SUPERSYMMETRY AND OTHER SCENARIOS

E. WITTEN

School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA
E-mail: witten@ias.edu

In this talk, I survey the merits and demerits of Supersymmetry, as well as other approaches to the gauge hierarchy problem.

1. Introduction

It has come to be a familiar story – most aspects of the Standard Model are increasingly well tested. This even includes CP-violation and the properties of the top quark, as has been reported earlier this week.

The one part of the Standard Model about which we really have no clear experimental information is the mechanism of electroweak symmetry breaking. Why are the weak interactions not obvious in everyday life, in the same sense that electromagnetism is obvious?

For a long time, this question has been the key indication that something really new is in store. Experiment in the next few years is surely approaching the decisive stage – either here at Fermilab, or at the LHC.

The most simple possibility is the original electroweak theory, which assumed a single elementary Higgs boson and nothing else. On the whole, although there are some very small discrepancies, this is in very good agreement with experimental data, which moreover suggest (in the context of the pure Standard Model) that the Higgs mass is no more than about 200 GeV/c^2. Some alternative theories predict a Higgs particle plus many additional things; some predict no Higgs particle but many other things instead. The pure Standard Model with only the Higgs is really the only picture that *doesn't* predict a host of new particles for current and planned accelerators.

The pure Standard Model with only the Higgs has numerous virtues:

- it is simple;
- it agrees quite well with a mass of experimental data; and
- it explains a lot of things that would otherwise be puzzles, like why Flavor-Changing-Neutral-Currents and baryon-, lepton-, and CP-violating interactions are so suppressed.

Basically, and despite a lot of ingenuity that has gone into this, we don't know a completely satisfactory extension of the Standard Model.

Despite this, most physicists (including myself) remain convinced that the minimal Standard Model with only the Higgs is unlikely to be the full story. The main reason for this is the "hierarchy problem." A scalar field ϕ can have a bare mass term m^2. Moreover, the quantity m^2 is not stable against quantum corrections; in the Standard Model, the renormalization of m^2 is quadratically divergent, so that if the Standard Model is somehow cut off at a mass scale M, the one-loop renormalization is of order αM^2 (where α is the fine structure constant). This is unnatural for $m^2 \ll \alpha M^2$.

In a model with spontaneous electroweak symmetry breaking, the problem really affects not only the Higgs mass, but also its expectation value, and hence it affects the masses of other particles that get their masses from gauge symmetry breaking – the W and Z, and the quarks and charged leptons. So it is unnatural to have the W and Z at 80 or 90 GeV/c^2, and the Higgs below 200 GeV/c^2, unless the Standard Model is somehow "cut off" and embedded in a richer structure that tames the ultraviolet divergence in the Higgs boson mass – at an energy no bigger than about 1 TeV.

Extensions of the Standard Model differ largely in how this is done. The question has central importance for the future of physics, because different outcomes in the exploration of electroweak symmetry breaking will tend to lead us in very different directions.

We have grappled with these issues for many years. Meanwhile, observation appears to have presented us with another phenomenon that we should discuss here as it seems fine-tuned in a similar way. This is the acceleration of the cosmic expansion, which points to a tiny but non-zero cosmological constant, or maybe a more complicated form of "dark energy." This actually poses a fine-tuning problem similar to the problem of the Higgs boson. In the Standard Model, the energy of the vacuum is quartically divergent. The simplest approximation is simply to add up zero point energies

$$\pm\frac{1}{2}\hbar\omega \tag{1}$$

for every Bose mode or Fermi mode of momentum k and energy $\hbar\omega = \sqrt{(\hbar ck)^2 + (mc^2)^2}$. The integral over k

$$\pm\int d^3k\sqrt{(\hbar ck)^2 + (mc^2)^2} \tag{2}$$

is quartically divergent, so the best we can say is that the energy of the vacuum is expected to be of order M^4, where M is the cut-off energy at which "something else" happens and the contributions to the vacuum energy are cut off. Experiment appears to point to a vacuum energy Λ of order $(10^{-3}\ \text{eV})^4$, where the mass scale 10^{-3} eV is way below any possible Standard Model cut-off. It actually is relatively close to what appears to be the neutrino mass scale, but so far no one has had much success in explaining this. A nice explanation of the fine-tuning of the vacuum energy has not yet emerged.

This puzzle has lent comfort to one line of thought *which I personally hope is wrong* but which I have to mention in any discussion of fine-tuning. This is the "anthropic theory," according to which the smallness of the cosmological constant is not a consequence of the laws of nature in the usual sense. According to this picture, the laws of nature allow for a plethora of physical states, which are realized in different parts of the universe, and have widely differing values of the cosmological constant. But we live in a region in which the cosmological constant is small, simply because elsewhere the Universe expands and cools too rapidly for life to emerge.

Once one starts to admit anthropic interpretations of fine-tuning problems like the cosmological constant, is is clear that such a proposal might be made for other fine-tuning problems, such as the problem of the Higgs boson mass. Certainly, we would not be here if the Higgs boson mass, and hence also the W and Z and quark and lepton masses, were greatly bigger. If they were near the Planck scale, for example, any collection of more than a few elementary particles would collapse to a Black Hole. More generally, if the elementary particle masses were scaled up by a factor N, the number of elementary particles in a star or planet would scale down like N^{-3}, and for very modest N the stars would stop shining. If experiment will uncover a Higgs boson at the range of masses suggested by the Standard Model, but (even at LHC energies) no further structure emerges that will explain how Nature solved the fine-tuning problem, this will certainly be viewed by some as support for anthropic explanations of fine-tuning.

On the other hand, at the moment, (virtually) no one seems to be predicting this. Physicists who do favor anthropic explanations tend rather to argue that if a fine-tuning problem, like the Higgs mass, can have a rational explanation, then regions of the Universe in which such a mechanism is manifested are far more abundant than regions in which the Higgs mass is small "accidentally."

So everyone seems to agree on one thing: we want from accelerators not just a Higgs boson, but a mechanism that will "stabilize" the scale of electroweak symmetry breaking and explain why the Higgs boson, and the rest of the particles, are not much heavier. But what? Numerous suggestions have been made:

- "Higgsless" models – based on dynamical symmetry breaking;
- models with branes and large extra dimensions, plus possible strong dynamics;
- "Little Higgs" – Higgs as a pseudo-Goldsone boson; and
- Supersymmetry.

One thing they all have in common is that there is no perfect model – all known approaches are at risk of spoiling some Standard Model successes. It seems impractical to review all the options. The range of models considered has grown too widely in the last few years. Many of the new proposals at the moment are scenarios more than models. Instead, I will concentrate in the last part of this talk in explaining the virtues, but also the drawbacks, of one approach that I think is especially interesting. This is Supersymmetry. First the virtues:

- SUSY can make a “small” Higgs mass natural;
- SUSY is part of a larger vision of physics, not just a technical solution;
- the measured value of $\sin^2\theta_W$ favors SUSY GUT’s;
- SUSY survives electroweak tests; and
- the top quark mass has turned out to be heavy, as needed for electroweak symmetry breaking in the context of SUSY.

SUSY is a unique new symmetry that relates bosons to fermions, in a sense explaining why fermions exist. Relating bosons to fermions also makes it possible to explain the smallness of the Higgs mass, since we do know why the smallness of fermion masses can be natural. So that is at least the germ of how SUSY solves the fine-tuning problem.

SUSY inherits the successes of Grand Unification, because given modern measurements of $\sin^2\theta_W$, as well as bounds on the proton lifetime, the supersymmetric version of Grand Unification is the one that works.

So here we really must remember the merits of Grand Unification, which are substantial in their own right.

- It makes sense of the quark and lepton quantum numbers, which look like quite a mess in the Standard Model. A generation of Standard Model quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_{1/3} \oplus \bar{u}_{-4/3} \oplus \bar{d}_{2/3} \oplus \begin{pmatrix} \nu \\ e^- \end{pmatrix}_{-1} \oplus e^+_2 \quad (3)$$

  turns into a simple $\bar{5}+10$ of SU(5), or 16 of SO(10).
- The unification scale M_{GUT} inferred from low energy data is relatively close to the Planck scale, but high enough to avoid disaster with the proton lifetime.
- The neutrino mass scale suggested in the late 1970’s based on GUT’s, $m_\nu \sim M_W^2/M_{GUT} \sim 10^{-2}$ eV, has apparently turned out to be about right.
- Grand Unification fits neatly with strings and Quantum Gravity.
- The observed fluctuations in the cosmic microwave radiation are naturally (but speculatively) interpreted in terms of an inflationary epoch close to the GUT scale.

In short, Grand Unification is a really nice story. But it really only makes sense with Supersymmetry, for two reasons:

- the measured value of $\sin^2\theta_W$ agrees with Grand Unification only if Supersymmetry is included; and
- the unification scale and proton lifetime come out to be too small without SUSY.

So the successes of GUT’s encourage the search for Supersymmetry, and discovery of Supersymmetry would enhance the attractiveness of GUT’s.

As I have tried to argue, SUSY is not just a technical solution to problems like the hierarchy problem. It is:

- a unique new symmetry principle;
- part of an attractive larger picture in GUT’s;
- and actually, an essential part of an even more ambitious picture in string theory.

In fact, the concept of Supersymmetry emerged historically at least in part because of its role in string theory. Experimental discovery of Supersymmetry would certainly give string theory a big boost, and learning how Supersymmetry is broken might very well give string theorists crucial clues about how to proceed. Moreover, while some alternative theories of the smallness of the electroweak scale – like models of composite Higgs bosons – have repeatedly run into trouble, Supersymmetry is comfortably consistent with the precision electroweak tests.

2. Problems

For good or ill, the SUSY models considered today are the same ones that were considered viable twenty years ago. In fact the old models remained viable because the top quark turned out to be sufficiently heavy, as was required for electroweak symmetry breaking. It really is not entirely good that the models of today are the same ones as twenty years ago. It means that the models have held up, but also that certain problems that troubled theorists twenty years ago have still not been solved!

For today, we are not going to dwell on the good news. We also want to look at the drawbacks of Supersymmetry. The most obvious drawback is simply that Supersymmetry hasn't been found yet, though we have been hoping for a long time. Looking back, for example, to the summary talk (by David Gross) at Lepton-Photon 1993, I see that ten years ago SUSY was already described as the "standard non-standard theory." He also gave a list of its successes and drawback rather similar to what I am explaining today. That is beginning to be a long time.

It is disappointing that we have not found SUSY yet, but for the most part it is perhaps not too surprising. If charged superpartners are just a little bit above M_Z, we would not have seen them yet. Superpartners get masses from electroweak breaking *and* SUSY breaking so it is natural for them to be a bit above the Z, which gets mass only from electroweak breaking. But there is perhaps one particle whose absence until now is a little embarrassing, namely the Higgs boson.

Assuming the minimal supersymmetric spectrum, one has at tree level

$$M_{\text{Higgs}} < M_Z \sim 91 \text{ GeV/c}^2. \tag{4}$$

We may compare this to experiment,

$$M_{\text{Higgs}} > 114 \text{ GeV/c}^2. \tag{5}$$

Actually, there is a large radiative correction due to the heavy top quark, and the theoretical bound on the Higgs mass is usually quoted as

$$M_{\text{Higgs}} < 130 \text{ GeV/c}^2. \tag{6}$$

So there is not quite a contradiction. But rather optimistic assumptions go into getting the radiative correction so large. One needs couplings not favored by many of the models, and/or superpartner masses so large as to make the smallness of M_Z look a little unnatural. Though there is no contradiction yet, it would certainly clarify things a lot to know what M_{Higgs} is. And it would really be nice if it turned out to be 115 GeV/c^2, the value hinted at by LEP.

At a different level, Supersymmetry would have been more convincing if it had achieved some simplification in the Standard Model. For example, could the Higgs boson be a superpartner of the electron? Unfortunately, no: models that tried things like that did not work. So the Minimal SUSY Standard Model essentially doubles the spectrum.

SUSY (like many attempts to resolve the fine-tuning problem) actually complicates some successes of the Standard Model. For instance, one triumph of the Standard Model is to naturally conserve baryon and lepton number, because there are no renormalizable (perturbative) couplings of Standard Model fields that violate those symmetries. This is lost with Supersymmetry, where renormalizable interactions causing catastrophic proton decay are possible. The most commonly adopted solution to this problem is to assume a new symmetry called R-parity; this is possible but not obviously compelling. Supersymmetry also potentially undoes some of the successes of the Standard Model in suppressing Flavor-Changing-Neutral-Currents and CP-violation, by introducing troublesome new loop diagrams involving superpartners. And Supersymmetry introduces at the GUT scale a new scenario for proton decay via dimension-five operators. This is troublesome for many models given modern experimental limits on the proton lifetime.

And how is SUSY broken? There are two major approaches:

- Gravity Mediation – Supersymmetry is broken at a very high scale and SUSY breaking is mediated to the Standard Model via Supergravity interactions; and
- Gauge Mediation – Supersymmetry is broken at 100 TeV or so and its breaking is communicated to the known world via gauge forces.

Each type of model has its virtues, and neither has yet given a clear path to solving all the problems. For example, thinking about the cosmological constant might lead us to favor gravity mediation. The reason can be seen by considering the potential energy in Supergravity:

$$V = \mid DW/D\varphi \mid^2 - G_N \mid W \mid^2 \tag{7}$$

Here G_N is Newton's constant. To make V small, a cancellation between the two terms is needed. This cancellation certainly involves gravity, as the second term is explicitly proportional to G_N. The inevitable role for gravity might make gravity mediation seem more natural.

If we instead consider excessive new sources of Flavor-Changing-Neutral-Currents and CP-violation, we find that gauge mediation gives much more obvious ways to eliminate them. In short, we don't have a fully convincing picture of Supersymmetry breaking. That is actually one of the things that makes Supersymmetry an exciting target for experiments. If we had a convincing, workable picture of what the weak scale Superworld would really look like, we'd be more convinced that it is there, but we'd have less to learn by finding it. As it is, it would be quite dramatic to learn how nature did solve all the problems. And if Supersymmetry is discovered, each perplexing question about how Supersymmetry might work in the real world will turn into an opportunity to learn a fundamental new lesson about nature.

In short, discovering Supersymmetry (or any other solution of the hierarchy problem, since all known options raise vexing problems) would put experiment ahead, as was the normal state of affairs in the days before the emergence of the Standard Model. Unraveling the details of the weak scale Superworld – with its host of new particles and new interactions – will be quite a long and complex project. It will provide an excellent target for the precision of lepton colliders, as well as the higher energy of proton colliders.

DISCUSSION

Ikaros Bigi (Notre Dame): You mentioned the prediction that the Higgs should be 130 GeV/c^2. If it were not found, would you with your long-established love of Supersymmetry give up, or will you find another option?

Edward Witten: It really depends on what is found by the experiments that hypothetically show that weak-scale Supersymmetry is not present. Hopefully, in the scenario you suggest, something else will turn up that will give us a good hint.

Maria Spiropulu (Chicago): I was surprised to see in your talk a discussion about the anthropic principle. Why did you think about that? Why did you put that in this talk?

Edward Witten: I hope that the anthropic point of view turns out to be wrong because I hope we will be able to understand the Universe better than this point of view would probably allow. I felt I should discuss it in the talk because of the conceivable analogy between the fine-tuning problem involved in the vacuum energy and the fine-tuning problem associated with the Higgs mass.

Bogdan Dobrescu (FNAL): You have mentioned that the discovery of SUSY would be nice among other things because it would support the case for string theory. Could you comment on the possibility of experimental tests of string theory, whether you are suggesting that if SUSY were not discovered it would make an important problem for string theory?

Edward Witten: Personally, I think that string theory is on the right track. Its elegance in incorporating the physics we know, reconciling quantum mechanics with gravity, and giving new insights about familiar theories convinces me of that. But there is a big gap between what we know and what we'd need to know to understand nature, and it isn't clear to what extent we can make rapid progress. Certainly, experimental discovery of Supersymmetry would improve the odds a lot. Other experiments – ranging from proton decay experiments to the search for a gravitational wave signature from inflation – can also make important contributions.