OP-ED CONTRIBUTOR

The Universe on a String

By BRIAN GREENE
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SEVENTY-FIVE years ago this month, The New York Times reported that Albert Einstein had completed his unified field theory — a theory that promised to stitch all of nature's forces into a single, tightly woven mathematical tapestry. But as had happened before and would happen again, closer scrutiny revealed flaws that sent Einstein back to the drawing board. Nevertheless, Einstein's belief that he'd one day complete the unified theory rarely faltered. Even on his deathbed he scribbled equations in the desperate but fading hope that the theory would finally materialize. It didn't.

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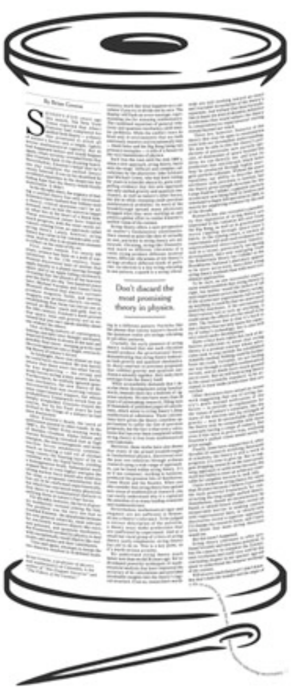

Christoph Niemann

In the decades since, the urgency of finding a unified theory has only increased. Scientists have realized that without such a theory, critical questions can't be addressed, such as how the universe began or what lies at the heart of a black hole. These unresolved issues have inspired much progress, with the most recent advances coming from an approach called string theory. Lately, however, string theory has come in for considerable criticism. And so, this is an auspicious moment to reflect on the state of the art.

First, some context. For nearly 300 years, science has been on a path of consolidation. In the 17th century, Isaac Newton discovered laws of motion that apply equally to a planet moving through space and to an apple falling earthward, revealing that the physics of the heavens and the earth are one. Two hundred years later, Michael Faraday and James Clerk Maxwell showed that electric currents produce magnetic fields, and moving magnets can produce electric currents, establishing that these two forces are as united as Midas' touch and gold. And in the 20th century, Einstein's work proved that space, time and gravity are so entwined that you can't speak sensibly about one without the others.

This striking pattern of convergence, linking concepts once thought unrelated, inspired Einstein to dream of the next and possibly final move: merging gravity and electromagnetism into a single, overarching theory of nature's forces.

In hindsight, there was almost no way he could have succeeded. He was barely aware that there were two other forces he was neglecting — the strong and weak forces acting within atomic nuclei. Furthermore, he willfully ignored quantum mechanics, the new theory of the microworld that was receiving voluminous experimental support, but whose probabilistic framework struck him as deeply misguided. Einstein stayed the course, but by his final years he had drifted to the fringe of a subject he had once dominated.

After Einstein's death, the torch of unification passed to other hands. In the 1960's, the Nobel Prize-winning works of Sheldon Glashow, Abdus Salam and Steven Weinberg revealed that at high energies, the electromagnetic and weak nuclear forces seamlessly combine, much as heating a cold vat of chicken soup causes the floating layer of fat to combine with the liquid below, yielding a homogeneous broth. Subsequent work argued that at even higher energies the strong nuclear force would also meld into the soup, a proposed consolidation that has yet to be confirmed experimentally, but which has convinced many physicists that there is no fundamental obstacle to unifying three of nature's four forces.

For decades, however, the force of gravity stubbornly resisted joining the fold. The problem was the very one that so troubled Einstein: the disjunction between his own general relativity, most relevant for extremely massive objects like stars and galaxies, and quantum mechanics, the framework invoked by physics to deal with exceptionally small objects like molecules and atoms and their constituents.

Time and again, attempts to merge the two theories resulted in ill-defined mathematics, much like what happens on a calculator if you try to divide one by zero. The display will flash an error message, reprimanding you for misusing mathematics. The combined equations of general relativity and quantum mechanics yield similar problems. While the conflict rears its head only in environments that are both extremely massive and exceptionally tiny — black holes and the Big Bang being two primary examples — it tells of a fissure in the very foundations of physics.

1 | 2 | 3 NEXT PAGE »

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Such was the case until the mid-1980's, when a new approach, string theory, burst onto the stage. Difficult and complex calculations by the physicists John Schwarz and Michael Green, who had been toiling for years in scientific obscurity, gave compelling evidence that this new approach not only unified gravity and quantum mechanics, as well as nature's other forces, but did so while sweeping aside previous mathematical problems. As word of the breakthrough spread, many physicists dropped what they were working on and joined a global effort to realize Einstein's unified vision of the cosmos.

String theory offers a new perspective on matter's fundamental constituents. Once viewed as point-like dots of virtually no size, particles in string theory are minuscule, vibrating, string-like filaments. And much as different vibrations of a violin string produce different musical notes, different vibrations of the theory's strings produce different kinds of particles. An electron is a tiny string vibrating in one pattern, a quark is a string vibrating in a different pattern. Particles like the photon that convey nature's forces in the quantum realm are strings vibrating in yet other patterns.

Crucially, the early pioneers of string theory realized that one such vibration would produce the gravitational force, demonstrating that string theory embraces both gravity and quantum mechanics. In sharp contrast to previous proposals that cobbled gravity and quantum mechanics uneasily together, their unity here emerges from the theory itself.

While accessibility demands that I describe these developments using familiar words, beneath them lies a bedrock of rigorous analysis. We now have more than 20 years of painstaking research, filling tens of thousands of published pages of calculations, which attest to string theory's deep mathematical coherence. These calculations have given the theory countless opportunities to suffer the fate of previous proposals, but the fact is that every calculation that has ever been completed within string theory is free from mathematical contradictions.

Moreover, these works have also shown that many of the prized breakthroughs in fundamental physics, discovered over the past two centuries through arduous research using a wide range of approaches, can be found within string theory. It's as if one composer, working in isolation, produced the greatest hits of Beethoven, Count Basie and the Beatles. When you also consider that string theory has opened new areas of mathematical research, you can easily understand why it's captured the attention of so many leading scientists and mathematicians.

Nevertheless, mathematical rigor and elegance are not sufficient to demonstrate a theory's relevance. To be judged a correct description of the universe, a theory must make predictions that are confirmed by experiment. And as a small but vocal group of critics of string theory justly emphasize, string theory has yet to do so. This is a key point, so it's worth serious scrutiny.

We understand string theory much better now than we did 20 years ago. We've developed powerful techniques of mathematical analysis that have improved the accuracy of its calculations and provided invaluable insights into the theory's logical structure. Even so, researchers worldwide are still working toward an exact and tractable formulation of the theory's equations. And without that final formulation in hand, the kind of detailed, definitive predictions that would subject the theory to comprehensive experimental vetting remain beyond our reach.

There are, however, features of the theory that may be open to examination even with our incomplete understanding. We may be able to test the theory's predictions of particular new particle species, of dimensions of space beyond the three we can directly see, and even its prediction that microscopic black holes may be produced through highly energetic particle collisions. Without the exact equations, our ability to describe these attributes with precision is limited, but the theory gives enough direction for the Large Hadron Collider, a gigantic particle accelerator now being built in Geneva and scheduled to begin full operation in 2008, to search for supporting evidence by the end of the decade.

« PREVIOUS PAGE 1 | 2 | 3 NEXT PAGE »

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(Page 3 of 3)

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Research has also revealed a possibility that signatures of string theory are imprinted in the radiation left over from the Big Bang, as well as in gravitational waves rippling through space-time's fabric. In the coming years, a variety of experiments will seek such evidence with unprecedented observational fidelity. And in a recent, particularly intriguing development, data now emerging from the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory appear to be more accurately described using string theory methods than with more traditional approaches.

To be sure, no one successful experiment would establish that string theory is right, but neither would the failure of all such experiments prove the theory wrong. If the accelerator experiments fail to turn up anything, it could be that we need more powerful machines; if the astronomical observations fail to turn up anything, it could mean the effects are too small to be seen. The bottom line is that it's hard to test a theory that not only taxes the capacity of today's technology, but is also still very much under development.

Some critics have taken this lack of definitive predictions to mean that string theory is a protean concept whose advocates seek to step outside the established scientific method. Nothing could be further from the truth. Certainly, we are feeling our way through a complex mathematical terrain, and no doubt have much ground yet to cover. But we will hold string theory to the usual scientific standard: to be accepted, it must make predictions that are verified.

Other detractors have seized on recent work suggesting that one of string theory's goals beyond unification of the forces — to provide an explanation for the values of nature's constants, like the mass of the electron and the strength of gravity — may be unreachable (because the theory may be compatible with those constants having a range of values). But even if this were to prove true, realizing Einstein's unified vision would surely be prize enough.

Finally, some have argued that if, after decades of research involving thousands of scientists, the theory is still a work in progress, it's time to give up. But to suggest dropping research on the most promising approach to unification because the work has failed to meet an arbitrary timetable for complete success is, well, silly.

I have worked on string theory for more than 20 years because I believe it provides the most powerful framework for constructing the long-sought unified theory. Nonetheless, should an inconsistency be found, or should future studies reveal an insuperable barrier to making contact with experimental data, or should new discoveries reveal a superior approach, I'd change my research focus, and I have little doubt that most string theorists would too.

But this hasn't happened.

String theory continues to offer profound breadth and enormous potential. It has the capacity to complete the Einsteinian revolution and could very well be the concluding chapter in our species' age-old quest to understand the deepest workings of the cosmos.

Will we ever reach that goal? I don't know. But that's both the wonder and the angst of a life in science. Exploring the unknown requires tolerating uncertainty.

« PREVIOUS PAGE 1 | 2 | 3

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