6 | 4.5 | 172 | 0.5 |

Let me emphasize that these Figures barely begin to do justice to the
Figure 3: A recent compilation of tests of QCD and asymptotic freedom, from\textsuperscript{5}, to which you are referred for details. Results are presented in the form of determinations of the effective coupling $\alpha_s(Q)$ as a function of the characteristic typical energy-momentum scale involved in the process being measured. Clearly the evidence for QCD in general, and for the decrease of effective coupling with increasing energy-momentum scale (asymptotic freedom) in particular, is overwhelming.

evidence for the Standard Model. Several of the results in them summarize quite a large number of independent measurements, any one of which might have falsified the theory. For example, the single point labeled ‘DIS’ in Figure 3 describes literally hundreds of measurements in deep inelastic scattering with different projectiles and targets and at various energies and angles, which must – if the theory is correct – all fit into a tightly constrained pattern.

The central theoretical principles of the Standard Model have been in place for nearly twenty-five years. Over this interval the quality of the relevant experimental data has become incomparably better, yet no essential modifications of these venerable principles has been required. Let us now praise the Standard Model:

- The Standard Model is here to stay, and describes \textit{a lot}.
Since there is quite direct evidence for each of its fundamental ingredients (i.e. its interaction vertices), and since the Standard Model provides an extremely economical packaging of these ingredients, I think it is a safe conjecture that it will be used, for the foreseeable future, as the working description of the phenomena within its domain. And this domain includes a very wide range of phenomena – indeed not only what Dirac called “all of chemistry and most of physics”\footnote{Dirac was referring, here, to quantum electrodynamics.}, but also the original problems of radioactivity and nuclear interactions which inspired the birth of particle physics in the 1930s, and much that was unanticipated.

- The Standard Model is a \textit{principled} theory.

  Indeed, its structure embodies a few basic principles: special relativity, locality, and quantum mechanics, which lead one to quantum field theories, local symmetry (and, for the electroweak sector, its spontaneous breakdown), and renormalizability (minimal coupling). The last of these principles, renormalizability, may appear rather technical and perhaps less compelling than the others; we shall shortly have occasion to re-examine it in a larger perspective. In any case, the fact that the Standard Model is principled in this sense is profoundly significant: it means that its predictions are precise and unambiguous, and generally cannot be modified ‘a little bit’ except in very limited, specific ways. This feature makes the experimental success especially meaningful, since it becomes hard to imagine that the theory could be approximately right without in some sense being exactly right.

- The Standard Model \textit{can be extrapolated}.

  Specifically because of the asymptotic freedom property, one can extrapolate using the Standard Model from the observed domain of experience to much larger energies and shorter distances. Indeed, the theory becomes simpler – the fundamental interactions are all effectively weak – in these limits. The whole field of very early Universe cosmology depends on this fact, as do the impressive semi-quantitative indications for unification and supersymmetry I shall be emphasizing momentarily.

  With this background, let me begin the questions.

  Question 1: Why does the Standard Model contain scattered multiplets, with peculiar hypercharge assignments?

  While little doubt can remain that the Standard Model is essentially correct, a glance at Figure 1 is enough to show that it is not a complete or final
SU(5): 5 colors RWBGP

10: 2 different color labels (antisymmetric tensor)

\[
\begin{align*}
\text{u}_L & : \text{RP}, \text{WP}, \text{BP} \\
\text{d}_L & : \text{RG}, \text{WG}, \text{BG} \\
\text{u}^c_L & : \text{RW}, \text{WB}, \text{BR} \\
\text{e}^c_L & : \text{GP} \\
\bar{5} & : 1 \text{ anticolor label}
\end{align*}
\]

\[
\begin{align*}
\text{d}^c_L & : \bar{\text{R}}, \bar{\text{W}}, \bar{\text{B}} \\
\text{e}_L & : \bar{\text{P}} \\
\nu_L & : \bar{\text{G}}
\end{align*}
\]

\[
Y = \frac{1}{6} (\text{R}+\text{W}+\text{B}) + \frac{2}{3} (\text{G}+\text{P})
\]

Figure 4: Organization of the fermions in one family in SU(5) multiplets. Only two multiplets are required. In passing from this form of displaying the gauge quantum numbers to the form familiar in the Standard Model, one uses the bleaching rules R+W+B = 0 and G+P = 0 for SU(3) and SU(2) color charges (in antisymmetric combinations). Hypercharge quantum numbers are identified using the formula in the box, which reflects that within the larger structure SU(5) one only has the combined bleaching rule R+W+B+G+P = 0. The economy of this Figure, compared to Figure 1, is evident.

theory. The fermions fall apart into five lopsided pieces with peculiar hypercharge assignments. This pattern needs explanation. Also the separate gauge theories of the strong, weak, and electromagnetic interactions, which are conceptually and mathematically quite similar, are practically begging to be seen as different aspects of a more encompassing structure.

Of all the questions I will discuss, this one is outstanding because it is the only one with a concrete and compelling answer, full of unexpected consequences.

Given that the strong interactions are governed by transformations among three color charges – say RWB for red, white, and blue – while the weak interactions are governed by transformations between two others – say GP for green and purple – what could be more natural than to embed both theories into a larger theory of transformations among all five colors? This idea has the additional attraction that an extra U(1) symmetry commuting with the strong SU(3) and weak SU(2) symmetries automatically appears, which we can attempt to identify with the remaining gauge symmetry of the Standard
Model, that is hypercharge. For while in the separate SU(3) and SU(2) theories we must throw out the two gauge bosons which couple respectively to the color combinations R+W+B and G+P, in the SU(5) theory we only project out R+W+B+G+P, while the orthogonal combination \((R+W+B)-\frac{2}{5}(G+P)\) remains.

Georgi and Glashow\cite{1} originated this line of thought, and showed how it could be used to bring some order to the quark and lepton sector, and in particular to supply a satisfying explanation of the weird hypercharge assignments in the Standard Model. As shown in Figure 4, the five scattered \(SU(3)\times SU(2)\times U(1)\) multiplets get organized into just two representations of \(SU(5)\). It is an extremely non-trivial fact that the known fermions fit so smoothly into \(SU(5)\) multiplets.

In all the most promising unification schemes, what we ordinarily think of as matter and anti-matter appear on a common footing. Since the fundamental gauge transformations do not alter the chirality of fermions, in order to represent the most general transformation possibilities one should use fields of one chirality, say left, to represent the fermion degrees of freedom. To do this, for a given fermion, may require a charge conjugation operation. Also, of course, once we contemplate changing strong into weak colors it will be difficult to prevent quarks and leptons from appearing together in the same multiplets. Generically, then, one expects that in unified theories it will not be possible to make a global distinction between matter and anti-matter and that both baryon number \(B\) and lepton number \(L\) will be violated, as they definitely are in \(SU(5)\) and its extensions.

As shown in Figure 4, there is one group of ten left-handed fermions that have all possible combinations of one unit of each of two different colors, and another group of five left-handed fermions that each carry just one negative unit of some color. (These are the ten-dimensional antisymmetric tensor and the complex conjugate of the five-dimensional vector representation, commonly referred to as the “five-bar”.) What is important for you to take away from this discussion is not so much the precise details of the scheme, but the idea that the structure of the Standard Model, with the particle assignments gleaned from decades of experimental effort and theoretical interpretation, is perfectly reproduced by a simple abstract set of rules for manipulating symmetrical symbols. Thus, for example, the object RB in this Figure has just the strong, electromagnetic, and weak interactions we expect of the complex conjugate of the right-handed up-quark, without our having to instruct the theory further. If you’ve never done it I heartily recommend to you the simple exercise of working out the hypercharges of the objects in Figure 4 and checking against what you need in the Standard Model – after doing it, you’ll find it’s impossible
Figure 5: Organization of the fermions in one family, together with a right-handed neutrino degree of freedom, into a single multiplet under SO(10). The components of the irreducible spinor representation, which is used here, can be specified in a very attractive way by using the charges under the SO(2) \( \otimes \) SO(2) \( \otimes \) SO(2) \( \otimes \) SO(2) \( \otimes \) SO(2) subgroup as labels. They then appear as arrays of \( \pm \) signs, resembling binary registers. There is the rule that one must have an even number of \( - \) signs. Strong SU(3) acts on the first three components, weak SU(2) on the final two. The SU(5) quantum numbers are displayed in the left-hand column, the number of entries with each sign-pattern just to the right, and finally the usual Standard Model designations on the far right.

Ever to look at the standard model in quite the same way again.

Although it would be inappropriate to elaborate the necessary group theory here, I’ll mention that there is a beautiful extension of SU(5) to the slightly larger group SO(10), which permits one to unite all the fermions of a family into a single multiplet. In fact the relevant representation for the fermions is a 16-dimensional spinor representation. Some of its features are depicted in Figure 5. The 16th member of a family in SO(10), beyond the 15 familiar degrees of freedom with a Standard Model family, has the quantum numbers of the right-handed neutrino \( N_R \).

We have seen that simple unification schemes are successful at the level of classification; but new questions arise when we consider the dynamics which underlies them.

Part of the power of gauge symmetry is that it fully dictates the interactions of the gauge bosons, once an overall coupling constant is specified. Thus if SU(5) or some higher symmetry were exact, then the fundamental strengths of the different color-changing interactions would have to be equal, as would the (properly normalized) hypercharge coupling strength. In reality the coupling strengths of the gauge bosons in SU(3) \( \times \) SU(2) \( \times \) U(1) are observed not to be equal, but rather to follow the pattern \( g_3 \gg g_2 > g_1 \).

Fortunately, experience with QCD emphasizes that couplings “run”. The
physical mechanism of this effect is that in quantum field theory the vacuum must be regarded as a polarizable medium, since virtual particle-anti-particle pairs can screen charge. Thus one might expect that effective charges measured at shorter distances, or equivalently at larger energy-momentum or mass scales, could be different from what they appear at longer distances. If one had only screening then the effective couplings would grow at shorter distances, as one penetrates deeper inside the screening cloud. However it is a famous fact that due to paramagnetic spin-spin attraction of like charge vector gluons, these particles tend to antiscreen color charge, thus giving rise to the opposite effect – asymptotic freedom – that the effective coupling tends to shrink at short distances. This effect is the basis of all perturbative QCD phenomenology, which is a vast and vastly successful enterprise, as we saw in Figure 3.

For our present purpose of understanding the disparity of the observed couplings, it is just what the doctor ordered. As was first pointed out by Georgi, Quinn, and Weinberg, if a gauge symmetry such as SU(5) is spontaneously broken at some very short distance then we should not expect that the effective couplings probed at much larger distances, such as are actually measured at practical accelerators, will be equal. Rather they will all have been affected to a greater or lesser extent by vacuum screening and anti-screening, starting from a common value at the unification scale but then diverging from one another at accessible accelerator scales. The pattern $g_3 \gg g_2 > g_1$ is just what one should expect, since the antiscreening or asymptotic freedom effect is more pronounced for larger gauge groups, which have more types of virtual gluons.

The marvelous thing is that the running of the couplings gives us a truly quantitative handle on the ideas of unification, for the following reason. To fix the relevant aspects of unification, one basically needs only to fix two parameters: the scale at which the couplings unite, which is essentially the scale at which the unified symmetry breaks; and their value when they unite. Given these, one calculates three outputs: the three a priori independent couplings for the gauge groups SU(3)$\times$SU(2)$\times$U(1) of the Standard Model. Thus the framework is eminently falsifiable. The miraculous thing is, how close it comes to working (Figure 6).

The unification of couplings occurs at a very large mass scale, $M_{un} \sim 10^{15}$ Gev. In the simplest version, this is the magnitude of the scalar field vacuum expectation value that spontaneously breaks SU(5) down to the standard model symmetry SU(3)$\times$SU(2)$\times$U(1), and is analogous to the scale $v \approx 250$ Gev for electroweak symmetry breaking. The largeness of this large scale mass scale is important in several ways:

- It explains why the exchange of gauge bosons that are in SU(5) but not in
Figure 6: Evolution of Standard Model effective (inverse) couplings toward small space-time
distances, or large energy-momentum scales. Notice that the physical behavior assumed
for this Figure is the direct continuation of Figure 3, and has the same conceptual basis.
The error bars on the experimental values at low energies are reflected in the thickness of
the lines. Note the logarithmic scale. The qualitative aspect of these results is extremely
encouraging for unification and for extrapolation of the principles of quantum field theory,
but there is a definite small discrepancy with recent precision experiments.

SU(3)×SU(2)×U(1), which re-shuffles strong into weak colors and generically
violates the conservation of baryon number, does not lead to a catastrophically
quick decay of nucleons. The rate of decay goes as the inverse fourth power
of the mass of the exchanged gauge particle, so the baryon-number violating
processes are predicted to be far slower than ordinary weak processes, as they
had better be.

- \( M_{\text{un}} \) is significantly smaller than the Planck scale \( M_{\text{Planck}} \sim 10^{19} \text{ GeV} \)
at which exchange of gravitons competes quantitatively with the other inter-
actions, but not ridiculously so. This indicates that while the unification of
couplings calculation itself is probably safe from gravitational corrections, the
unavoidable logical next step in unification must be to bring gravity into the
mix.
• Finally one must ask how the tiny ratio of symmetry-breaking mass scales \( v/M_{\text{un}} \approx 10^{-13} \) required arises dynamically, and whether it is stable. This is the so-called gauge hierarchy problem, which I shall discuss in a more concrete form momentarily.

The success of the GQW calculation in explaining the observed hierarchy \( g_3 \gg g_2 \gg g_1 \) of couplings and the approximate stability of the proton is quite striking. In performing it, we assumed that the known and confidently expected particles of the Standard Model exhaust the spectrum up to the unification scale, and that the rules of quantum field theory could be extrapolated without alteration up to this mass scale – thirteen orders of magnitude beyond the domain they were designed to describe. It is a triumph for minimalism, both existential and conceptual.

However, on further examination it is not quite good enough. Accurate modern measurements of the couplings show a small but definite discrepancy between the couplings, as appears in Figure 6. And heroic dedicated experiments to search for proton decay did not find it; they currently exclude the minimal SU(5) prediction \( \tau_p \approx 10^{31} \text{ yrs.} \) by about two orders of magnitude.

Given the scope of the extrapolation involved, perhaps we should not have hoped for more. There are several perfectly plausible bits of physics that could upset the calculation, such as the existence of particles with masses much higher than the electroweak but much smaller than the unification scale. As virtual particles these would affect the running of the couplings, and yet one certainly cannot exclude their existence on direct experimental grounds. If we just add particles in some haphazard way things will only get worse: minimal SU(5) nearly works, so the generic perturbation from it will be deleterious. This is a major difficulty for so-called technicolor models, which postulate many new particles in complicated patterns. Even if some \textit{ad hoc} prescription could be made to work, that would be a disappointing outcome from what appeared to be one of our most precious, elegantly straightforward clues regarding physics well beyond the Standard Model.

Fortunately, there is a theoretical idea which is attractive in many other ways, and seems to point a way out from this impasse. That is the idea of supersymmetry. Supersymmetry is a symmetry that extends the Poincare symmetry of special relativity (there is also a general relativistic version). In a supersymmetric theory one has not only transformations among particle states with different energy-momentum but also between particle states of different \textit{spin}. Thus spin 0 particles can be put in multiplets together with spin \( \frac{1}{2} \) particles, or spin \( \frac{1}{2} \) with spin 1, and so forth.

Supersymmetry is certainly not a symmetry in nature: for example, there is certainly no bosonic particle with the mass and charge of the electron. More
generally if one defines the $R$-parity quantum number

$$R \equiv (-)^{3B+L+2S},$$

which should be accurate to the extent that baryon and lepton number are conserved, then one finds that all currently known particles are $R$ even whereas their supersymmetric partners would be $R$ odd. Nevertheless there are many reasons to be interested in supersymmetry, and especially in the hypothesis that supersymmetry is effectively broken at a relatively low scale, say $\approx 1$ Tev. Anticipating this for the moment, let us consider the consequences for running of the couplings.

The effect of low-energy supersymmetry on the running of the couplings was first considered long ago, well before the discrepancy described above was evident experimentally. One might have feared that such a huge expansion of the theory, which essentially doubles the spectrum, would utterly destroy the approximate success of the minimal SU(5) calculation. This is not true, however. To a first approximation, roughly speaking because it is a space-time as opposed to an internal symmetry, supersymmetry does not affect the group-theoretic structure of the unification of couplings calculation. The absolute rate at which the couplings run with momentum is affected, but not the relative rates. The main effect is that the supersymmetric partners of the color gluons, the gluinos, weaken the asymptotic freedom of the strong interaction. Thus they tend to make its effective coupling decrease and approach the others more slowly. Thus their merger requires a longer lever arm, and the scale at which the couplings meet increases by an order of magnitude or so, to about $10^{16}$ Gev. Also the common value of the effective couplings at unification is slightly larger than in conventional unification ($\frac{g^2}{4\pi} \approx \frac{1}{12}$ versus $\frac{1}{40}$). This increase in unification scale significantly reduces the predicted rate for proton decay through exchange of the dangerous color-changing gauge bosons, so that it no longer conflicts with existing experimental limits.

Upon more careful examination there is another effect of low-energy supersymmetry on the running of the couplings, which although quantitatively small has become of prime interest. There is an important exception to the general rule that adding supersymmetric partners does not immediately (at the one loop level) affect the relative rates at which the couplings run. This rule works for particles that come in complete SU(5) multiplets, such as the quarks and leptons (which, since they don’t upset the full SU(5) symmetry, have basically no effect) or for the supersymmetric partners of the gauge bosons, because they just renormalize the existing, dominant effect of the gauge bosons themselves. However there is one peculiar additional contribution, from the supersymmetric partner of the Higgs doublet. It affects only the weak SU(2)
and hypercharge U(1) couplings. (On phenomenological grounds the SU(5) color triplet partner of the Higgs doublet must be extremely massive, so its virtual exchange is not important below the unification scale. Why that should be so, is another aspect of the hierarchy problem.) Moreover, for slightly technical reasons even in the minimal supersymmetric model it is necessary to have two different Higgs doublets with opposite hypercharges. The main effect of doubling the number of Higgs fields and including their supersymmetric partners is a sixfold enhancement of the asymmetric Higgs field contribution to the running of weak and hypercharge couplings. This causes a small, accurately calculable change in the calculation. From Figure 7 you see that it is a most welcome one. Indeed, in the minimal implementation of supersymmetric unification, it puts the running of couplings calculation right back on the money.

Since the running of the couplings with scales depends only logarithmically on the mass scale, the unification of couplings calculation is not terribly sensitive to the precise scale at which supersymmetry is broken, say between 100 Gev and 10 Tev. (To avoid confusion later, note that here by “the scale at which supersymmetry is broken” I mean the typical mass splitting between Standard Model particles and their supersymmetric partners. The phrase is frequently used in a different sense, referring to the largest splitting between supersymmetric partners in the entire world-spectrum; this could be much larger, and indeed in popular models it almost invariably is. The ambiguous terminology is endemic in the literature; fortunately, the meaning is usually clear from the context.) There have been attempts to push the calculation further, in order to address this question of the supersymmetry breaking scale, but they are controversial. For example, comparable uncertainties arise from the splittings among the very large number of particles with masses of order the unification scale, whose theory is poorly developed and unreliable.

Let me summarize, now, this long answer to our first question.

- The unification of strong and weak color charges works beautifully, at the level of symmetry.
- The ugly ducklings of the Standard Model, the hypercharges of the fermions, become elegant swans in unified theories.
- The superficially most severe problems facing this unification: the inequality of observed coupling strengths, and the existence of baryon-number violating processes with substantial strength, are removed, or at least drasti-

\[\text{Perhaps the simplest, though not the most profound, way to appreciate the reason for this has to do with anomaly cancelation. The minimal spin-1/2 supersymmetric partner of the Higgs doublet is chiral and has non-vanishing hypercharge, introducing an anomaly. By including a partner for the anti-doublet, one cancels this anomaly.}\]
Figure 7: Evolution of the effective (inverse) couplings in the minimal extension of the Standard Model, to include supersymmetry. The concepts and qualitative behaviors are only slightly modified from Figure 6 (a highly non-trivial fact!) but the quantitative result is changed, and comes into adequate agreement with experiment. I would like to emphasize that results along these lines were published well before the difference between Figure 6 and Figure 7 could be resolved experimentally, and in that sense one has already derived a successful prediction from supersymmetry.

cally tempered, by careful attention to the running of couplings.

• This points to a very high scale where the unified symmetry is spontaneously broken.

• The unification of couplings does not quite work out for the minimal Standard Model.

• On the other hand, if we augment the minimal Standard Model to include low-energy supersymmetry, there is stunning agreement with experiment.

• Low-energy supersymmetry is attractive in several other ways; especially, it can address the hierarchy problem. (see Figure 8)

All this provides, in my opinion, very good reasons to be optimistic about
Figure 8: Contributions to the Higgs field self-energy. These graphs give contributions to the Higgs field self-energy which separately are formally quadratically divergent, but when both are included the divergence is removed. In models with broken supersymmetry a finite residual piece remains. If one is to obtain an adequately small finite contribution to the self-energy, the mass difference between Standard Model particles and their superpartners cannot be too great. This – and essentially only this – motivates the inclusion of virtual superpartner contributions in Figure 7 beginning at relatively low scales.

the future of experimental particle physics at the high energy frontier. For much more information on supersymmetry, I heartily recommend a lively recent review by Dienes and Kolda.

Question 2: Can gravity be brought into the unification?

A remarkable consequence of the unification of couplings calculation is the emergence of a very large mass scale, comparable to the Planck scale

\[ M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} \]  

which is the value of the cutoff, such that loop integrals involving virtual graviton exchange become of order unity. If we had plotted the effective coupling of gravity on the same graph as the other couplings, it would start much smaller (or with much larger inverse coupling), evolve as a power rather than logarithmically, and – since the unified coupling is slightly smaller than unity – meet the others slightly below the Planck scale.
I said the scales were ‘comparable’, but actually the unification scale is 2-3 orders of magnitude smaller. This difference is important for the self-consistency of the calculation, since gravitational effects were ignored. But it is close enough to force the question, always of course present in principle, of getting a fully unified theory including all four interactions. One of the first challenges such a theory should meet, is to account for this residual scale discrepancy.

String theory, or its elaboration into M theory, currently supplies the best ideas for how a fully unified theory might be achieved. This brings up the next question ...

Question 3: Can string/M theory be made algorithmic? testable? user-friendly?

Professor Green told you about the latest developments in this impressive and dynamic subject. One cannot help but be dazzled by the wealth of new concepts and results. There is so much structure and mathematical consistency that one comes to feel, as Einstein said when asked whether he thought general relativity might be wrong (before the measurement of the bending of light) “then the Lord will have missed a great opportunity.”

Yet very fundamental questions and limitations remain. They are not just technicalities, and should not be underestimated. My question attempts to identify them in a precise and I hope constructive way.

A theory is algorithmic if one knows, in principle, how to compute its consequences. It may be easy to compute some consequences, and very difficult in practice to compute others. QCD is an excellent example of this. Calculating short distance properties is easy (or at least straightforward) while calculating nuclear binding energies is hard. It may be that one can only compute up to a certain accuracy, and the theory will break down if pushed too hard. QED provides an excellent example of this. Its perturbation expansion has given us far and away the most accurately tested results in natural science, yet this expansion does not converge and the theory, as normally defined and used, does not properly exist. (More precisely, one cannot satisfy the full axioms of relativistic quantum field theory in using just electrons coupled to photons. One can work with a version of QED cut off at an astronomically large energy scale, which ultimately fails to satisfy the axioms, but has the same practical consequences as naive QED.) In any case, both for QCD and for QED there is a mechanical procedure to answer all physically meaningful questions within their scope. On the other hand, I don’t think anyone would know how to program a computer, even in principle, to compute whether string theory gives us, for example, exactly four macroscopic space-time dimensions.
Another criterion is whether the theory is testable. This is not as clear-cut a question as it might sound. One can imagine different reactions to a given body of evidence—juries are not always unanimous. Feynman was expressing doubts about QCD well into the 1980s. Certainly the discovery of supersymmetry would be extremely encouraging for string theory, since the theory incorporates supersymmetry in its sinews. But on the other hand supersymmetry is an idea that can stand on its own, and the idea that it should be broken only at low energies is by no means an obvious consequence of string theory (compare, in this regard, ten-dimensional Lorentz invariance). In any case, I think we can all agree that more characteristic, less generic sorts of predictions would be welcome.

This brings us to the final desideratum, that the theory should become user friendly. Concretely, what I mean is this: we may have the germs of an overarching theory that is supposed to contain answers to each one of the questions I am posing here (except this one, and number 20). Yet I think it is fair to say that no such answers, derived from string theory, are currently in place. We shouldn’t have to guess whether this is due to temporary mathematical difficulties, or something more fundamental. We must aspire to more meaningful contact between high theory and the major features of observable reality beyond the Standard Model.

Question 4: Why is the cosmological term so small?
We have become accustomed to the idea that the vacuum, which evolution has encouraged us to regard as empty and void, is in reality full of various symmetry-breaking condensates and fluctuating fields. Yet gravity seems to be oblivious to this structure: the energy-momentum tensor of empty space, proportional to the cosmological term, is either zero or at least smaller by many orders of magnitude than naive expectations (from condensation energies, for example.)

In operator language, the cosmological term corresponds to the interaction with the unit operator, $\sqrt{g}L = \Lambda\sqrt{g}$. No ordinary symmetry can banish such a term. Its absence is a profound problem. To explain it might require symmetry principles of a new type, or a re-examination of fundamental aspects of the formulation of general relativity.

For a recent review, see [15].

Question 5: How is the hierarchy of electroweak and unified symmetry breaking established?
If we believe in the picture suggested by the unification of couplings, there is a vast disparity between two fundamental scales of symmetry breaking. In a
broad sense this is explained by the fact that the running of couplings – both
gauge couplings, and the Yukawa couplings appearing in effective potentials – is
logarithmic, so the range of energy scales over which significant changes occur
can easily be very large. I have also mentioned how, at a very heuristic level,
supersymmetry can protect the low-energy effective interactions (specifically,
the Higgs mass) from being infected and pulled up to the high scale. There
are a lot of complications, however, in making this work in detail.

A very specific problem in this circle of ideas is to understand why the
Higgs doublet – unlike any other component of the Standard Model or its
supersymmetric extension – does not unify at low energies. By rights it should
be part of a vector representation of $SU(5)$, with a triplet partner. But the
triplet partner mediates proton decay, and so on phenomenological grounds it
must be extremely heavy, of order the unification scale. This split multiplet,
you will recall, also played a major role in making the unification of couplings
come out right in the MSSM. The phenomenon of doublet-triplet splitting is
striking and qualitative, so it might be one of our best clues for reconstructing
the symmetry-breaking dynamics at the unification scale.

Question 6: How is supersymmetry broken?
The unification of couplings calculation gives us some confidence that su-
persymmetry is broken at the weak scale. However, both the strength and the
weakness of this calculation is its relative insensitivity to details. Since the
running of couplings is logarithmic, and the couplings are small, only gross
changes in the overall scale could significantly alter the results. Thus the
question whether the overall scale of breaking is 100 Gev or 10 Tev, and the
question of relative values of different squark, slepton, higgsino and gaugino
masses are left wide open, from a phenomenological point of view.

There are several different scenarios for supersymmetry breaking, with
quite different phenomenological consequences. For an introduction, I refer
you again to [14].

Question 7: Why are there three families? What explains the pattern of
masses and mixing?
Nobody knows.

One important possibility, that could potentially anchor the discussion of
this question, is that the top quark mass corresponds to an infrared fixed point
of the renormalization group [19]. That is, it could well be that any sufficiently
large value of the top quark- Higgs doublet Yukawa coupling at the unification
scale flows down to something close to the observed value at low energy. This
could also be true of the bottom quark, if (as in supersymmetric models) two
separate Higgs fields, with significantly different values of their expectation values, were responsible for top and bottom masses. The ratio of vacuum expectation values, in supersymmetric models, is conventionally written \( \tan \beta \); it will be very interesting, in this connection, to see if \( \tan \beta \gg 1 \).

Question 8: What are the neutrino masses and mixings?

Professor Totsuka has addressed experimental and phenomenological aspects of this question at length, so I will confine myself to a few theoretical remarks.

At the level of the Standard Model, neutrino masses are generated through the unique \( SU(3) \times SU(2) \times U(1) \) invariant dimension 5 interaction

\[
L = h^{ij} \epsilon_{\alpha \beta} t^i_{\rho \sigma} j^\beta \phi^\rho \phi^\sigma
\]

where \( i \) and \( j \) are family indices, \( \alpha \) and \( \beta \) are spinor indices, and \( \rho \) and \( \sigma \) are weak \( SU(2) \) indices. \( t \) is the fermion doublet, \( \phi \) is the Higgs doublet, and \( h^{ij} \) is a coupling matrix. Due to weak \( SU(2) \) the neutrino mass term comes together with lepton-number violating term involving charged leptons, which however seem to be much less accessible experimentally.

It is very significant, from a conceptual point of view, that one must go to such an elaborate interaction to generate lepton number violation. All \( SU(3) \times SU(2) \times U(1) \) invariant terms of dimension 4 or less involving minimal Standard Model fields automatically conserve lepton number. Because of the dimensions of the fields, the \( h^{ij} \) must have the dimensions of inverse mass. Thus the smallness of lepton number violation can be cleanly traced to the existence of a large mass scale, where interactions beyond the Standard Model set in.

In supersymmetric extensions of the Standard Model, on the contrary, there are lower dimension lepton-number violating terms. One must suppress them in some other way, presumably by imposing appropriate symmetries.

At a slightly more microscopic level, one attractive mechanism for generating neutrino masses is the ‘see-saw’ mechanism. It postulates the existence of one or more \( SU(3) \times SU(2) \times U(1) \) singlet, space-time spinor fields \( N_{i\alpha} \). Three such fields – one for each family – arise naturally in \( SO(10) \) unification schemes, as we saw before. Now one has the possible, \( SU(3) \times SU(2) \times U(1) \) invariant interactions

\[
L_M = M^{ij} \epsilon^{\alpha \beta} N_{i\alpha} N_{j\beta}
\]

and

\[
L_\phi = k^{ij}_{\alpha \beta} N_{i\alpha} \phi^\rho \phi^\sigma
\]

20
In the first of these equations the coupling matrix $M$ has dimensions of mass, and the interaction can be considered as a Majorana mass term for the right-handed neutrinos $N$. In the second of these equations the coupling matrix $k$ is dimensionless. This interaction has the same structure as the interaction responsible for the masses of ordinary quarks and leptons in the Standard Model, arising as $\phi$ acquires a vacuum expectation value.

Now if the eigenvalues of $M$ are very large compared to the weak scale, then in analyzing processes at the weak scale we can ignore the kinetic energy of the $N$ fields and integrate them out (solve their field equations algebraically). This procedure gives us a dimension 5 operator involving purely Standard Model fields, precisely of the type we discussed earlier. Its magnitude is, roughly speaking, inversely proportional to the mass scale associated with $M$.

A major theoretical challenge is to get some concrete insight into the matrices $M$ and $k$ (and thereby $h$), so that we can take proper advantage of the brilliant, heroic work our experimental colleagues are doing to determine the properties of neutrinos.

Although it would not be appropriate to go into greater detail here, I would like to emphasize that there are likely to be important connections among all the elements of the complex of problems involving quark masses and mixing angles, CP violation, lepton and baryon number violation, neutrino masses and mixing angles (and the supersymmetric generalization of all these). There are great opportunities here; even partial insights could help correlate and guide experimental investigations.

Question 9: How badly is baryon number broken? What protects it?

A similar analysis of possible baryon-number violation reveals many possibilities for dimension 5 and 6 (or even dimension 3 or 4) interactions involving squarks. One has to work very hard to suppress them sufficiently, typically by invoking discrete symmetries $ad hoc$. Could these have a profound origin?

Conversely, the experimental search for nucleon decay should remain a top priority.

Question 10: What is the origin of the observed CP violation?

Thus far, despite more than thirty years of intense searching after the Cronin-Fitch experiment, CP violation has still only been observed in the $K$ meson system.

Kobayashi and Maskawa had the brilliant idea that CP violation would be induced, generically, by mixings among three generations of quarks. With three generations, but not with two, the generalized Cabibbo-like angles characterizing the weak currents contain a phase that cannot be removed by field
redefinitions. In this way, they anticipated the discovery of the third generation. However, we still do not know if they were right about the original problem. Their possible phase has not been measured, and we do not know if it accounts quantitatively for CP violation in the K meson system.

There are ambitious experimental programs being mounted to study CP violation in B meson decays, which should decide this question. For a review, see [1].

Question 11: What are the P, T violating electric dipole moments?

Another sort of CP violating effect is an electric dipole moment of an elementary particle. An electric dipole moment for an elementary fermion comes from the dimension-5 interaction

$$\mathcal{L}_{edm} = \kappa \bar{f} \gamma_5 \sigma^{\mu \nu} f F_{\mu \nu}. \quad (5)$$

It is odd under both P and T. Supersymmetric extensions of the Standard Model contain many additional potential sources of P and T violation, besides the phase in the weak current that (as we mentioned) is plausibly, though not surely, responsible for the CP violation in the K meson system.

An excellent review of both the theoretical situation and the experimental prospects is given in Barr [21].

It is noteworthy that some of the most sensitive tests involve searching for electric dipole moments of atoms and molecules, as opposed to what we ordinarily think of as elementary particles. Since this is a school, I’m going to take half a minute to clear up a point that several people have found confusing, and asked me about. “Wait a minute”, they say, “didn’t I read in my chemistry textbook that water molecules have an electric dipole moment? Surely this doesn’t signal fundamental symmetry breaking!” And of course it doesn’t. The point is that the true dipole moment, in our sense, is defined by a strictly energy shift in response to an electric field, $\Delta \varepsilon \propto E \cdot \langle J \rangle$, where the angular momentum $J$ is the only available vector. Since the matrix element is manifestly unnatural under $P$, and $T$ odd, a nonvanishing shift of this type does indeed violate these symmetries. For a water molecule, however, there are very low-lying rotational states, with opposite $P$ and $T$, that will mix with the nominal ground state even for quite weak fields. A non-vanishing matrix element of $J$ between such states need violate no symmetries. It is a simple exercise in near-degenerate perturbation theory to show that under these conditions the energy shift behaves as $\Delta \varepsilon \propto \sqrt{E^2 + \delta^2}$, with a very small $\delta$. Evidently this can mimic, for practical purposes if the electric fields are not too weak, the response of a true, fundamental dipole.

Question 12: How is the strong P, T problem solved? Do axions exist?
I lectured on these subjects at length at a previous Erice school. The main development since then is that experiments capable of seeing axionic dark matter, for an interesting range of couplings, are underway. It remains true, I think, that there is no other comparably attractive solution to the problems that Peccei-Quinn symmetry, and the concomitant axions, address.

Question 13: Why is the $\mu$ term what it is?
This is a rather more specialized technical problem than most on my list, but quite fundamental. In supersymmetric models of particle physics one needs not one but two Higgs doublets. This is because supersymmetry assigns a definite character to fields, holomorphic or antiholomorphic, and only holomorphic fields occur in the superpotential. Thus the trick of using the complex conjugate of the doublet to supply an order parameter with the opposite hypercharge, used in the minimal Standard Model, will not work in a supersymmetric theory. One needs two separate doublets to give masses to up and down quarks. A more down-to-earth explanation, is that the doublets have fermionic partners, whose potential anomalies need to be cancelled.

In any case, a cross-coupling between the two doublets in the superpotential is allowed by supersymmetry. It has the dimensions of mass. There would seem to be two natural options: either there is a symmetry which forbids the coupling, or it acquires (like the right-handed neutrinos we discussed before) an extremely large mass. The first option leads to the original weak-scale axion, which is a very pretty possibility, but excluded by experiment. The second option effectively obliterates the weak scale: the Higgs doublets are removed to the high mass scale, or (worse) electroweak symmetry is broken at the high scale. So it is a serious problem, why this so-called $\mu$ term is of order the electroweak scale. It endangers the whole idea of weak-scale supersymmetry.

There are some promising ideas to address this problem. They exploit details of supergravity. So the $\mu$ problem may turn out to provide a particularly clean window into the unification of gravity with the other interactions. For more information see.

Question 14: Are there additional macroscopic forces?
A variety of ideas in particle physics suggest the existence of very light, very weakly coupled spin-0 particles. We have already discussed axions. Other possibilities appearing in the literature include exact or approximate Nambu-Goldstone fields associated with family symmetries (familon) or, closely related to these, so-called moduli fields, and dilatons.

Exchange of such particles, if they exist, will induce forces whose range is the Compton wavelength of the particle. Thus $10^{-5}$ eV particles will give
forces which die off as a power at distances shorter than about 1 cm, then exponentially. This sort of mass scale, or slightly smaller, arises from the combination

$$\mu \sim \frac{M_W^2}{M_{\text{Planck}}}$$

that occurs in many speculations. Of course, true Nambu-Goldstone bosons would mediate forces of infinite range. They give a $1/r^3$ potential.

I discussed these matters in considerable detail at a previous Erice school,\(^{22}\) See also the excellent experimentally oriented review by Adelberger, et al \(^{23}\). Much more could be done with this subject, especially on the experimental side.

**Question 15:** How (and how well) are flavor symmetries protected, outside the Standard Model?

Neutrino masses, probed in oscillation experiments, provide one window into lepton-number violating processes, as we have already discussed. Rare decays such as $\mu \rightarrow e\gamma$ provide another. Supersymmetric theories introduce many possibilities for additional lepton-number violating interactions.

Indeed, there is a big problem in understanding why mixings among the various sparticles do not induce unacceptably large lepton-number violation and flavor-changing processes among quarks.\(^{14}\) (Dienes-Kolda)

A long-shot, but very informative if true, is the possibility that very light particles associated with spontaneous breaking of flavor symmetries (familons) could be produced in rare decays such as $K \rightarrow \pi f$.

**Question 16:** Can we provide foundations for, or alternatives to, inflation?

Professor Linde gave us inspired lectures on inflationary models. So you know how appealing the basic ideas are. However, we should remember that the foundation of facts which support these speculations, although profound, is extremely limited. The main results – spatial flatness (or maybe not?), scale invariant fluctuation spectrum (maybe not?) – are simple and qualitative, so that it does not seem ridiculous to imagine that some completely different idea could explain them. Of course, one must produce the idea! Or, one must give names and faces to the postulated inflation fields, explain the required flat potentials, and properly ground inflation in our knowledge of the laws of physics.

**Question 17:** What is the ‘dark matter’ of cosmology?

The evidence for a dominant non-baryonic component to the mass of the Universe has become overwhelming. Particle physics provides two excellent candidates: the lightest supersymmetric (R-parity odd) particle or LSP, and
axions. Neutrinos could also provide a significant fraction, if their mass is of order a few eV. A cosmological term could be considered another, most unusual, form of dark matter. Future measurements of the cosmic microwave anisotropy will make it clear what astronomers need; and there are promising experimental programs to check out the individual candidates. For a review, see A.

Question 18: Why is there a cosmic asymmetry between matter and antimatter?

The general idea, that baryon-number violating processes operating in Big Bang conditions could generate the asymmetry between matter and antimatter, starting from symmetric conditions, has been well established. Many variations on the theme have appeared in the literature. Early work especially focussed on processes near the unification scale; more recently there has been much work on the possibility of generating the asymmetry at the weak scale. Since there are so many possibilities, most of which are rather well insulated from laboratory experimentation, this important problem might only be elucidated as a by-product of better understanding of particle physics over a broad front. For a review, see B.

Question 19: Are the laws of physics historically determined? Are they the same everywhere?

Spontaneous symmetry breaking is a prominent feature of the Standard Model. In models of unification, there are typically several layers of spontaneous symmetry breaking. One can easily construct models in which there are several local minima, with different values of the condensed fields and thus several different sets of ‘laws of physics’. This is especially common in supersymmetric models. Indeed, in that context it is common to have continuous so-called moduli fields, which parametrize different zero-energy, vacuum states. String theory, it appears, also supports many physically inequivalent solutions.

Even if the ground state were to be in some sense unique, in any of these contexts, one would face the question whether we could live in a metastable vacuum, either a local minimum or with slowly varying ‘constants of nature’. These could be realized, concretely, as very weakly coupled fields. We are already familiar with one example of this kind, of course – the gravitational field.

These considerations suggest that the problem of vacuum selection – which, in the sense used here, is an integral part of deriving the laws of nature – may not have a unique, universal solution, even supposing that there is a unique, universal fundamental theory. It could well be that the constants of nature we
experience are determined accidentally, and differ from those in other parts of the Universe. This idea is very much encouraged by inflationary models, since they readily explain how the Universe could be homogeneous on very large scales, though ultimately extremely inhomogeneous.

Question 20: Are there essentially new phenomena within the Standard Model?

This is, as it stands, an open-ended question whose answer is obviously 'yes', since the Standard Model implicitly (very implicitly!) contains chemistry and condensed matter physics as subtheories. The spirit of it, of course, is to ask whether there are essentially new phenomena involving core concepts of the Standard Model in a reasonably direct way. I think the answer is still very much yes.

Professor Satz has told you about recent exciting developments around the quark-gluon plasma. The whole subject of phase transitions in QCD is opening up from several angles: theory, numerical experiments, and now physical experiments. There is good reason to think that confinement is abolished, and chiral symmetry restored, at high temperature. There is good reason to think that both color and strangeness are spontaneously broken at densities a few times nuclear. Figuring out how these changes occur is potentially important for understanding neutrons stars and experiments using heavy ion collisions; and in any case it is an integral part of understanding QCD properly.

As we learn more about the world at and above the weak scale, it will be fascinating to understand the transition or transitions that occurred as electroweak symmetry was broken in the early Universe. Both inflation and genesis of matter-antimatter asymmetry have been ascribed to events during this epoch, in slight extensions of the Standard Model.

The central mission of particle physics has always been to find the fundamental laws of nature. This is surely a grand goal. But we should also recognize and take pleasure in the intrinsic beauty of a phenomenon like color coherence [27], where fundamental concepts – in this case, the quantum interference of color fields – are cleverly isolated and demonstrated in concrete experimental realities.

Clearly, fifty years into particle physics there is no shortage of important, interesting open questions. Your homework assignment is to answer one – or, for extra credit, more than one.
Acknowledgments

I thank Keith Dienes for supplying Figures 6 and 7.

This paper is from lectures given at the Ettore Majorana Summer School, Erice, Italy, August 1997. F.W. is supported in part by DOE grant DE-FG02-90ER40542

1. For recent reviews of the Standard Model, see References 4 and 5.
2. After several partial and tentative proposals, the $SU(2) \times U(1)$ electroweak theory took on in its essentially modern form in: S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in Elementary Particle Physics, ed. N. Svartholm (Almqvist and Wiksells, Stockholm, 1968), p. 367; S. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2, 1285 (1970).
3. After several partial and tentative proposals, the $SU(3)$ strong interaction theory took on its essentially modern form in: D. Gross and F. Wilczek, Phys Rev. D 8, 3633 (1973); Not coincidentally, the key discovery that allowed one to connect the abstract gauge theory to experiments, asymptotic freedom, was first demonstrated just prior to these papers, in: D. Gross and F. Wilczek, Phys. Rev. Lett. 30, 1343 (1973); H. D. Politzer, Phys. Rev. Lett. 30, 1346 (1973).
4. LEP Electroweak Working Group, preprint CERN-PPE/96-183 (Dec. 1996).
5. M. Schmelling, preprint MPI-H-V39. hep-ex/9701002. Talk given at the 28th International Conference on High-energy Physics (ICHEP 96), Warsaw, Poland, 25-31 July 1996.
6. H. Georgi and S. Glashow, Phys. Rev. Lett. 32, 438 (1974).
7. H. Georgi, in Particles and Fields – 1974, ed. C. Carlson (AIP press, New York, 1975).
8. N. Nielsen, Am. J. Phys. 49, 1171 (1981); R. Hughes, Nucl. Phys. B 186, 376 (1981).
9. H. Georgi, H. Quinn, and S. Weinberg, Phys. Rev. Lett. 33, 451 (1974).
10. See for example G. Blewitt, et al, Phys. Rev. Lett. 55, 2114 (1985), and the latest Particle Data Group compilations.
11. A very useful introduction and collection of basic papers on supersymmetry is S. Ferrara, Supersymmetry (2 vols.) (World Scientific, Singapore 1986). Another excellent standard reference is N.-P. Nilles, Phys. Reports 110, 1 (1984). See also [26].
12. S. Dimopoulos, S. Raby, and F. Wilczek, Phys. Rev. D 24, 1681 (1981).
13. J. Ellis, S. Kelley, and D. Nanopoulos, Phys. Lett. B260, 131 (1991); U. Amaldi, W. de Boer, and H. Furstenau, Phys. Lett. B260, 447 (1991);
for more recent analysis see P. Langacker and N. Polonsky, Phys. Rev. D 49, 1454 (1994).
14. K. Dienes and C. Kolda, IASSNS-HEP-97-68. hep-ph/9712322 (Dec 1997).
15. S. Weinberg, Rev. Mod. Phys. 61, 1 (1989).
16. The existence of the infrared fixed point was first discussed in: C. Hill, Phys. Rev. D 24, 691 (1981). More recent examinations including supersymmetry appear in: V. Barger, M. Berger and P. Ohmann, Phys. Rev. D 47, 1093 (1993); P. Langacker and N. Polonsky, Phys. Rev. D 47, 4028 (1993); M. Carena, S. Pokorski and C. Wagner, Nucl. Phys. B 406, 59 (1993).
17. M. Gell-Mann, P. Ramond, and R. Slansky, in Supergravity, ed. P. van Nieuwenhuizen and D. Freedman (North Holland, Amsterdam, 1979), p. 315; T. Yanagida, Proc. of the Workshop on Unified Theory and Baryon Number in the Universe, eds. O. Sawada and A. Sugamoto (KEK, 1979).
18. J. Christenson, J. Cronin, V. Fitch and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).
19. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
20. Y. Nir and H. Quinn, Ann. Rev. Nucl. Part. Sci. 42, 211 (1992).
21. S. Barr, Int. J. Mod. Phys. A 8, 209 (1993).
22. F. Wilczek, The U(1) Problem: Instanton, Axions, and Familons, in How Far Are We from the Gauge Forces, ed. A. Zichichi (Plenum, 1985).
23. E. Adelberger, B. Heckel, C. Stubbs, and W. Rogers, Ann. Rev. Nucl. Part. Sci. 41, 269 (1991).
24. The principles are explained in C. Jones, A. Melissinos, Cosmic Axions, (World Scientific, 1990).
25. G. Jungman, M. Kamionkowski, K. Griest, Phys. Reports 267, 195 (1996).
26. A. Cohen, D. Kaplan and A. Nelson, Ann. Rev. Nucl. Part. Sci. 43, 27 (1993).
27. For a gentle introduction, see F. Wilczek, Colour Takes The Field, Nature 390, 659 (18/25 Dec. 1998).
DISCUSSION I

CHAIRMAN: Professor F. Wilczek

February 1, 2008

Scientific Secretaries: A. Adamantini, D. Ghilencea,
and R. Harlander

Shovkovy: As you demonstrated, the running couplings in the Standard Model do not quite match at high energy, but why should we expect a perfect match?

Wilczek: We do not expect a perfect match. In fact, if you extrapolate the minimal supersymmetric extension of the Standard Model (MSSM) with all the superpartner masses set equal, say to 100 Gev, then the couplings do not quite meet. Putting it another way, if you take the weak and electromagnetic couplings as known, and demand unification (with the SU(5) normalization of hypercharge) then the strong coupling – that is, the $\alpha_s$ evaluated at the $Z$ mass is calculated to be a bit large, roughly .13 compared to the experimental value .118 ± .002. Fortunately, there are known corrections to the simple extrapolation which are plausibly of the right size. These come from the fact that the straight inverse logarithmic running of the coupling, which is valid for massless particles, is modified for massive particles. At a given scale, particles whose masses are much larger than the scale do not contribute significantly to the vacuum polarization, and very light particles can be regarded as massless. However particles with masses comparable to the scale must be handled more carefully. The procedure is straightforward in principle, although it can get messy in detail.

We expect that there is considerable complexity in the spectrum at two places, at least: at the electroweak symmetry breaking scale, and at the unification scale. The incomplete symmetries of the mass spectrum at these scales means that the running of the coupling, as it is affected by these masses, does not obey the symmetries one would have if the masses were negligible. One has what are called “threshold corrections” to the naive extrapolation.

Unfortunately, we do not have a reliable theory of the spectrum, either at the electroweak scale or the unification scale. The best we can do, at present, is to try different possibilities – that is, concretely, different Higgs multiplets, vacuum expectation values, and soft supersymmetry breaking terms – to get a rough idea what the magnitude of the corrections could be, within some class of models that seem reasonable. This is a somewhat subjective process – what
seems reasonable to me might not to you – but the general consensus is that threshold corrections, especially at the unification scale, are quite adequate to accommodate the slight discrepancy between the naive extrapolation of running couplings and experiment. If we are bold, we can try to turn this argument around, and learn something about the pattern of masses near the unification scale by demanding accurate meeting of the couplings at low energy.

On the other hand, extrapolation of the ordinary Standard Model, without supersymmetry, differs from experiment by an amount that cannot be easily accommodated with minor threshold corrections. One must drastically alter the theory. Of course, since we are only fitting one or two parameters, it is possible to find alterations that will do the job. But it would be a cruel joke on the part of Nature, to fool us this way.

Zichichi: May I make a comment, right away: the story of MSSM is incomplete, because, after all, it is not enough for them to meet - this is geometry - afterward they have to continue together. This is why SU(5) is needed. Please point out that in order to have unification you need a higher group.

Wilczek: This is an important additional point that I did not stress in the lecture. I drew the graphs for running of the couplings in an oversimplified way, just extrapolating the renormalisation group evolution linearly in the inverse logarithm, as if the symmetry continued to be broken past the unification scale. In a more refined treatment, the symmetry is restored at that scale, and some particles that were very massive before can no longer be neglected, which changes the answer. Clearly symmetry dictates that the couplings will then all run together.

Giusti: What is the value of the supersymmetric scale you can have without losing unification of the gauge couplings?

Wilczek: A very important motivation for supersymmetry is that it protects us from very large radiative corrections to, if you like, the mass of W or perhaps better, the mass of the Higgs particle. There is a very dangerous radiative correction in the Standard Model to the mass term of the scalar Higgs field. This radiative correction is quadratically divergent. Formally, one can add a counter term to cancel off the divergence. If one had no expectation for where essentially new physics beyond the Standard Model occurs, it might appear reasonable simply to adjust the counterterm so that the symmetry breaking scale associated with the Higgs field vacuum expectation value comes out right, following the prescription that the senseless (infinite) correction must somehow be zero. But with unification, there really is another scale that seems quite relevant, the unification scale, which is something like $10^{15}$Gev. I think it is quite fair to estimate the radiative correction by putting in the unification scale for the ultraviolet cut-off; there is no known way to protect structure at that scale leaking down in this way. Of course, if we do this, we get a ridiculously
large correction to the mass term, much larger than what we want the total answer to be. This, in a nutshell, is the naturality problem associated with the quadratic divergence of radiative corrections to the Higgs mass.

It is a very great virtue of supersymmetry that for every bosonic virtual exchange contributing to radiative corrections of this kind, there is a fermionic exchange contributing with the opposite sign which would, if the masses of the boson and fermion were equal, exactly cancel it. If the masses of these particles are not exactly equal, their contributions do not cancel exactly, but only approximately. It will (because of the underlying quadratic divergence) go like the square of the mass difference, at least for large splittings. Now, if we want the squared mass parameter of the Higgs particle to be of the order of \(250 \text{ GeV}^2\), and the radiative contribution to be not much larger than the total answer, then we have to say that the square of the mass of the supersymmetric partners of the known Standard Model particles times the fine structure constant (perhaps divided by \(\pi\)) is not much greater than this. In this simple-minded way, we find strong motivation to assume that the mass of the supersymmetric particle is of the order of a few TeV. It could be less, of course, but at most it should be a few TeV. So, now coming back to the unification calculation, we can ask if we vary the masses from nothing to a few TeV, does the calculation stay adequately accurate. The answer is that it works quite well, as I have already mentioned. Perhaps superpartner masses on the high side are favored, but it is really within the uncertainties due to possible threshold effects on the other unification side. On the other hand if we drive the masses orders of magnitude larger than this it would start to upset the agreement of the running of the couplings with experiment. So, you have to take the whole package, with low-energy supersymmetry – asymptotic (e.g., Planck scale) supersymmetry is not good enough. Both in protecting the weak scale and in making the couplings unify correctly, supersymmetry can only do its job if the scale for finding visible supersymmetric partners is a few TeV or less. This should be very encouraging for anyone involved in experimental work at LHC, for example.

**Buchel:** Is it fair to say that when people are writing unification of the gauge couplings, they usually do one loop running?

**Wilczek:** The calculations have been done certainly to two-loop and I think maybe even to three-loop order.

**Buchel:** My second question: can you discuss the status of the Yukawa coupling unification? One would like to push these ideas further.

**Wilczek:** I think it is appropriate to emphasize gauge coupling unification because gauge couplings are related to the central parts of the theory, the parts that we understand profoundly. Also, the relevant predictions concern are gauge couplings which have been measured very well, so there can be are reliable and robust tests of the basic ideas.
Emboldened by success for the gauge couplings, one can become more ambitious and ask about Yukawa couplings and their running. Any such discussion has to begin with a big caveat: if the Higgs sector is complicated, containing several fields, then we cannot from what is known at present determine all the Yukawa couplings and their expectation values separately. A unique relationship between what we know – namely the particle masses and mixing angles – and the size of the Yukawa couplings, arises only if there is a single Higgs field. For then the masses are equal to a single universal vacuum expectation value multiplied by the corresponding Yukawa couplings. The vacuum expectation value is fixed by the observed mass of the W boson, because in that case we know both the mass and the (gauge) coupling. In general, however, we cannot pin things down, because the W mass fixes only one combination out of many possible vacuum expectation values. For instance in the MSSM one needs two Higgs fields, and the ratio of their vacuum expectation values is an unknown parameter in supersymmetric model building, labelled tan\(\beta\).

Keeping that in mind, we can still ask: is there anything in the observed spectrum that suggests the relevance of the running of the Yukawa coupling? I would say there are two hints, though I must emphasize again that they are by no means on the same footing as unification of gauge couplings. One suggestion is that the ratio of quark to lepton masses for particles in the same family evolves by renormalizing from a value of unity at the unification scale to what we observe. This equality at the unification scale can arise for group-theoretic reasons in a unified theory such as SU(5), where quarks and leptons are put in common multiplets. If you try this idea you obtain a pretty good value for the mass of the b-quark divided by the mass of the tau. Taking this idea to its logical conclusion, one would predict a universal ratio between the mass of the charge-(-1/3)-quark and the mass of the corresponding negatively charged lepton in each family, which does not work in the other cases. So something is missing. There has been a lot of work to suggest what it is, but no consensus has yet emerged.

The other, and I think much more profound, suggestion for relevance of running ideas to masses has to do with the top quark mass. Although we certainly do not understand the masses of all the quarks and leptons, there is one whose mass might be much simpler to understand than all the others, and that is the top quark. People sometimes say that the top quark is anomalously heavy but actually, from a higher perspective, it is the only known elementary fermion that has a reasonable mass. \(M_t\) is the Yukawa coupling times the expectation value of the Higgs field. In the minimal model Standard Model this expectation value of the Higgs field is 250 GeV. This is determined from the W mass. Given this, one sees that it is only for the top quark that the Yukawa coupling is at all close to one. In all other cases it is very very small. For the electron, e.g., it is about a part in a million. This raises the possibility that the top quark mass is governed by an infrared fixed point. That is, it might be that the top quark mass is understood in the following way: no matter what the Higgs coupling is at the unification scale, when we run it down we find there is a focusing effect, implying that more or less any large value of the Yukawa coupling at the
unification scale would run down to something close to the observed one at low energies. This running, of course, is only important for Higgs couplings that are strong at unification; very small values stay small. In models with more than one Higgs field it is conceivable that this mechanism applies to other fermions as well. The most plausible possibility, perhaps, is that the b quark sits at an infrared fixed point; this can arise in supersymmetric models with large tan β.

**Armoni:** At the beginning of your lecture you mentioned the basic principles of the SM, like unitarity and locality. It is believed that in quantum gravity at least one of these principles must be abandoned. Is there any proof of the possibility of having some extended gravity which is given in terms of local quantum field theory? Is it theoretically excluded that we can have a local quantum field theory including gravity?

**Wilczek:** No, I think it is not excluded at all. In my opinion the jury is still out on quantum gravity. But one cannot deny that the conceptual world of gravity is quite different from the usual conceptual world of local quantum field theory. For example, already using the word locality assumes that you have some notion of nearness, and if your basic symmetry is just diffeomorphism invariance, as it is perhaps in quantum gravity – if the metric is a derived concept – then that just does not make sense. But maybe the metric is not a derived concept, we just do not know. To say something constructive, let me address the situation in string theory, which is the closest thing we have at present to a quantum theory of gravity. Despite some prominent claims in the literature, it is very far from obvious to me that string theory is non-local in any real sense. In string theory, you really have interactions just when the strings touch, and the effects of this interaction travel along the strings at a speed limited by the speed of light, so I believe that at least perturbatively the theory is local.

It was one of the great achievements of Galileo to realize that science is local, that you do not have to worry very much for experiments here about what is going on on the far side of the moon, that astrology is misguided, and so forth. These are assumptions that are implicit in almost all scientific work, and if there were really significant non-locality one might have expected something to go terribly wrong in all this work by now. So I am a bit nervous about giving up locality; but I am also not sure that it is given up in string theory. I am not aware anybody who has pointed at a specific non-local effect and made a testable prediction, even for a thought experiment or impractical observable. Without that, the discussion is metaphysical.

**Ryan:** I have to complain a bit about the presentation of the running of the strong coupling. A naive student might come away with the impression that we calculate the coupling constant completely from first principles and that the data points fall dutifully on top of the curve. Since this is a School, I think it should be emphasized that the evolution equations describe the shape of the curve, but the absolute magnitude must be derived from fits to the data points.
Wilczek: We can look at the data, as presented in the lecture, and address this point. The point I am making about the absolute coupling is simply that the curve giving the effective strong coupling is highly focusing. More quantitatively, the phenomenon is as follows. In solving the renormalization group equation for the running of the coupling, a mass parameter called lambda appears. Roughly speaking, it sets the scale at which the effective coupling becomes large. Lambda has to be derived from measurements; as you say, therefore, the prediction is a one-parameter set of curves. However, if lambda is chosen to be any typical strong interaction scale, ranging from, say, 100 MeV to 1 GeV, any specific choice will give you almost identically the same value of the effective strong coupling at scales of a hundred GeV. In that sense, this coupling is given with about 10 per cent accuracy as a no-parameter prediction of the theory.

Zichichi: Do you place lattice QCD at the same level as an experimental finding?

Wilczek: Lattice QCD is not an abstract game; it is a well-defined method for calculating consequences of a well-defined theory. So it is as legitimate to compare its results with experiments, as to compare the results of perturbative QCD with experiment. In practice, the determination of the strong coupling from using lattice QCD is based on fitting its results to the experimental measurement of heavy quark spectra. It is a comparison of theory and experiment, as are all the other points on the curve, so it is really no different in principle. By the way, many of these points summarize tens or hundreds of independent measurements under different circumstances. Any of them could have falsified QCD, but none has.

Paus: I might make a comment on your plot. There are quite a few measurements missing, e.g., LEP now measures the strong coupling at 183 GeV and still theory and experiment are in very good agreement.

Wilczek: Yes, thank you. I do not think the essential correctness of QCD, and of our methods of calculation, are negotiable items anymore.

Let me add one more remark: when we defined 'years' of particle physics, one of the remarkable things taken to mark the beginning was the Lamb shift; that supplied convincing evidence for virtual particles and the correctness of quantum field theory. The features of heavy quark spectra that are calculated by combining perturbative calculations and lattice QCD, and used in determining the strong coupling, are the exact analogs to the Lamb shift. In fact, one of them is just the strong interaction version of Lamb shift.

Roos: Your classification of states in a 16-dimensional representation of SO(10) made use of a notation with five signs, pluses and minuses. It struck me that this representation did not exhaust all the permutations of signs. Those which
are absent, do they live in another representation or are they forbidden by some principle?

**Wilczek:** There is a rule here that you have to have an even number of pluses. That is to make the representation irreducible. By the way, the ones with the same number of pluses are the SU(5) multiplets. There are ten entries with two plus signs which fill out the antisymmetric tensor of SU(5), five entries with four plus signs, those being the 5 of SU(5), and then there is the singlet.

**Bruyninckx:** What is your opinion about what the QCD phase diagram should look like?

**Wilczek:** I think I have understood for a long time what it looks like, as a function of the temperature, and even maybe temperature and strange quark mass, at zero chemical potential. This is a little complicated to discuss here, but well documented in the literature. On the other hand adding a chemical potential, as is necessary to discuss high-density situations like neutron stars or certain aspects of heavy ion collisions, rapidly brings us into poorly explored territory. I will say a little about it tomorrow. It will be some time before the dust settles on these questions, in my opinion.
DISCUSSION II

CHAIRMAN: Professor F. Wilczek

February 1, 2008

Scientific Secretaries: K. Riesselmann, S. Tapprogge, and A. Wodecki

Ghilencia: We had a long discussion on the so-called threshold effects and the two-loop corrections in the running of the gauge couplings. I just want to add that these threshold effects, considered in their one loop approximation - which is consistent for a two loop running - are cancelled by the two loop terms in the beta function. This greatly simplifies the renormalization group equations, which, interestingly enough, get a one-loop-like form if expressed in terms of wave function renormalization coefficients.

Ghilencia: Do you see any physical meaning of the Grassman variables we integrate over, as they are, to my knowledge, introduced only on mathematical grounds?

Wilczek: Grassmann variables are an implementation of Fermi statistics. I do not know of any other physical meaning. They play an important role in supersymmetry, of course.

Brown: Are there any more profound, a priori, reasons for an SU(5) or SO(10) gauge principle?

Wilczek: Well, one widely held speculation is that one should be working with weakly coupled heterotic strings that are compactified to four space-time dimensions. In the overlying ten dimensional theory, the gauge group is E8 x E8 emerges. This group naturally contains E6 and hence SO(10), SU(5), and of course the Standard Model gauge group. A well-studied class of compactifications involves putting a non-trivial gauge field on the compactified manifold, which reduces the symmetry of one E8 factor down to E6 or less. Whether something along these lines describes reality, it is too soon to say.

Let me make a couple of more naive remarks. A particularly intriguing feature of SO(10) is its spinor representation, used to house the quarks and leptons, in which the states have a simple representations in terms of basis states labelled by a set of “+” and “−” signs. Perhaps this suggests composite
structure. Alternatively, one could wonder whether the occurrence of spinors both in internal space and in space-time is more than a coincidence. These are just intriguing facts; they are not presently incorporated in any compelling theoretical framework as far as I know.

Here is another interesting question: do spinor representations occur in quantum mechanical systems other than the ones connected to the SO(3) rotational group? Note that the spinor representation is a projective representation: there exists a phase which cannot be absorbed into the unitary transformations of the group. Non-trivial projective representation also arise for the group $S_N$ relevant to the quantum kinematics of identical particles, for $N > 3$. Remarkably, they have the same structure as spinor representations, including exponential growth with $N$ of the dimension of the irreducible representation. So perhaps there is a connection between exotic quantum statistics and the existence of internal spinor representations.

’t Hooft: In your theory of colour-superconductivity with non-zero expectation value for a diquark state, how is the complete flavour/colour group $SU(N_f)_L \times SU(N_f)_R \times U(1) \times SU(3)_C$ broken?

Wilczek: I have looked most carefully at the case of two light flavours. In this case the diquark forms an isosinglet (in fact, chiral isosinglet) scalar. With three light flavors, there is a very interesting and probably energetically favorable possibility to break the $SU(3) \times SU(3)$ of color times flavor to the diagonal subgroup; this of course breaks both color and strangeness spontaneously. I have not thought much about more flavors.

’t Hooft: Will nucleons become massless in this approach?

Wilczek: In the phase where chiral symmetry is restored it is not useful anymore to think about nucleons because the elementary excitations are quark excitations which feature a Fermi surface, generally with a gap. Its spectrum very much resembles that of a Higgs phase. In the 2-flavor case an SU(2) subgroup of the original SU(3) colour group survives, and it can possibly lead to confinement of two colors. There are also, however, colour-neutral quarks. With three flavors, and the symmetry breaking pattern I mentioned, there is no local symmetry left, and presumably no question of confinement. There is, however, a gap for all elementary excitations, even though the underlying theory is full of massless particles.

Masiero: This morning you mentioned that you have some reasons for skepticism towards inflationary scenarios. Can you detail them?

Wilczek: Skepticism is too strong a term; I just think the evidence is very thin, and in such a situation one can imagine alternatives will arise. In any case it is a healthy exercise to take a critical look.
Inflationary models clearly leave room for improvement with respect to fundamental physics even though there are - to my knowledge - no serious cosmological objections to inflationary models. First, there is the cosmological term problem. From experiment we know both that $\Lambda = 0$, very nearly, and that the structure of the present-day vacuum state is quite complicated. Inflation, however, depends on $\Lambda$ sitting far from zero for a long period of time when the vacuum was simpler. This is scary. Second, it is disturbing that the postulated inflation field is not connected to a fundamental theory or microscopic model. And third, predictions from inflation are mostly of a rather generic character, and not very characteristic. The predictions of a flat universe and a nearly flat fluctuation spectrum, for example, were already proposed by Harrison, Zeldovich and others based on naturality and stability arguments before inflation was proposed. Hence inflation seems to provide largely “postdictions” of qualitative features that - because they are simple - might have alternative explanations.

**Veneziano:** My strong support for SUSY is wearing thin. On one side, SUSY helps to understand hierarchy, the mass of the Higgs boson and grand unification. However the standard model - which SUSY should replace - contains automatically the conservation of lepton and baryon quantum numbers, which has to be introduced in a complicated way in SUSY models, so as not to be in contradiction with existing data. What is your honest opinion about SUSY?

**Wilczek:** I find the unification of couplings, deduced in a straightforward way from an unforced fit, most convincing. If this were to prove a mere coincidence, it would be a cruel joke on the part of the Creator. There are several other nice features of supersymmetry, including its ability to protect the weak scale as I discussed yesterday, its general helpfulness in reducing ultraviolet divergences, its potential to unify gauge fields and matter fields – both of which we know to exist, and its connection to string theory. But these are rather generic, like the evidence for inflation. To me, the unification of couplings is on a different plane, and provides by far the best reason to believe in SUSY.

**Veneziano:** SUSY might be the only chance to understand why the cosmological constant is 0 (by leaving it 0 during the breaking of SUSY).

**Wilczek:** Maybe, but in the present state of understanding this is problematic, on at least two grounds. First, in supergravity, as opposed to global supersymmetry, the connection of energy to cosmological term is not so direct, and it is not necessarily so that the ground state of unbroken supersymmetry occurs with zero cosmological term – indeed, in some ways supersymmetry is happiest in anti-deSitter space. Second, we know that in reality supersymmetry is broken, and that the vacuum energy density associated with the breaking, at least if we focus attention on the manifest low-energy degrees of freedom, exceeds by many orders of magnitude the upper limit on the cosmological term.
So if supersymmetry is to address the cosmological term problem, it will need help from additional ideas.