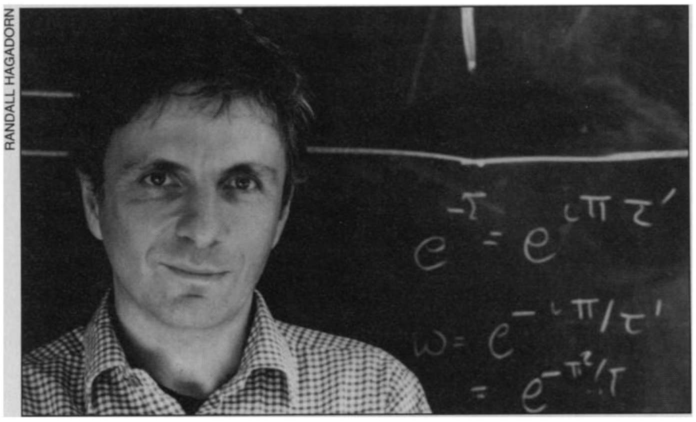
The Quest for a Theory of Everything Hits Some Snags

In the 1980s many leading physicists thought they had caught a glimpse of their finish line—they believed they were closing in fast on a final, all-encompassing theory that would serve as a fundamental framework for physics. They even went so far as to talk of a "theory of everything." But now, like marathoners who have "hit the wall," they are sagging under the weight of the effort—in this case the intractable mathematics—and are wondering whether the finish line is in fact an illusion.

As physicists envisioned it 8 years ago, this finish line was made of superstrings—a single fundamental entity said to make up all of the diverse particles and forces recognized by traditional physics. By envisioning the world as made of these superstrings, scientists were going to tie up reality into one neat package. But since then they have gotten caught on several major snags. "The equations don't yield to our efforts," says superstring theorist Andrew Strominger of the University of California, Santa Barbara (UCSB). Now, while physicists continue to study superstrings, they've lowered their expectations. Bring up the term "theory of everything," and you'll see a physicist flinch.



RANDALL HAGADORN

"I don't like that term," says Princeton physicist Frank Wilczek. "It's very, very arrogant and misleading, especially when our theory of everything isn't a theory of anything yet." Agrees Michael Green of London's Queen Mary College, one of the founders of superstring theory: "I hate that terminology."

"Everything," in the eyes of physicists, includes the basic building blocks of the universe—the myriad particles that make up matter and the four forces that hold them together. A theory of everything, to be worthy of the name, has to provide a single, coherent explanation for the observed mix of particles—an electron and its heavier counterparts, a handful of quarks, several types of neutrinos, and the like—and for forces as different as the strong force that binds atomic nuclei and the gravity that holds stars together in galaxies.

Until 1985, physicists' best descriptions of the universe seemed divided by an unbridgeable gulf. On one side was quantum mechanics, the theory of the very small, which describes particles and forces on the scale of the atom as waves in a variety of fields. On the other was Einstein's theory of general relativity, which describes the gravity exerted by very large masses. When physicists try to reconcile the two theories by combining the equations describing gravity with those of quantum mechanics, the results are nonsensical.

Each theory, it seemed to physicists, must be revealing only part of an invisible elephant—a deeper reality, built of some building block more fundamental than the familiar particles and forces. In 1984, in the hands of Green and John Schwarz of the California Institute of Technology, superstrings became the best candidate for being that fundamental stuff. The strings Green and Schwarz envisioned come in just one variety, says Green, each one measuring no longer than 10^{-35} centimeter along its single dimension. All of the masses, charges, and other properties of subatomic particles arise from vibrations of these superstrings at different frequencies—a uniform chorus of violins playing a symphony of different notes. Force-carrying strings sustain the liaisons that hold atoms together and swing Earth through its orbit.

Green and Schwarz didn't invent this picture; a few physicists had been toying with strings since the early 1970s. But that work had seemed little more than a mathematical diversion, because strings as originally conceived had the drawback of making senseless predictions—particles with negative probabilities of existing, for example.

Green and Schwarz's breakthrough was to combine string theory with supersymmetry, an idea that posits new mathematical symmetries among existing particles and pairs every known particle with a hypothetical "supersymmetric" partner. With the addition of supersymmetry, strings lost their ugliest blemishes. Now called superstrings, they still didn't predict anything testable, but they no longer made predictions that were embarrassing.

What sealed physicists' infatuation with superstrings, though, was that they finally tied together the subatomic forces with gravity. Besides yielding a common description for all subatomic particles and forces, superstring theory predicts gravity—in the form of general relativity. "Out pops general relativity without us ever asking for it," says Green. If Einstein hadn't found this theory, the string theorists would have, says Edward Witten of the Institute for Advanced Study in Princeton. "Learning about that," says Witten, "was one of my biggest intellectual thrills."

Such feats struck a powerful aesthetic chord among physicists. "The theory's so beautiful it must be true," Green recalls feeling at the time. That's when physicists, swept up in the excitement, began talking of a theory of everything—a term for which superstring researcher John Ellis of CERN confesses responsibility.

Coming up short. But 8 years later, physicists are sounding a different note. "There are some big problems," says Strominger. "A lot of people are backing away." Green, despite his role in creating the basis for the idea, agrees that superstrings have come up short. "The idea generated too much hype," he says. "It's an unfinished story. Superstrings are an approximation to something, and we don't yet know what it is."

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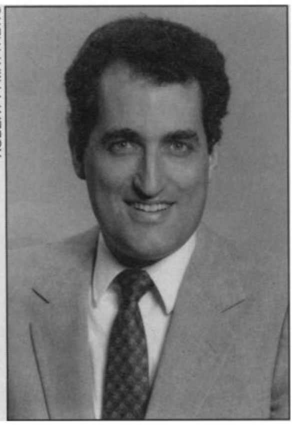
>
> **–Michael Green**

He and other researchers believe that superstrings may still provide a cornerstone for the overarching theory they thought was in their grasp. "It's inconceivable to me that superstrings are irrelevant," Green says. But he and his colleagues now say that much of the foundation is missing. Finding it will probably take a heroic leap of imagination. "I think there is a big, big conceptual gap," says Witten. "I'd be surprised if we get there without a more complete fundamental understanding [of the nature of matter and forces]."

One signal that something is missing is superstrings' inability to provide a single picture of physics. The theory comes in an infinite number of versions, says Green, each predicting a different reality. "It's really one set of equations with too many solutions," he says. Some solutions look rather like the real world, but with "extra things" thrown in, says Wilczek, such as unseen particles and crazy dimensions. And even if people stumbled on one solution that neatly described reality, physicists would be left with a nagging worry that the fit had come about by blind chance. A theory of everything should do better, says Green: "We want to know why nature gave us this particular set of solutions."



ROBERT P. MATTHEWS

"I think there is a big, big conceptual gap" in the current picture of particles and forces.

–Edward Witten

A few scientists have decided not to worry about the surplus of solutions, but to go ahead and pick one version that seems to work well, solve the equations, and see how well its predictions fit with reality. If they come across a promising variant, they can try to work backward to figure out why it works better than the millions of other choices. That's the strategy taken by CERN's Ellis and Texas A&M's Dimitri Nanopoulos, who have found one pretty good version, known as flipped SU(5), and worked through the equations to show that it predicts something like the real world of particles. They call the approach string model building, and Ellis says he wishes more physicists were doing it.

He and Nanopoulos lament that the rest of the field has fractured into two camps—the so-called phenomenologists who deal in observations of the real world, and the theorists who work in the abstract mathematical realm where superstrings lie. "That's the gap we're trying to bridge," says Nanopoulos. "I don't know whether people are just lazy or old, but it will take some time to bring them together." Others, however, say that effort at bridge-building is premature—that Nanopoulos and Ellis are just palming off guesswork as insight. "It's just like picking lottery tickets," says Joseph Polchinski of the University of Texas.

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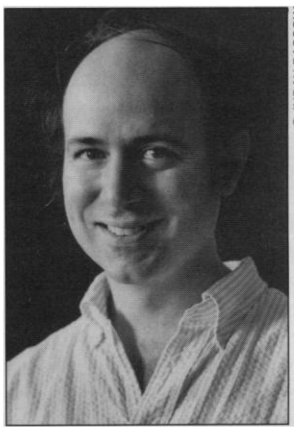
Nanopoulos says he spent a lot of time evaluating different possibilities before zeroing in on SU(5). But even if superstrings can't "explain" the whole of physical reality, researchers, including UCSB's Strominger, are finding that superstrings can help them cope with more limited problems—what happens inside black holes, for example. One of the major puzzles posed by black holes, Strominger explains, is their ability to suck information—in the sense of the bits of data needed to describe the organization of any system—out of the universe. Strominger says that in a closed system like the universe, you expect to conserve the total amount of information. Though information can change forms, he says, the total should remain constant. But in black holes, the universe seems to have sprung a leak: In a scenario proposed by University of Cambridge astrophysicist Stephen Hawking, black holes can evaporate into a mist of stray particles, taking information with them. "Your computer can fall into a black hole and the black hole can evaporate and all the information is gone," says Strominger.

Insight into black holes. String theory may offer a way out, says Strominger, by drastically simplifying the impenetrable tangle of equations that describe black holes. He and his colleagues haven't figured out where all the information goes as a black hole evaporates, but the simplified equations are equipping them to find an answer. And Strominger was gratified, he says, when a black hole theorist—not a string theorist—told him at a conference that this was the first time he had found that string theory could be useful.

Witten and Green have both embarked on a larger mission. They are struggling to achieve the original promise of superstrings by tinkering with the theory's mathematical framework. "Many people now are exploring the mathematical implications of superstrings," says Green, and he's encouraging the trend by organizing a conference to bring together physicists and mathematicians in the field.



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To some physicists, the transformation of superstrings from a candidate theory of everything to an abstract mathematical pursuit is a sign of the theory's irrelevance. But Green thinks that a breakthrough in the mathematics of superstrings might be just what the physicists need. And Witten says that, just as many parts of general relativity—a theory whose relevance is not in dispute—can be seen as either math or physics problems, the same is true with superstrings.

High on Green and Witten's list of mathematical tasks is fixing the theory's description of space-time. Green explains that space-time gets very strange when you look at it on a small scale—the scale of the superstring, also known as the Planck scale. On this scale space isn't smooth and empty but "foamy": Microscopic black holes pop in and out of existence due to the combined workings of quantum mechanics and general relativity.

That's not the ideal environment for a string, says Green. On a bigger scale, he says, imagine trying to draw a line on a paper that's all crumpled up and full of holes. "How do you unify the idea of particles or strings moving through space-time with the idea that space-time is shimmering and foaming on the Planck Scale?" he asks. "We have to come up with a new way of thinking so that space-time will be unified with particles in a qualitative way," he says.

That will be the key, he says, to unlocking the deeper theory he believes underlies superstrings. But if superstrings do open the way to a single framework for existing physics—a "theory of everything"—will physicists revive the term? Most would rather not; physicists are wary of any suggestion that their field will soon reach its limits. "I'm not planning to retire early," says theorist Jeffrey Harvey of the University of Chicago. He and his colleagues recall what happened the last time physicists thought their work was done, near the end of the last century. That was when physicist Albert Michelson infamously quipped that "the grand underlying principles have been firmly established...future truths of physics are to be looked for in the sixth place of decimals." As it happened, the next three decades proved among the richest in the history of physics, bringing the discovery of subatomic particles and the development of quantum mechanics and relativity.

Even the originator of the expression "theory of everything," CERN's John Ellis, calls the notion of an end to physics "just crap. Just because you've found the organizing principle—it doesn't mean you've answered all the questions." And who knows what new questions will come up, says Strominger. "People are always thinking we're near the end, but I'm sure there's some stone we haven't turned over. Even if string theory is proven, there will still be other levels it doesn't explain."

–Faye Flam