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Supersymmetry: what? why? when?

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This article is a colloquium-level review of the idea of supersymmetry and why so many physicists expect it to soon be a major discovery in particle physics. Supersymmetry is the hypothesis, for which there is indirect evidence, that the underlying laws of nature are symmetric between matter particles (fermions) such as electrons and quarks, and force particles (bosons) such as photons and gluons.

1. Introduction

The Standard Model of particle physics [1] is a remarkably successful description of the basic constituents of matter (quarks and leptons), and of the interactions (weak, electromagnetic, and strong) that lead to the structure and complexity of our world (when combined with gravity). It is a full relativistic quantum field theory. It is now very well tested and established. Many experiments confirm its predictions and none disagree with them.

Nevertheless, we expect the Standard Model to be extended—not wrong, but extended, much as Maxwell's equation are extended to be a part of the Standard Model. There are two sorts of reasons why we expect the Standard Model to be extended.

(A) It does not describe some aspects of nature:
- (i) The electroweak ($SU(2)\times U(1)$ symmetry of the Standard Model must be broken to allow quarks, leptons, and W and Z bosons to have masses. That breaking cannot be explained, or originate within the Standard Model (though its effects can be parameterized in the Standard Model), so some other physics must be present to induce it.
- (ii) The Standard Model cannot explain the fact that the universe is made almost completely of matter and not antimatter, rather than equal amounts of both.
- (iii) The Standard Model cannot describe the cold dark matter of the universe.
- (iv) Studies of neutrinos have shown that at least one neutrino has mass.

(B) In addition, there are a number of questions we hope will be answered:
- (i) Can the forces of nature be unified and simplified so we do not have four independent ones?
- (ii) Why is the symmetry group of the Standard Model $SU(3)\times SU(2)\times U(1)$?
- (iii) Why are there three families of quarks and leptons?
- (iv) Why do the quarks and leptons have the masses they do?
- (v) Can we have a quantum theory of gravity?
- (vi) Why is the cosmological constant much smaller than simple estimates would suggest?

Some of these issues are partially or fully explained by supersymmetry. Some require the full apparatus of string theory (which probably implies supersymmetry). We will examine several of these in the following.

The Hamiltonian, or equivalently the Lagrangian, of the Standard Model is invariant under some symmetry operations (as mentioned above). In addition to the space-time symmetries, these include some internal symmetries. For these internal symmetries the theory is unchanged if certain particles are interchanged, such as the left-handed electron and its neutrino, $e_L \leftrightarrow \nu_e$, or the left-handed up and down quarks, $u_L \leftrightarrow d_L$. (In the Standard Model, fermion are classified in $SU(2)$ representations differently depending on the handedness, i.e. left-handed (right-handed) for spin anti-parallel (parallel) to momentum. They then interact differently also. This accounts for parity violation.) We will see that supersymmetry implies the interchange of particles too.

The perturbative Standard Model theory can be summarized by a small set of vertices. Let $f = e,\mu,\tau,d,s,b,u,c,t$ and $\ell^{\pm} = e^{\pm},\mu^{\pm},\tau^{\pm}, U = u,c,t, D = d,s,b$ and $\nu_\ell = \nu_e,\nu_\mu,\nu_\tau$.

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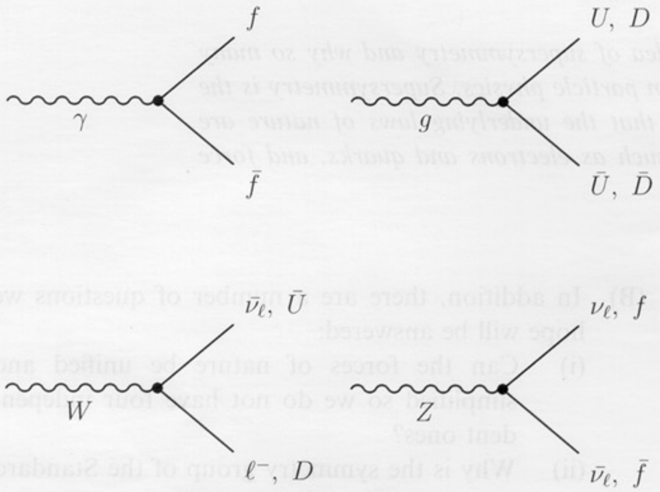
W, Z are the electroweak gauge bosons, γ the photon, and g represents the eight gluons that mediate the strong force. Then all the phenomena in nature involving fermions that we see are described by gravity plus the four vertices (for simplicity we do not show vertices with Higgs bosons (introduced below) since their main effects are to allow a consistent description of mass).

a



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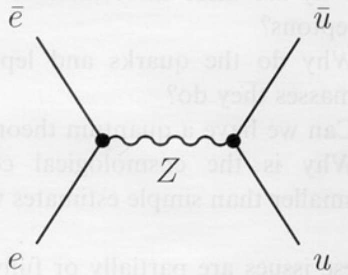


As always with Feynman diagrams, the vertices are combined into all possible Feynman diagrams. For example, the process $e^+e^-\rightarrow u\bar{u}$ has a contribution from joining two of these vertices,

Each diagram represents a possible physical process. The rules of quantum theory assign the probability for each process to occur. We will see below that supersymmetry adds some vertices.

2. What is supersymmetry?

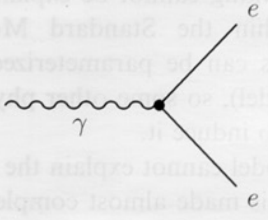
In the Standard Model quarks and leptons (both fermions) are the matter particles. The particles that mediate the forces are the 'gauge bosons', γ, W, Z, g. Another particle, the Higgs boson, is introduced to allow a consistent treatment of the mass of particles—its role is described below. Fermions and bosons are treated very differently in quantum theory and in the Standard Model.

Supersymmetry is the idea that at the fundamental level the basic laws of nature are invariant if fermions and bosons are interchanged in the theory (i.e. in the Lagrangian). It is remarkable that all of the constraints of a relativistic quantum field theory, and consistency with the interactions of the Standard Model + gravity, can be satisfied when bosons and fermions are interchanged in the equations.

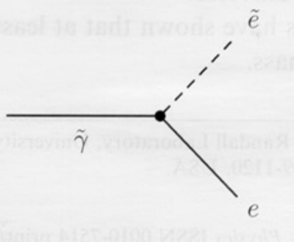
At present supersymmetry is still a hypothesis. It was first formulated [2] in 1970–71, then demonstrated to work for four-dimensional relativistic quantum field theories in 1973–74. Its most striking implication is that each of the known particles, each of the quarks and leptons and gauge bosons, must have an associated partner (a 'superpartner') that differs only by bosons↔fermions. If the supersymmetry were unbroken, an electron would have a partner that had spin zero but had the mass and electric charge and weak interactions of the electron. There is indirect evidence (which will be described below) that nature is indeed supersymmetric. None of the superpartners has yet [3] been directly observed. Though we could have been lucky and detected one or more already, the first accelerator that explores a major part of the energy region where we expect to find the superpartner is the upgraded collider at Fermi National Accelerator Laboratory (Fermilab) west of Chicago. It will begin to take data in 2001.

A convenient nomenclature exists to talk about the superpartners. Each superpartner is written with a tilde: $e\leftrightarrow\tilde{e}$, $\gamma\leftrightarrow\tilde{\gamma}$, etc. Standard Model fermions get a pre-s, and Standard Model bosons a suffix-ino, so selectron, squark, photino. As someone has said, we have a complete slanguage.

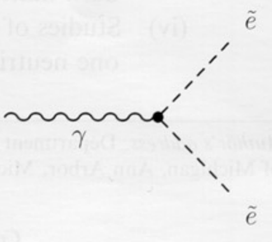
There are also new interactions. Each of the Standard Model vertices above leads to new vertices obtained by replacing Standard Model particles by their superpartners in pairs (changing an even number is obviously required to conserve angular momentum). Thus to the Standard Model vertex



we add



and



To find the probability of any process involving superpartners one draws all diagrams starting with the relevant initial particles leading to the desired final particle and calculates the associated probabilities by the normal procedures. Each new vertex has the same coupling strength as its Standard Model counterpart. For example, the vertex $ee\gamma$ is of strength e (the magnitude of the electric charge), and therefore so are the two associated vertices $\tilde{e}\tilde{e}\gamma$ and $e\tilde{e}\tilde{\gamma}$

All physics ideas and theories in the past have been invented to explain data or puzzles or theoretical inconsistencies. Remarkably, supersymmetry was introduced for purely theoretical reasons. Originally no one imagined supersymmetry was crucial, or even relevant, to explaining how nature works. In the middle 1970s supersymmetry was sometimes spoken as 'a solution in search of a problem'. It was a beautiful mathematical theory, but with no known connection to reality.

Then, as people studied the theory, they realized that it provided explanations for several major physics issues, and led to new approaches to others. In the 'Why' section below we will examine some of these.

Supersymmetry can also be viewed as a manifestation of the quantum, fermionic structure of space-time. The theory extends special relativity to include fermionic coordinates in addition to the usual bosonic coordinates. That is, from the point of view of quantum theory, our familiar space-time coordinates commute and are bosonic operators. New coordinates θ_α are 'superpartners' of the usual x^μ, leading to a formulation of the theory in 'superspace'. These extra dimensions are not related to the extra dimensions of string theory. The latter, while probably extremely small, can be thought of as tangible extra dimensions. The superspace dimensions are fermionic and effectively of zero size. If nature is indeed supersymmetric the study of the superpartners will also be a study of the quantum nature of space-time. If one imagines the original formulation of the theory to be in superspace, then supersymmetry requires the existence of fermions.

Since the supersymmetry transformations affect spin, and spin is part of angular momentum, and the generators of angular momentum transformations are part of the Poincaré group, which is connected to gravity, supersymmetry has physical connections to gravity. The precise way this connection enters the theory is not yet clear, but one reason supersymmetry is an attractive property of a theory is that its presence suggests there will be ways to unify the Standard Model forces with gravity.

Supersymmetry cannot be an unbroken symmetry, or the superpartners would already have been detected. That's obvious—if there were a spin-zero particle with the mass and electric charge of the electron it would have formed bosonic atoms and been easily produced and detected in many experiments. Similar remarks could be made about other superpartners.

Broken symmetries are familiar in physics. The electroweak symmetry is spontaneously broken by the Higgs mechanism in the Standard Model (as mentioned in point A(i) above and described further in the next section). Spontaneous breaking does not alter the existence of the quantum number of the particles. The interaction vertices are also unchanged—that is, the Lagrangian of the theory is unchanged, but the ground state (the vacuum here) does not respect the symmetry. A familiar example of an analogous system is a permanent magnet. The magnetic field points in some direction, breaking the symmetries the material had before the material cooled into the ground state. Thus the superpartners can get mass not only from the electroweak symmetry breaking but also from supersymmetry breaking. This implies that in looking for the superpartners, and in describing the indirect evidence for them, we can assume we know all their properties except their masses. Once superpartners are directly detected, understanding the origin of supersymmetry-breaking will become the central problem of the field, just as understanding the origin of the Higgs physics became the central problem of the Standard Model after the 1970s.

3. Why?

Although there is not yet direct evidence for the existence of superpartners, nearly 10 000 papers have been written on supersymmetry. Supersymmetry is usually viewed as the default candidate for physics to strengthen the foundations of the Standard Model and extend it. In this section we examine the reasons for the widespread acceptance.

To understand some aspects of the following results we need to recall that coupling strengths for any interaction in a relativistic quantum field theory change as the interactions are studied at different distance scales or energies or momentum transfers. This effect is well understood and verified—for example, the fine structure 'constant', α, takes the well-known value $\alpha \approx 1/137$ at low energies. A quantum theory calculation of the value of α at the scale of the Z boson mass predicts $\alpha \approx 1/128$, and experiments involving the Z agree with this value to good accuracy. (Appendix I has a brief explanation of this.)

3.1. *Unification of forces*

Since Coulomb showed that the electrical force had the same form as the gravitational force, many physicists have thought about how to unify the basic forces, perhaps into one that manifests itself in several ways as the forces we apparently see. In the Standard Model all the forces arise by the same gauge invariance mechanism, so the idea they could be related is reinforced. After the Standard Model was formulated, theorists studied how the forces behaved when their strengths were calculated at shorter distances, or higher energies, and found that the Standard Model forces approached one another in strength, though they did not actually meet. In the early 1980s it was realized that if superpartners were included in the calculation the forces came together rather precisely, at a somewhat higher energy, about 2×10^{16} GeV. At that time the measured values of the coupling strengths were not very accurately known, so data did not distinguish between the Standard Model and the supersymmetric Standard Model versions. Data from LEP in the early 1990s showed that the supersymmetric version led to a significantly better unification.

This unification occurs at a scale somewhat below the Planck scale, where gravity is expected to become strong. At that scale, the strength of the gravitational force is similar to the strength of the other forces. [From the universal quantities h, c, and G (Newton's constant) one can construct quantities with units of length, time, and mass or energy. These are then expected to be the natural units for the most basic theory. They are $(hG/c^3)^{1/2}\approx 10^{-35}$ m, $(hG/c^5)^{1/2}\approx 10^{-44}$ s, and $(hc/G)^{1/2}\approx 10^{19}$ GeV. Max Planck first pointed these units out, soon after he defined h. The gravitational force between two particles, e.g. protons having the Planck energy, is about equal to the electrical force between them, encouraging us to expect that at these energy or distance scales the forces are related.] Thus it is very encouraging that in a supersymmetric world it may indeed be possible to unify all the forces.

This unification works if the superpartners are light but not if they are too heavy. Unfortunately, it is not very accurate, so it implies they have to be lighter than about ten times the masses of W, Z, and the top quark, but doesn't distinguish between superpartners with masses about the same as the Z and those several times heavier.

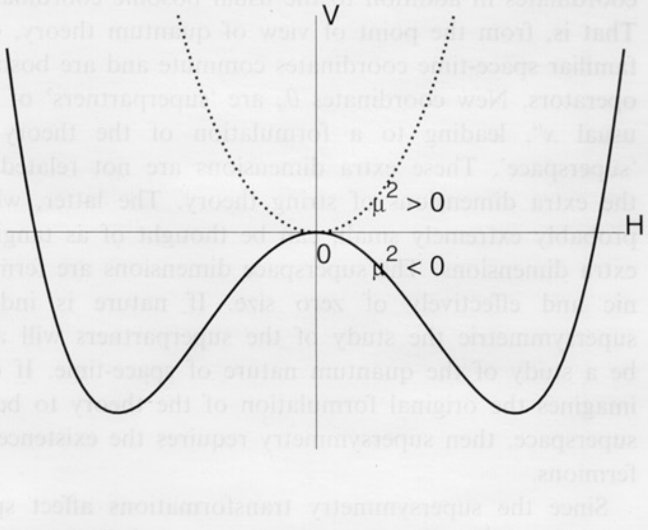
This unification says that physics is simpler at a scale $\gtrsim 10^{16}$ GeV, even though nothing in the Standard Model requires that to happen. It has two major implications. First, unless it is simply an irrelevant accident, it strongly suggests that nature is indeed supersymmetric, with superpartners having masses below a TeV. Second, because the field theory calculations of the ways the force strengths vary are perturbative calculations (through two loops), it suggests that as the energy scale is increased no strong non-perturbative effects enter that would cause the couplings to run differently. It does not imply, contrary to what is sometimes stated, that there is a desert as energy increases, but only that whatever is in the desert (e.g. right-handed heavy neutrinos, additional quarks and leptons perhaps with different SU(2)×U(1) properties, etc.) does not interact strongly with our three families and the gauge bosons.

3.2. *Higgs physics*

Probably the most important result explained by supersymmetry is the 'Higgs Physics' of the Standard Model. The theory of the Standard Model appears to be correct only if all quarks and leptons and gauge bosons have zero mass. This result follows from the symmetries of the Standard Model. The $SU(2)$ symmetry says the theory is invariant under interchanges of whatever particles are placed in $SU(2)$ representations, for example the electron and the electron neutrino, or the up and down quarks. Such an invariance can only hold if the interchangeable particles have the same mass. It turns out that to hold in all cases, the only mass they can have is zero mass.

But particles do have mass. It is the interaction with the Higgs field that allows all particles to have mass, and each a different mass. The Higgs field is assumed to have a non-zero value in the ground state of the universe (called its vacuum expectation value, vev), and particles that interact with the Higgs field obtain mass proportional to that vev.

Technically this works perfectly well. The vev of H is argued to be non-zero as follows. Suppose the potential energy of H is $V=\mu^2H^2+\lambda H^4$. λ must be positive for the potential not to be unbounded from below. Take μ^2 to be negative. Then the potential looks like this,



and the ground state will indeed occur for a value of H different from zero.

Conceptually this approach is unsatisfactory. We don't know the physical origin of the Higgs field, or why $\mu^2<0$. Supersymmetric theories can explain this 'Higgs Physics'. The Standard Model has no scalar fields apart from the assumed Higgs field. Supersymmetric theories, on the other hand, automatically have scalars, and unified supersymmetric theories naturally have scalars with the properties of the Higgs field. More importantly, in the supersymmetric theory μ^2 is not assumed to be negative—rather, that is derived!

That derivation works as follows. The basic input is that nature is simpler near the unification scale, as described in the previous section. The various masses of superpartners, etc., do not have any special values. But just as coupling strengths change when examined at different distance or energy scales, so do masses. In the supersymmetric case the entire potential energy is calculable from the basic Lagrangian. One identifies the $(\text{mass})^2$ quantity that corresponds to the μ^2 parameter of $V = \mu^2 H^2 + \lambda H^4$, and calculates how that quantity changes as it is examined at lower energies. The appropriate quantity indeed goes negative, and the shape of the effective potential looks like the one sketched above. This automatically happens at energy scales in the tens or hundreds of TeV region as it must for the results to work numerically, so long as the spectrum contains a fermion significantly heavier than the W, which it does (the top quark). Further, in the supersymmetric case the quantity corresponding to λ in V is determined and the shape of V can be calculated approximately. From that shape one can predict the mass of the lightest Higgs boson to be about 90 ± 40 GeV in a large class of models. In the most general cases that mass can get somewhat larger.

When this derivation of the Higgs mechanism was first recognized in the early 1980s, the top quark mass was not known. It was thought to be a few times the b mass, while it turned out to be about 35 times the b mass. This successful prediction that m_{top} would be large reinforces our confidence that this is the correct explanation of the Higgs mechanism.

It is very important to understand that the electroweak symmetry-breaking of the Standard Model cannot be explained or generated within the Standard Model. Some new physics is required. The success of supersymmetry in providing the explanation for the breaking of the electroweak symmetry via the Higgs mechanism is the most important reason why we expect supersymmetry to be part of our description of nature. Every effort to consider new physics beyond the Standard Model should be evaluated in terms of its ability to explain the breaking of the electroweak symmetry.

3.3. *The 'hierarchy problem'*

There is another conceptual problem for the Standard Model. If one calculates loop corrections to the Higgs boson mass in the Standard Model, or the Standard Model extended to include most kinds of new physics, the resulting integrals are infinite and the theory is not defined. If one says that some new physics enters so one can define the theory by parameterizing the new physics, one finds corrections of order Λ^2/M_h^2, where Λ is the scale of the new physics. Such quadratic corrections essentially move the Standard Model scale up to the new physics scale, wherever it is. Thus the Standard Model is really incomplete as a basic theory.

In the late 1970s it was noticed that supersymmetry could provide a solution to this problem. In the supersymmetry case, the particles and their superpartners both enter the loops. The standard sign of fermion loops in field theory is opposite to that of boson loops, so if the particles and superpartners have the same masses and couplings (as they do in the supersymmetric limit), their contributions cancel exactly. When the supersymmetry is broken, the divergent Λ^2/M_h^2 is replaced approximately by $g^2(\tilde{m}^2 - m^2)/M_h^2$, where $\tilde{m}$ is a superpartner mass, m is a typical Standard Model mass, and g the electroweak coupling strength. If $\tilde{m}$ is not very large, such corrections eliminate the hierarchy problem. This is yet another clue that the superpartner masses are not too large, but again it is too qualitative to tell us precise predictions for the masses. It suggests the masses should be below a TeV, perhaps much below.

3.4. *Cold Dark Matter*

In the late 1970s it was realized that the vertices of the supersymmetric Standard Model, as written above, allowed all superpartners to decay into lighter ones, except that the lightest superpartner (LSP) was expected to be stable by energy conservation. Soon thereafter people calculated the relic densities of various possible choices for the LSP, and saw that in typical models the LSP could provide the Cold Dark Matter of the universe. At that time astronomers knew that dark matter was needed to understand the amount of matter in galaxies and galaxy clusters, but did not know if dark baryonic matter such as Jupiters could provide what was needed. That the LSP could provide the Cold Dark Matter was a prediction of supersymmetry.

The relevant calculations are qualitatively straightforward. Just after the big bang all kinds of particles are in equilibrium. All heavier ones decay as the universe cools, leaving stable particles (γs, νs, u and d quarks, electrons, and LSPs). The γs and νs remain, but comprise only a tiny part of the energy density of the universe. The quarks bind into protons and neutrons, which in turn bind into nuclei, which combine with electrons to make atoms. Matter composed of baryons and electrons provides at most a few per cent of the energy density of the universe. All superpartners originally present end up as an LSP. Some of the LSPs annihilate each other as the universe evolves. If the masses of the superpartners (including the LSP mass) were known, the number that annihilate could be calculated since the Lagrangian of the supersymmetric theory is known. Using models for the masses leads to estimates for the number of relic LSPs. Multiplying that number by their mass gives an estimate of the LSP energy density. One finds a number consistent with the LSP providing all the Cold Dark Matter of the universe, though the range resulting from the calculation is large. Thus supersymmetry provides a candidate for the Cold Dark Matter of the universe. The Standard Model cannot account for the Cold Dark Matter.

To confirm that the LSP is indeed the Cold Dark Matter the LSP will first have to be observed directly. That will require a combination of experiments. If superpartners are discovered at colliders, the LSP will have been discovered in laboratories on Earth. But there are two subtleties. LSPs could appear to be stable at colliders, but still not live as long as the universe before decaying (it only takes a few billionths of a second to traverse a detector). Several kinds of experiments are searching explicitly for the relic LSPs, and could find a signal in the next few years. There are three kinds of searches. Perhaps the most promising uses the fact that LSPs would be spread uniformly throughout the galaxy. As we move in the galaxy a nucleus in a detector would occasionally recoil from an LSP and deposit tens to hundreds of keV in the detector. Clever detectors have been developed to observe such signals. The other two approaches use the decay products from LSP annihilation. Detectors in balloons, and one (acronym AMS) that will fly on the space station, look for an excess of positrons or antiprotons that could arise from LSP annihilation. The other uses the fact that LSPs, being heavy and only interacting weakly, will concentrate at the centre of the sun and the earth. Then LSP annihilations sometimes lead to energetic muon neutrinos, which then interact in the earth to produce muons which in form can be detected in large underground detectors.

In addition, all of the supersymmetry parameters that enter the calculation of the relic density of the LSP will have to be accurately measured so that the relic density can be determined to indeed be essentially equal to the actual Cold Dark Matter. When LSPs are initially discovered it should be possible to estimate their relic density to a factor of perhaps a few. When the parameters are well-measured it should eventually be possible to calculate the amount of LSP Cold Dark Matter to better than twenty per cent accuracy from laboratory data.

3.5. *New approaches from supersymmetry*

The three examples just described are the clearest where supersymmetry explains phenomena that the Standard Model cannot explain, or provides stimulating new approaches to basic questions. There are several more areas where supersymmetry may explain basic phenomena, but results are not yet strong enough to be sure. As with its earlier successes, supersymmetry was not invented to explain any of these phenomena.

One is the rate at which protons decay. In some versions of unified theories quarks can make transitions into leptons and vice versa. Then the quarks in the proton can turn into lighter leptons, and the proton can decay. The simplest non-supersymmetric versions led to predicted proton decay rates that were too rapid compared to data, but the supersymmetric ones are not in contradiction with experiment.

Another is the goal of understanding why the universe is made of baryons rather than an equal mixture of baryons and anti-baryons. This is a fundamental property of the universe that the Standard Model cannot explain. There is not a unique, agreed on explanation; rather, there are several approaches. All of them require supersymmetry.

A third is inflation, a very rapid and large expansion of the universe before the big bang. Before inflation is fully accepted as part of the explanation for the observed properties of the universe, it will be necessary to identify the physical particles whose interactions led to the expansion. Supersymmetry provides scalar fields that can play this role, and supersymmetry-breaking is expected to give masses to the scalars of string theory, to determine the potential that fixes the dynamics of inflation. This is a newer area of activity, and a promising one.

A fourth is CP violation, a small ($\sim 10^{-3}$) but extremely important effect such that particles and their CP conjugates have slightly different interactions. The Standard Model can describe CP violation in the Kaon system, but it cannot explain the baryon asymmetry, which requires CP violation. We have recently shown that supersymmetry can provide a unified explanation of all CP violation. The Standard Model CP violation is not required. Whether the supersymmetric version of CP violation is correct can be tested at b-factories. If this is a valid approach, it has interesting implications for how string theory relates to the real world.

3.6. *Successful predictions from supersymmetry*

Since superpartners have not yet been directly observed, sometimes people say supersymmetry has not yet made successful predictions. But in fact at least three experimental results were predicted by supersymmetry.

One is the heavy top quark. In the early 1980s people were searching for top quarks a few times heavier than the b-quarks, 15 GeV or so. A major justification for the Tristan collider was to find the top quark—it could only search up to 30 GeV top mass. As mentioned above in the explanation of the Higgs mechanism, supersymmetry provides this explanation if the top quark is heavy, where heavy means compared to M_W. Uncertainties in other quantities meant the prediction could not be precise—could not distinguish between (say) 1.2 M_W and 2 M_W, but M_{top} had to be large compared to the typical estimates of the time, as it indeed was.

A second prediction is the value of the quantity called $\sin^2\theta_W$ (essentially determined by M_W/M_Z) in the Standard Model. From the Standard Model perspective,

$\sin^2\theta_W$ is an unexplained parameter. In a unified theory $\sin^2\theta_W$ can be predicted. The unified Standard Model theory predicted $\sin^2\theta_W = 0.215$, while the unified supersymmetry theory predicted in 1982 that $\sin^2\theta_W = 0.231$, consistent within errors with the value later measured at the CERN LEP collider, in Geneva, Switzerland, and the SLAC SLC collider in Stanford, CA.

A third prediction was made for the LEP study of 20 million Z decays and precision measurements. All supersymmetry effects could only enter through loop corrections. The loop corrections could only be large enough to lead to deviations from the Standard Model if the superpartners were light. Therefore either the superpartners would be light enough to directly detect at LEP, or no precision measurements should deviate significantly from their Standard Model values. Other approaches to extending the Standard Model generally suggested that large deviations should be seen. The superpartners were not directly produced, and no significant deviations from the Standard Model were observed, consistent with the supersymmetric prediction.

3.7. *Window on the Planck scale*

If nature is indeed supersymmetric, the most important consequence will be to provide a window to see the Planck scale. We expect a fundamental theory that describes the most basic law(s) of nature to be formulated at the Planck scale. But we do experiments at the 'collider' scale, many orders of magnitude lower in energy, or larger in distance. How can we test the formulations of the ultimate theory? We have learned that our description of the physical world can be organized in terms of 'effective theories', each for part of the picture, e.g. atomic physics. As we probe smaller distances, we move to the theory of the nucleus, of protons and neutrons, of quarks and leptons (i.e. the Standard Model). Then there is a large gap to the ultimate theory near the Planck scale. In this effective theory sense I think a good name for the ultimate theory is the 'primary theory', since all the effective theories coexist together yet this one will be the most basic.

Most effective theories break down at higher energies or shorter distances. Supersymmetry has special properties so that it can remain valid down to the primary theory. If the world is supersymmetric, it will be possible to write theories near the Planck scale and make predictions for colliders and rare decays, or conversely write the Lagrangian based on data at the collider scale and extrapolate to near the Planck scale. With supersymmetry we can expect to have extensive guidance from experiment toward formulating the primary theory. That does not, of course, mean that nature is supersymmetric, but it does help understand why many physicists are excited by the possibility.

4. When will Higgs bosons and superpartners be detected?

Since supersymmetry is a broken symmetry, we do not know the masses of the superpartners. We do know how they interact, so for a given choice of masses we can calculate the production cross-sections and decay branching ratios. Consequently, we can systematically look for signals of superpartners at any collider, and set lower limits on masses if no signal is found.

The current limits are not very strong. Gluinos and squarks feel the strong force, so their production cross-sections are largest. But model-independent limits for them are only about the top quark mass. Since superpartners obtain mass from both the supersymmetry-breaking and the electroweak symmetry-breaking, it is not surprising if the squarks and gluinos are heavier than the top quark. Limits for partners of Ws and sleptons are only a little larger than M_W, again not surprising. There are no general limits for the electrically neutral partners. In specific models the limits can be stronger.

What superpartner masses should we expect? There is only one aspect of supersymmetry that can quantitatively normalize the masses for us, and even this requires some interpretation. That aspect is the derivation of the Higgs mechanism from supersymmetry. Since the W and Z obtain mass from the Higgs mechanism the result of that derivation is an equation of the form:

$$M_Z^2 = \sum_i C_i \tilde{m}_i^2$$

Here $\tilde{m}_i$ are various superpartner masses, and C_i are coefficients that are calculated; some C_i are larger than one, and some are negative.

If all the $\tilde{m}_i$ were independent, in order to avoid taking differences of larger numbers ('fine tuning') we would expect several $\tilde{m}_i$ to be of order m_Z itself, so that signals should be in the reach of present colliders, and surely accessible to the upgraded Fermilab TeVatron that takes data in 2001. However, when there is a theory of supersymmetry-breaking it is expected that there are relations among the $\tilde{m}_i$, so cancellations may occur. We have studied this by constructing models where the $\tilde{m}_i$ are all related, and studying how long the $\tilde{m}_i$ can be made without invoking too much fine tuning. While the results are somewhat subjective, we find that after gathering luminosity for a few years the upgraded TeVatron should definitely have observed a signal if supersymmetry indeed explains the Higgs mechanism. Of course we could be lucky and one could be found in 2000 at LEP, or early at Fermilab. The Large Hadron Collider, LHC, under construction at CERN, will be a superpartner factory.

There is an analogous situation for Higgs bosons. Since light Higgs bosons are a necessary consequence of supersymmetry, they must be detected. Studies show that they can be found at Fermilab too, though there is a signal/noise problem so it may take several years of running to observe them. LHC will be a Higgs factory, though observation will be challenging. Again, with luck a Higgs boson may be found at LEP in 2000.

Unfortunately, the very nature of supersymmetry implies that the nature of the signal for superpartners will not be an unambiguous, clear effect. That is because the superpartners must be produced in pairs (see the vertices described earlier), so after decays two LSPs occur in every event. The LSPs do not have colour or electric charge, so they only interact weakly, essentially as neutrinos. Therefore, they escape the detectors. That means that the missing energy for superpartner events will be larger than for Standard Model events, which is one of the main signals for supersymmetry. It also means that because the energy is carried away by two particles rather than one it is very difficult to reconstruct any observables that show dramatic effects. Establishing the existence of superpartners, and measuring their properties, will require careful, detailed study.

5. Concluding remarks

The Standard Model of particle physics provides a well-tested and theoretically robust description of the physical world. It is here to stay. For the reasons outlined earlier, we know it is not the final answer. It is an effective theory, valid at the energy scale of order 100 GeV.

It seems very likely that some form of string theory (or more generally M-Theory) will be the primary theory. But that is formulated in 10 (or 11) space-time dimensions at the Planck scale and has unbroken supersymmetry. It is unlikely that theorists can guess how to break supersymmetry and how to compactify to four dimensions without guidance from experiment. Even if they do guess (or already have), without data to confirm it they will not be confident they got it right.

If nature is indeed supersymmetric, supersymmetry can mediate between these extremes. It provides a stronger foundation for the Standard Model. It can allow us to relate data to string ideas, to test approaches to compactification and supersymmetry-breaking against data, or even to have data point the way to solve these problems. Supersymmetry is the penultimate effective theory.

We have seen in this review that supersymmetry provides explanations for a number of the basic questions raised in the Introduction (A(i),(ii), B(i)), and string theory can address some of these and others (B(i) – B(vi)). It is not yet known if string theory plus supersymmetry can explain neutrino masses, but this is an active research area. Together supersymmetry and string theory can explain most of our deepest questions about understanding our universe and why it is the way it is.

A historical analogy provides a useful perspective on the time-scale. Dirac in 1929 was led by a beautiful theory that unified special relativity and quantum theory to predict the existence of anti-particles, a doubling of the number of particles. Luckily the positron was light, and it was observed a few years later. Suppose the positron had not been light. To observe antiprotons a new facility had to be built. They were observed 27 years after the prediction of antiprotons.

Supersymmetry is also a beautiful theory. It unifies bosons and fermions, forces and matter, and also predicts a doubling of the number of particles. It was written for relativistic quantum field theories about 1974. If we add 27 years, we would be right on schedule if superpartners were detected in 20001 – 2003 at Fermilab (or even before at LEP).

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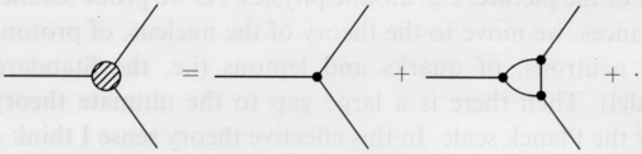
Appendix I

In a quantum theory, all observables change with the distance scale probed. Basically this is simply the effect of the familiar perturbative expansion of any matrix element, as a Born term plus a sum over intermediate states. The terms involving intermediate states depend explicitly on the energies of the external particles, so at higher energies (corresponding to larger momentum transfers or shorter distances), more intermediate states can come into play.

In particular, for couplings one can have an expansion so the true coupling is a point-like piece, the Born term, plus loop diagrams with intermediate states,



At a given energy, all intermediate states with masses below or near that energy can contribute significantly to the loop term. This is the origin of most of the Lamb-shift, and this same effect allowed the top quark to be ‘detected’ as a loop contribution before any collider had enough energy to produce it directly. The result is usually presented as an equation relating any coupling, such as the fine-structure ‘constant’ α, at one energy scale to its value at others.

The important question is then what particles go in the loop. If the Standard Model particles were the only particles in the world, they would be the only ones in the loop. If superpartners exist, they go in the loop too, and change the way the coupling varies as the energy scale changes. The results are described in the text.

References

[1] A treatment of the Standard Model at the level of this review is available from Kane, G. L., 1993, *Modern Elementary Particle Physics*, updated edition, Addison-Wesley. A review of recent tests of the Standard Model is Riles, K., 1998, Testing the Standard Model, *Contemporary Physics*, Volume 39, pp. 1 – 11.

[2] The history of early supersymmetry can be traced from Shifman, M. (ed.), 1999, *Many Faces of the Superworld*, Singapore, World Scientific.

[3] A detailed review of the experimental limits on superpartner, and other aspects of supersymmetry and phenomenology, can be found in Kane, G. L. (ed.), 1998, *Perspectives on Supersymmetry*, World Scientific, Singapore, 1998. For the experimental situation see the chapter by Carena *et al.* It is possible to write more complicated versions of supersymmetry—for example, in this review we are assuming there is a conserved quantum number distinguishing SM particles and superpartners called R-parity; the chapter by H. Dreiner describes the theory if R-parity is not conserved. For a study of the potential of the upgraded Fermilab collider to detect superpartners and Higgs bosons, see the report of the Run II Working Group, ed. J. Lykken, in press.

Gordon Kane received his PhD from the University of Illinois in 1963, under J. D. Jackson. He has been at the University of Michigan since 1965, except for sabbaticals and leaves at Rutherford Lab and Oxford, Stanford Linear Accelerator Center, and CERN. For over two decades he has studied particle physics beyond the Standard Model, focusing on how experiment and theory can inform each other to extend the Standard Model and strengthen its foundations. His work has emphasized supersymmetry and Higgs physics. In addition to numerous research papers, he has published and edited several books, including *Modern Elementary Particle Physics* that gives a modern explanation of the Standard Model of particle physics at the senior level, and two books for the general public, *The Particle Garden* and, very recently, *Supersymmetry*.