

STRING THEORY IS TESTABLE, EVEN SUPERTESTABLE

Suppose we could understand the laws of nature that govern the particles and their interactions, and in addition why the laws are as they are, and also how the universe evolved and perhaps even how it originated—an active research area today. That understanding—a theory—would be formulated not in terms of everyday units, but rather units built from constants such as the speed of light, Planck's constant and Newton's constant. From these constants one obtains the natural scales: the Planck length ($\sim 10^{-33}$ cm) and the Planck mass ($M_P \sim 10^{19}$ GeV/ c^2). I will call this theory the primary theory, a name I like because it suggests that as we go through a hierarchy of effective theories, from macroscopic sizes to atoms to nuclei, we end at a primary one that is not related to another at a deeper level.

Since we cannot ever do experiments at 10^{19} GeV or at 10^{-33} cm, how could we ever test the primary theory experimentally? Would we be doing philosophy instead of physics, or as John Horgan has recently described it in *The End of Science*,¹ doing “ironic science”? A decade ago in *PHYSICS TODAY* (May 1986, page 7), Paul Ginsparg and Sheldon Glashow raised this question dramatically, and effectively began a widely repeated myth that string theories, candidates for a primary theory, are not testable. Here I want to dispel this myth, and describe some of the many ways in which string theories are testable. If nature is supersymmetric on the electroweak scale, for which there is exciting but not yet compelling evidence, then string theories are even testable in essentially the same ways as traditional ones. All the tests I describe are doable now or in the foreseeable future with existing or proposed facilities or projects. Please forgive a little jargon because of space limitations.

It is useful to split the discussion into four categories of known tests, plus a speculative one: profound questions, “why” questions, phenomena at low energy, connections to the Planck scale and unexpected tests.

Profound questions

There are a few profound questions that cannot even be asked as research topics in most contexts. In string theories, however, they can be formulated and perhaps answered. These questions include explaining the smallness of the cosmological constant, defining space and time, providing a derivation that we live in four spacetime dimensions and explaining what a particle is and what electric charge is. An answer to any of these (or similar questions) would be a powerful clue to the validity of string theory.

“Why” questions

A theory that can explain why we observe three families of chiral quarks and leptons (chiral means that the left- and

Many believe that superstring theory, because of its extraordinarily tiny length scale and gargantuan energy scale, cannot be tested. That belief is a myth.

Gordon Kane

there should or should not be additional kinds of matter that can be detected in collider experiments, such as particles to complete a representation of a larger group.

Similarly, the Standard Model of particle physics is based on certain symmetries under interchange of the particles: an SU(3) symmetry for interchanging quarks of different colors, an SU(2) symmetry for interchanging the up and down quarks and so on, and a U(1) symmetry for which the particles have different eigenvalues. Why those symmetries and no others?

Phenomena at low energy

There are ways to probe small distances without explicitly going to high energies or small distances.

▷ Perhaps the principle that determines the electron, muon, tau and quark masses is part of the primary theory; this happens in some superstring models. Calculating the ratio of tau to muon masses correctly will be a convincing test. (That's the best mass ratio to calculate because it is known accurately and the small electron mass is sensitive to corrections.) The rotation from symmetry eigenstates to mass eigenstates (the Cabibbo–Kobayashi–Maskawa angles), and the associated electroweak CP violation phase, have to emerge from a successful model too.

▷ Quarks and leptons occur in similar patterns and may be related as parts of multiplets of a large group. If so, they can turn into one another, and the proton can decay. Whether it does, and the associated lifetime and final states, may probe distances near the Planck scale.

▷ The forces might unify into a larger symmetry group at a unification scale or the Planck scale. If so, as that group breaks at lower energies into the observed gauge groups—SU(3) × SU(2) × U(1)—there may be extra U(1) symmetries that lead to one or more Z' bosons. The presence (or absence) of these bosons and their properties would be a major test of the theory.

▷ Neutrino masses are zero in the Standard Model, but not for general reasons. They are expected to be nonzero in general. The primary theory has to explain why they are so small, and predict or explain the (present and future) observed neutrino data. Present thinking suggests that the neutrino masses arise in ways different from the quark and charged lepton masses, probing both the Planck scale and intermediate scales in different ways.

▷ The strong interaction conserves CP to much greater accuracy than quantum chromodynamics requires (the “strong CP problem”). In the Standard Model this is reflected by a free parameter (a phase) set close to zero to match the experimental results. String theories will predict that parameter, and some won't get it right. The primary theory has to get it right and explain why the

right-handed fermions are treated differently)—that is, why there is a muon and a tau so like the electron—will have passed a big test. It must also explain why matter comes as quarks and leptons but not as other possible forms such as leptoquarks. The theory will predict that

GORDON KANE is a professor of physics at the University of Michigan in Ann Arbor.

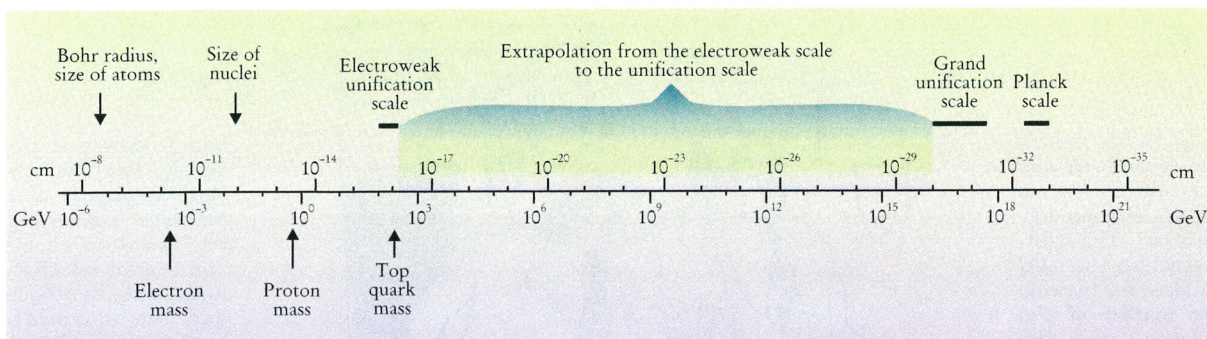


FIGURE 1. THE NATURAL SCALES of atoms, nuclei and electroweak unification are many orders of magnitude removed from the Planck scale—the primary theory’s natural scale. It is not necessary, however, for experiments to probe the Planck scale directly to test such a theory. Nor is the extrapolation from the experimentally accessible regime as impractical as it may seem: In quantum field theory the natural variable for the extrapolation is the logarithm of the scale. Also, in supersymmetric models the extrapolation to the unification scale can be perturbative.

parameter is close to zero. (For an engaging discussion of the strong *CP* problem, see the article by Pierre Sikivie, *PHYSICS TODAY*, December 1996, page 22.)

▷ Finally, some rare decay processes, such as $\mu \rightarrow e + \gamma$ or $K \rightarrow \mu + e$, are forbidden in the Standard Model, but not for general reasons. They occur at some level in extensions of the Standard Model and will give us information about small-distance interactions.

Connections to the Planck scale

All of the above tests are important even if we can never make direct contact with the primary theory at the Planck scale. Most of them explain a known property or quantity rather than predicting an as-yet-unmeasured one. That’s fine as long as the explanation is unique. We don’t recreate the Big Bang to test it, we deduce consequences such as expansion, nucleosynthesis and the microwave background radiation. If nature is supersymmetric, however, then in all probability we *can* connect with the primary theory at the Planck scale and we have many more tests, mostly predictive ones. Supersymmetry will connect us to the Planck scale if the theory remains perturbative all the way from the electroweak scale ($\sim 10^2$ GeV) to the unification scale. Although it is not yet proven that this must happen, the most promising types of supersymmetric models behave this way. Further evidence is provided by the gauge couplings α_1 , α_2 and α_3 (the generalizations of the fine-structure coupling α to the three standard model forces), which seem to become equal above 10^{16} GeV when calculated perturbatively in supersymmetric models.

In a quantum field theory, all quantities (masses, couplings and so on) depend on the scale at which they are measured. If the theory predicts them at one scale (say the Planck scale) and the theory is perturbative between there and the scale where experiments are done, then predictions for the experiments can be calculated and the theory tested. Alternatively, quantities can be measured and then their Planck-scale values calculated

and compared with theory. While doing that depends on assumptions about other matter at intermediate scales and similar things, it also tests such assumptions. Sometimes people argue the extrapolation is too long, but the theory says the correct variable is the logarithm of the energy and in that variable it is not a large distance between the experimental and Planck scales.

Some of the additional tests that arise in this way:

▷ First, that nature *is* supersymmetric. The *Wall Street Journal* assures us (in an op-ed piece by David Gross and Edward Witten²) that “supersymmetry is one of the basic predictions of string theory.”

▷ The values of the coupling strengths α_1 , α_2 and α_3 , the scale M_U where they unify and other observables all depend on the theory, both because of their initial values at the unification scale and because the supersymmetric partners (sparticles) play a role in the equations that determine how the observables change as they go from the unification scale to the collider scale.

▷ Each standard model particle must have a superpartner, so the masses of over 30 sparticles must be predicted.

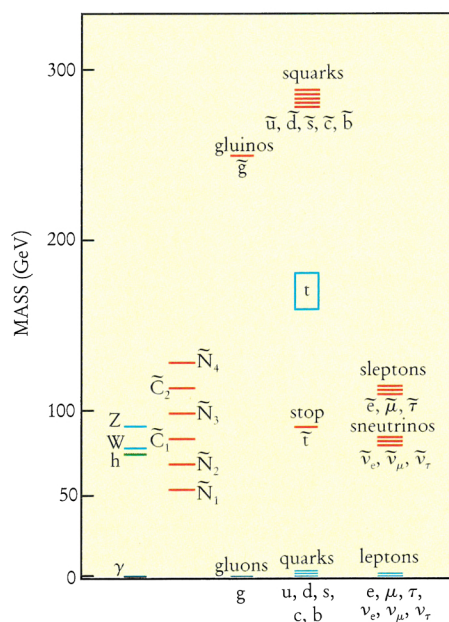


FIGURE 2. A POSSIBLE SPECTRUM of particles (blue) and their superpartners (red). The existence of superpartners is a prediction of supersymmetry, which, in turn, is a prediction of string models. The spectrum shown is consistent with all data at present. The neutralinos ($\tilde{N}_i$) and charginos ($\tilde{C}_i$) are mass eigenstates of the electroweak superpartners $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{W}$ and so on. The Higgs boson (h , green) will be accompanied by three other Higgs boson states with higher mass. The primary theory would predict a specific spectrum of particles and superpartners that can be compared with experimental data.

The patterns among them depend strongly on the theory and on how supersymmetry is broken. The lightest sparticle is a good candidate for the cold dark matter of the universe, and the properties the primary theory predicts for it will be thoroughly tested.

▷ At least two more phases that can produce *CP* violating effects will enter in addition to that from the Standard Model. They can affect a number of experiments for electric dipole moments and experiments on the neutral meson systems, as well as the origin of the baryon asymmetry of the universe.

▷ The theory will or will not predict some discrete symmetries (such as "*R*-parity" that is sufficient to forbid too-rapid proton decay and to provide a stable lightest sparticle as a cold dark matter candidate). Such symmetries are common in models.

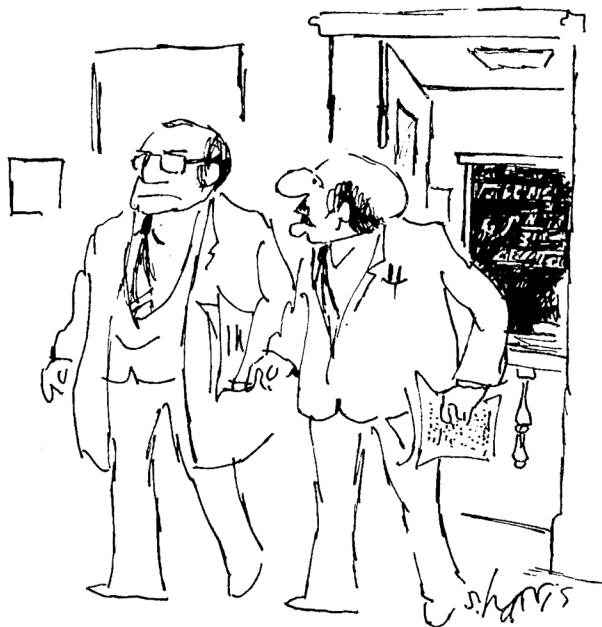
▷ Inflation of the early universe is driven by one or more scalar particles; a potential determines how inflation works in detail. In supersymmetric theories those scalar particles are the scalar sparticles, and the potential is their scalar potential energy. The same coefficients in the equation for that potential can affect structure formation (such as the formation of galactic clusters), the neutrino masses, the baryon asymmetry and how many inflations occur as the universe cools.

▷ The ratios of the amounts of cold and hot dark matter to each other and to baryons are part of the theory and must be calculable.

▷ Finally, there are contributions to the Lagrangian of order $1/M_P$ that can be detectably large. Which operators occur in the Lagrangian depends on the theory, and they affect many of the observables mentioned above in interesting ways. They also contribute to the potentials of some scalar particles that would otherwise be massless; that is, the $1/M_P$ terms determine masses in some cases. There are a number of ways to study these observables and masses and learn about the form of the theory at the Planck scale or test it.

Unexpected tests

The final class of tests that the primary theory must pass is inherently more speculative than those discussed above, but it would be inappropriate to leave it out of the argument. Established theories have always had unexpected tests that could not be known until one had the theory. Historically these tests include electromagnetic waves for electromagnetism, the effect of gravity on light



"BUT DON'T YOU SEE, GERSHON - IF THE PARTICLE IS TOO SMALL AND TOO SHORT-LIVED TO DETECT, WE CAN'T JUST TAKE IT ON FAITH THAT YOU'VE DISCOVERED IT."

being different for general relativity and classical gravity, anti-particles from unifying quantum theory and special relativity, and nucleosynthesis and the microwave background radiation for the Big Bang theory of the universe. Of course, I cannot say what the unexpected tests will be for the primary theory, but I can list some candidates that might occur:

▷ Perhaps the number of particle families will be related to the number of space dimensions or to the Yukawa coupling (and therefore mass) of the heaviest fermion (the top quark) or to some other observable, as happens in models.

▷ Some of the scalar fields are expected to be massless until the supersymmetry is broken. Some of the scalars may remain very light, and give rise to long-range forces or contribute to neutrino masses in a predictable way.

▷ Some interactions that are forbidden in any point-particle quantum field theory can occur in string theory. For example, certain quantities described by Lorentz tensors in the theory can acquire nonzero vacuum expectation values. This breaks Lorentz invariance and *CPT* symmetry. In models, such effects could appear at detectable levels in the neutral *K*, *D* and *B* systems, or in decays such as $K^+ \rightarrow \pi^+ + \gamma$, or in appropriate atomic or nuclear systems.

Thus, particle physics is not approaching its end because it is not testable. Horgan and many others have been misled about the testability of string theory—the study of string theories is ordinary science. Whether particle physics will end because funding is insufficient for it to proceed, or because of priority choices, is less clear. If the experimental hints for relatively light superpartners are not misleading us, then a significant part of the path can be covered using the facilities and experiments that exist today and their luminosity upgrades (now in progress), plus appropriate detector upgrades and further experiments and observations on proton decay, neutrino masses, rare decays, and inflation and structure formation. If particle physics ends because a primary theory is found, tested and verified, it will be a wonderful human accomplishment. Perhaps that great achievement will be tempered by sadness that the quest has ended.

References

1. J. Horgan, *The End of Science: Facing the Limits of Knowledge in the Twilight of the Scientific Age*, Helix (Addison-Wesley), New York (1996).
2. D. Gross, E. Witten, *Wall Street Journal*, 12 July 1996, p. A12. ■