Is string theory phenomenologically viable?

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String theory is entering an era in which its theoretical constructs will be confronted by experimental data. Some cherished ideas just might fail to pass the test.

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String theory has a strange and remarkable history in which the conventional wisdom of the field has sometimes changed chaotically. After the mathematical consistency of superstrings (strings that accommodate a "supersymmetry" relating bosons and fermions) was demonstrated in 1984, a consensus arose that string theory would offer a unique solution that describes our universe. The belief in a unique vacuum is, to me, a Ptolemaic view—akin to the ancient belief in a unique place for Earth. As I wrote in 1989, a Copernican view, in which our universe is only one of an infinity of possibilities, is my preference, but there were very few Copernicans in the 1980s. Today, the string-theory community is engaged in a lively debate about a "landscape" with many solutions.[1] That debate represents a shift away from the idea of uniqueness and toward the possibility of multiple universes, a multiverse. Another idea from string theory that may be ripe for reevaluation is its "prediction," derived in the 1980s, of extra, hidden dimensions beyond those of the staggeringly successful standard model.

The foundation of the standard model is a fiber bundle—a union of four-dimensional spacetime with a souped-up version of the isotopic spin space suggested in 1938 by physicist Nicolas Kenmer (see figure 1). His idea, very simple from a modern perspective, is exemplified by the electromagnetic four-vector potential and its so-called gauge invariance: Two potentials related by an appropriate gauge transformation lead to the same electromagnetic force. The gauge transformation, in turn, may be characterized by gauge parameters. In the standard model, the four-vector potential is quantized to become a spin-1 bosonic field, the photon, and one can speak of gauge-equivalent photons. Kenmer noted that the gauge parameters possess many of the geometrical properties of angles as viewed in the everyday world. However, Kenmer angles do not measure properties of hidden dimensions. In the standard model, they distinguish between gauge-equivalent spin-1 bosons and directions in the modified isotopic spin space.

The construction of superstrings was a magnificent accomplishment in string theory. So was the later construction of heterotic strings, which mix supersymmetric and bosonic string elements. The heterotic strings revealed a remarkable embedding of gauge theory into string theory. Initial heterotic string presentations had clear connections to gauge theory but no place to directly accommodate Kenmer angles. In later work, Warren Siegel and I uncovered a formulation of the 10D heterotic string in which the Kenmer angles naturally appear.[2] That work also clearly implied the existence of genuinely 4D heterotic strings. Our result was unique in that it made a direct connection to fiber bundles, but our approach was only one of three that independently showed a way to avoid going beyond four dimensions.[3]

Today, warped passages and hidden dimensions have

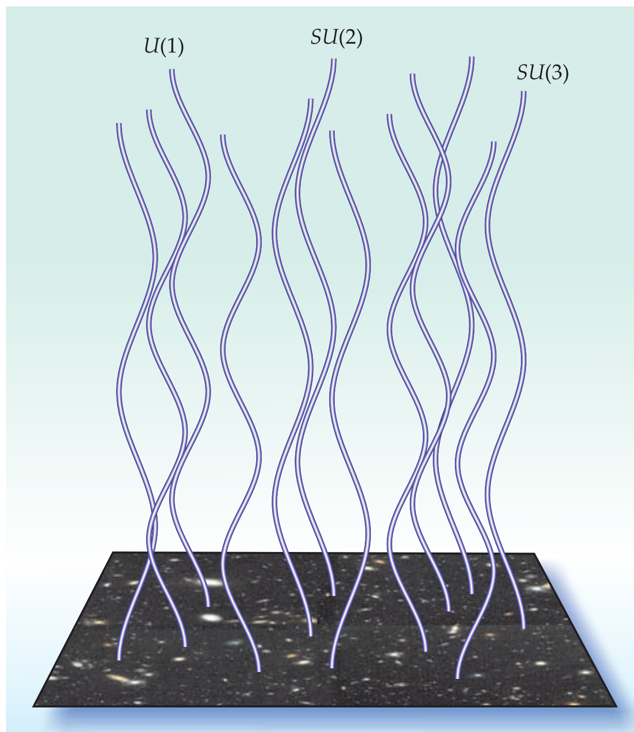

Figure 1. A fiber bundle is built from a base that has a fiber emerging from each of its points. In the standard model, the base is the four-dimensional spacetime of our universe, and each of the fibers, the simple depictions notwithstanding, is one of the gauge groups $SU(3)$, $SU(2)$, or $U(1)$ that mathematically define the gauge transformations of the model. In 4D string theories, fibers can represent gauge groups that are not part of the standard model. (Hubble Deep Field image courtesy of Robert Williams, Space Telescope Science Institute, the Hubble Deep Field team, and NASA.)

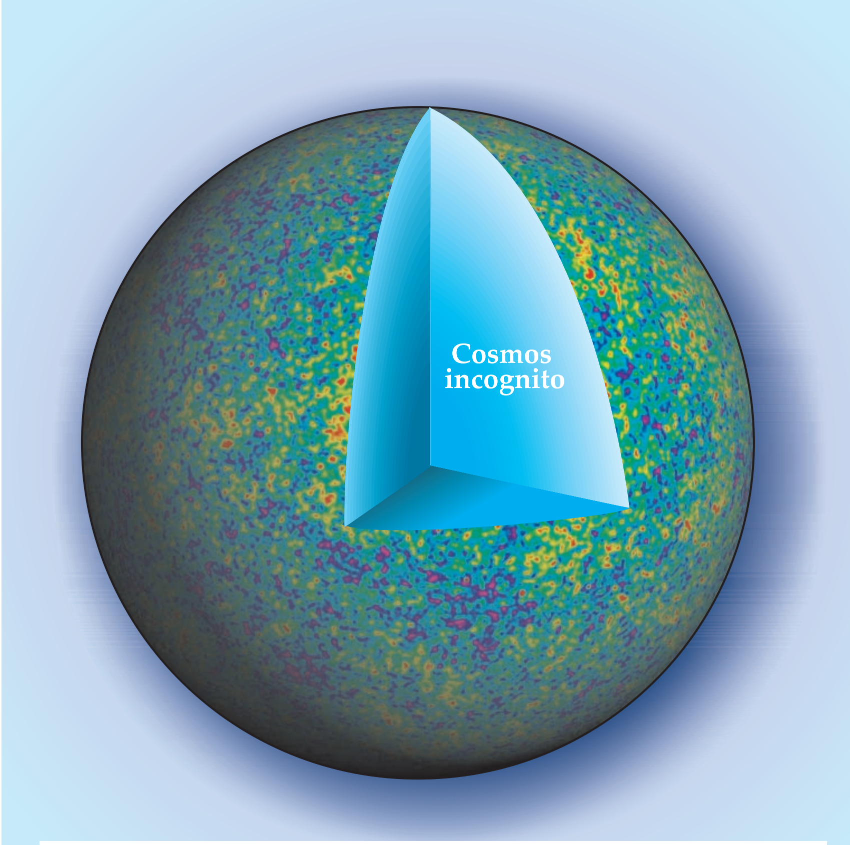

Figure 2. In brane-world scenarios, our four-dimensional universe is merely a surface in a higher-dimensional space. In this fanciful rendition, our universe, represented by a map of the cosmic microwave background, lies on the surface of a ball. What is inside the ball is completely unknown. (CMB image courtesy of Max Tegmark, MIT, based on *WMAP*-team data.)

garnered vast support, not only in string theory but also in cosmological models.[4] But as I have just discussed, string theory, though consistent with extra dimensions, possesses more baroque formulations that avoid them ab initio by including fiber bundles.

Observation has its say

Will the string community shift its opinion on the question of hidden dimensions? There is no simple way to make predictions. However, an undeniable shift will occur in the environment in which string theory—elegant, but so far unverified—will compete for survival. Fundamental science has a yin–yang quality: If mathematics is the yin, then observation is the yang. And the field is entering an era that promises an explosion of data. In some ways the promise is already being fulfilled. The data most relevant to string theory are results from astrophysics and cosmology and data about particle phenomenology. The physics community's current acceptance of the concordance model shows that astrophysical and cosmological data have already had influence.

According to the concordance model, our universe had equal amounts of gravitational and matter energy at its inception. It now has a positive cosmological constant but one ridiculously tiny compared to theoretical expectations; a substantial amount of cold dark matter; and, at about the 5% level, stuff with which our science is familiar. It is difficult to conceive of a more exciting set of data with which a theory of everything must contend.

Some attributes of the concordance model are quite comfortably accommodated in the context of superstring theory, but the positive cosmological constant is a glaring exception. Usually, theories with supersymmetry are inconsistent with the spacetime geometry associated with a positive cosmological constant. And theorists expect that the effective action of string theory, which describes our low-energy universe, will have supersymmetry. How to convincingly reconcile that expectation with the positive cosmological constant will require additional research.

As astrophysical and cosmological data improve, they will allow important tests of string theory. As is well known in the string community, the low-energy limit of the theory describes gravitational dynamics that are modified from those predicted by Einstein's theory of general relativity (GR). Presently, one of the challenges confronting physics is to detect waves of gravity; LIGO, the Laser Interferometer Gravitational-Wave Observatory, is one attempt to meet that challenge. In time, it might ultimately be possible to explore gravitational-wave birefringence. One mechanism for inducing such birefringence involves modifying Einstein's theory of gravitation with certain higher-curvature terms.[5] Notably, one possible modification term is also required by the mathematical consistency of heterotic superstrings. Distinctive signatures of GR modifications may be present in the fine details of the cosmic microwave background. Should such phenomenological signatures prove consistent with the higher-curvature terms in the low-energy effective action of string theory, that would tend to confirm the superstring paradigm.

Particle-phenomenology data from the Large Hadron Collider (LHC) should open new vistas. Perhaps most relevant to string theory is whether evidence for hidden dimensions or supersymmetry will emerge. But an experimental observation of either would not, perforce, demand acceptance of string theory; many competing concepts and models are compatible with such potential observations.

Still, the discovery of extra, hidden dimensions would be a spectacular validation of a key idea from string theory. The particle theory community has put in considerable effort, especially during the past decade, to explore the potential signatures of extra dimensions. Theorists have worked on this both in the context of string theory and outside its boundaries. One particular idea that has received enormous attention is the so-called brane-world scenario, which posits that our universe is a four-dimensional "pane of glass" in a universe with at least one extra dimension. Figure 2 illustrates the idea.

The experimental observation of supersymmetry would provide a big, albeit indirect, piece of evidence validating the superstring paradigm. The most spectacular result would be the direct production of a particle that is the superpartner of a known particle. However, it will take great fortune for a superparticle to be directly observable. The range of masses discussed in the literature for superpartners is something like 1000 to 30 000 times the mass of the proton, which is roughly

1 GeV/c^2. With the dates of discovery and masses of the neutron and W bosons as benchmarks, one can crudely estimate the rate at which humanity is progressing in its ability to detect massive particles: about 1.5 GeV/c^2 per year. Thus, if Nature is kind enough to provide light superpartners, one might still expect about a century to pass before a superparticle is directly observed.

Much more likely, evidence for supersymmetry will emerge by indirect means. Such evidence might be provided by precision measurements of the rates of change of coupling constants, anomalies in lifetimes or branching ratios in decays of known particles, and so forth. Even the detection of a Higgs boson and an indication of its mass would be relevant to the question of whether supersymmetry exists in Nature. The community of particle physicists has, over the past two decades, been working with great energy to explore the experimental signatures associated with superparticle production.[6]

In addition to perhaps providing evidence of extra dimensions or supersymmetry, the LHC will probe quantum chromodynamics, the theory of strong interactions. Several years ago, evidence arose suggesting an unexpected link between gauge theories like QCD and gravitational theories that are subsumed in string theory. Most prominent along those lines has been the AdS/CFT (anti–de Sitter/conformal field theory) correspondence and the so-called KLT (Kawai-Lewellen-Tye) relations.[7] Such constructions suggest that concepts derived from string theory may be used to carry out high-precision calculations in gauge theories. Nowadays, an active group of theorists is indeed using the methodologies of modern string theory to explore QCD. In an era in which data on hadron physics is increasingly available, the interplay between experiment and string theory is likely to continue to thrive.

The ultimate challenge

String theory has shown a remarkable ability to morph into forms that show up in unexpected arenas. One recently realized example is that some aspects of string theory seem relevant to quantum information theory. That insight is the latest manifestation of a phenomenon seen throughout the past decade: The structure of string theory is so rich that the theory seems able to make connections with myriad areas of mathematics. Even should no experimental results supporting string theory be forthcoming in the immediate future, it is likely that the subject will have a long life as a topic in mathematics.

A number of challenges confront string theory, but the greatest among them receives little attention despite its existential importance. An imaginary trip in time back to the 1920s will set the stage for stating the problem. One could imagine traveling to 1923 and asking the world's most eminent physicists, What is the meaning of quantum theory? A similar trip to the year 1927 would yield vastly different responses. Between those four years is what I call the Schrödinger–Heisenberg extinction. Prior to 1926, one could find all sorts of theories about the quantum nature of matter and energy. Once Erwin Schrödinger's and Werner Heisenberg's ideas appeared, almost all those theories became logically untenable. The mass extinction of ideas previously thought viable required a genuine paradigm shift: The centrality of the point particle was replaced by the centrality of the wavefunction.

Many string theorists regard an analogous change of perspective as having already occurred in string theory. I do not. The type of paradigm shift needed is one associated with the completely successful construction of covariant string field theory. Its "Schrödinger" equation holds the key to fundamental progress.[8] It may seem that such a breakthrough will not happen in an era dominated by data. I would argue that such a conclusion is not so certain. After all, the period that saw the creation of the Schrödinger equation was also rich with data.

Data stimulate physicists. And given what I understand about how this community works, it seems to me that the serendipitous stimulation of profound mathematical ideas is not outside the realm of possibility.

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