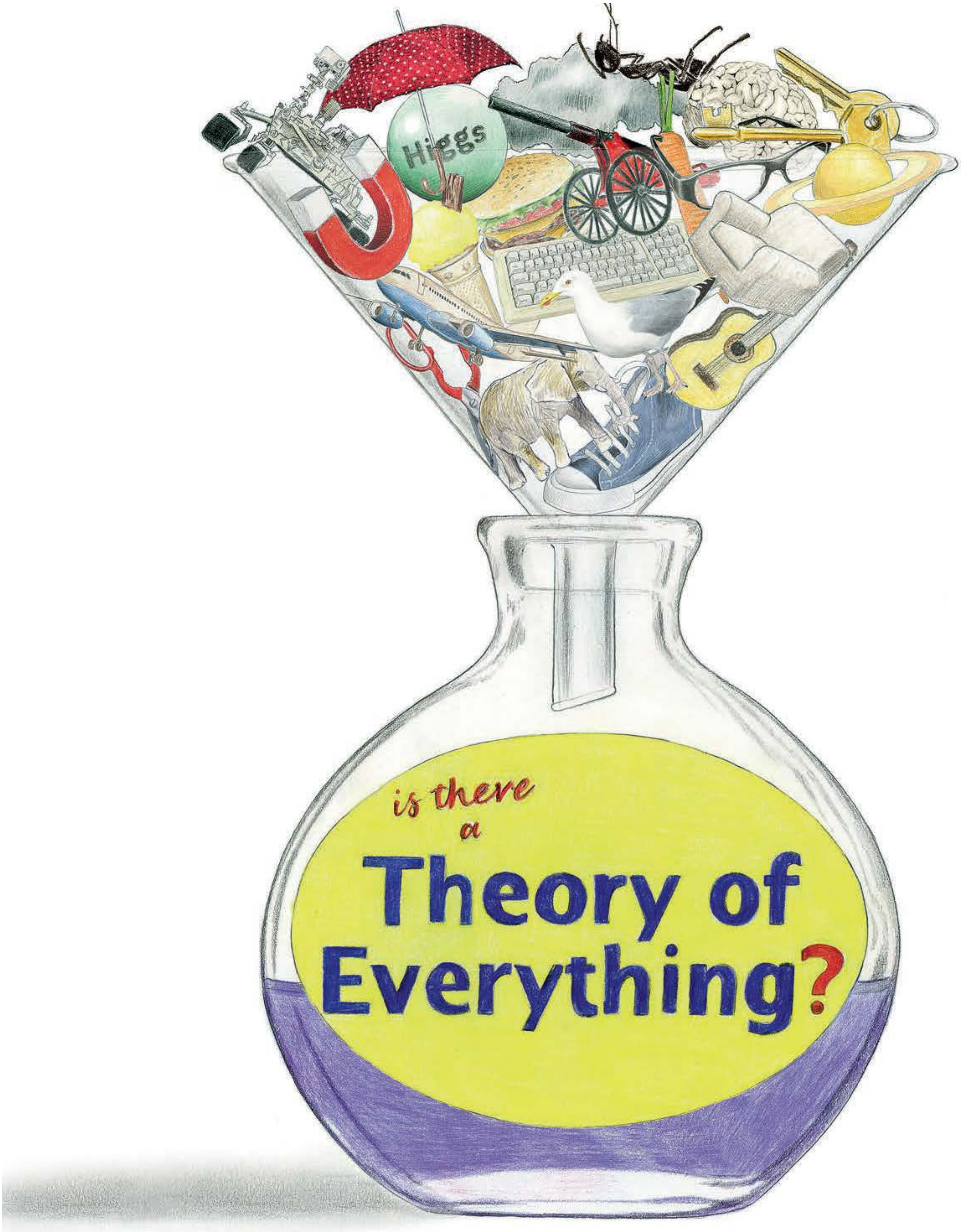
is there a Theory of Everything?



By Marcus Y. Woo

It's beautiful, even elegant, in its simplicity. It's profound, encapsulating all of nature in a few mathematical symbols and relationships pithy enough to fit on a T-shirt. It's the so-called theory of everything, a complete understanding of the laws that govern the entire universe—and it's a dream that physicists have been pursuing for centuries.

One of the first attempts at a basic theory of nature was made in Greece in the fifth century BC, when Democritus proposed that everything was made of atoms. Science has since not only proven the existence of atoms, but has shown that atoms themselves are composed of even smaller, more fundamental particles such as electrons and quarks. But despite breakthroughs over the last century, physicists have yet to develop a single, unifying framework that explains all natural phenomena at their most basic level. Even Albert Einstein spent the final chapter of his life hunting—in vain—for such a theory.

And, if so, what is it?

Admittedly, the theory of everything is a bit of a gimmick. After all, no theory can explain *everything*. Such a theory, if and when physicists find it, won't explain why unemployment is high, why people fall in love, why life exists on Earth, or whether it will rain tomorrow. "You're never going to explain everything from just the basic laws of physics—it's crazy," says Caltech physicist John Schwarz, who for more than 40 years has been on his own quest for a unified theory. "When people use that phrase—theory of everything—what do they mean by 'everything'? That can cause a lot of confusion."

So what exactly is it? The theory of everything—or, as some physicists prefer to call it, a unified theory—refers to a single, cohesive framework that explains how and why all the fundamental particles and forces in the universe behave and interact as they do. That may sound esoteric, but you can indeed argue that such a theory is the basis for, well, everything. From carrots to brains, from planets to stars, everything is made of elementary particles, and the properties of everything ultimately depend on how those particles interact with one another.

TOWARD UNIFICATION

There are four fundamental forces of nature: gravity, the electromagnetic force, the strong force (which holds atomic nuclei together), and the weak force (which is responsible for the nuclear reactions that keep the sun shining and for radioactive decay, which generates the energy that drives geological processes on Earth). Those forces govern the behavior of a smorgasbord of elementary particles, including electrons, neutrinos, quarks, and the Higgs boson, the probable discovery of which physicists announced amid much fanfare last summer at the Large Hadron Collider (LHC) in Geneva.

Those particles, along with the electromagnetic, strong, and weak forces, are described by the so-called standard model, a theory that's been confirmed again and again by experiments, making it one of the triumphs of 20th-century physics. Many Caltech physicists—including Nobel laureates Richard Feynman, Murray Gell-Mann, and David Politzer—helped lay its foundations. But, as many physicists today are eager to note, it's incomplete.

“The standard model is great,” says Caltech theoretical physicist Hirosi Ooguri. “It explains almost everything we know about the physics of elementary particles. But that’s only 5 percent of our universe.” The other 95 percent? Dark matter and dark energy. Dark matter is the unseen stuff that makes up 27 percent of the cosmos. Dark energy is an entirely different beast, a force that accelerates the expansion of the universe and accounts for about 68 percent.

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And then there’s gravity.

“From the theorist’s perspective, the most pressing issue is that the standard model of particle physics does not contain gravity,” Ooguri says.

Indeed, gravity is a bit of an oddball. Although it seems such a tangible and ubiquitous force in our daily lives, it’s extremely weak compared to the other forces. After all, a small magnet can lift a paperclip off a table using the electromagnetic force, thus overpowering Earth’s gravity.

Einstein’s theory of general relativity is a theory of gravity, describing the force as a warping of space and time—the fabric of the universe—caused by anything with energy or mass (which are equivalent, according to $E = mc^2$). General relativity has been proven accurate time and time again, from explaining a peculiar shift in Mercury’s orbit to helping your GPS pinpoint your location. Still, it’s limited.

One problem is that general relativity does not get along with the bizarre, probabilistic laws of quantum mechanics, which is the backbone not only of the standard model but of all physics—especially at small scales. In order to probe things like the centers of black holes or the moments after the Big Bang, physicists need to fuse quantum mechanics with gravity. But when they try, they get nonsensical descriptions of nature that involve infinite numbers. “There’s no evidence that quantum mechanics is wrong,” notes Caltech physicist Mark Wise. “It seems to be the foundational concept for physics—and gravity should fit into that.” But right now it doesn’t.

The unifying theory that physicists long for is therefore a quantum theory of gravity, one that unifies quantum mechanics with gravity and that also includes everything the standard model explains—plus dark matter and dark energy. But does such a theory even exist?

“I’m convinced there *is* a theory,” Schwarz says. After all, there must be *some* explanation for what we don’t yet understand. Whether physicists will ever come up with such a unified theory, however, is uncertain. Over the decades, they’ve proposed various candidates. So far, the most successful among them—though not yet fully formulated—is string theory.

ALL STRUNG UP

As its name suggests, string theory—sometimes known as superstring theory—posits that the universe isn’t made of fundamental particles, but rather of stringlike objects that weave through reality like thread in the fabric of space and time. These strings vibrate, and the modes in which they vibrate manifest themselves as electrons, neutrinos, quarks, and other fundamental particles—much as the vibrations of guitar strings manifest themselves in a variety of musical notes. In string theory, the properties of different types of string—their tension, for example—give rise to the characteristics of their particular particles, such as mass, spin, and electric charge.

String theory was originally developed in the 1960s as a way to explain how the strong force works. It couldn’t, as it turned out. And so, within a few years, physicists had tossed it aside in favor of a more successful theory called quantum chromodynamics—contributions to which in the ’70s would win Politzer his Nobel in 2004.

Then, in 1974, Schwarz, who had joined Caltech two years previously as a research associate, and Joel Scherk, a visiting scientist at Caltech at the time, realized that string theory predicted the existence of a strange new particle whose properties precisely fit those of a hypothetical particle called the graviton.

To understand why this is significant, you need to know that, in the standard model, every fundamental force is mediated by a particle. The electromagnetic force, for example, is carried by photons. (A photon is a particle of light, which, by way of quantum weirdness, can also be thought of as a wave made up of electric and magnetic fields.) And so, if there is to be a quantum theory of gravity, it too will need a particle to carry it: the still-undiscovered graviton. String theory, which had been an esoteric idea destined for the scrap heap of physics, became reimagined as a possible quantum theory of gravity once Schwarz and Scherk realized it incorporated the graviton.

The discovery, Schwarz says, was at once startling and mathematically beautiful. "What kept me going was the realization that it could make gravity consistent with quantum mechanics," he recalls. "It wasn't a problem that I had set out to solve, but it kind of hit me over the head, and I thought, 'Hey, that's pretty good—I'd better follow that up.'"

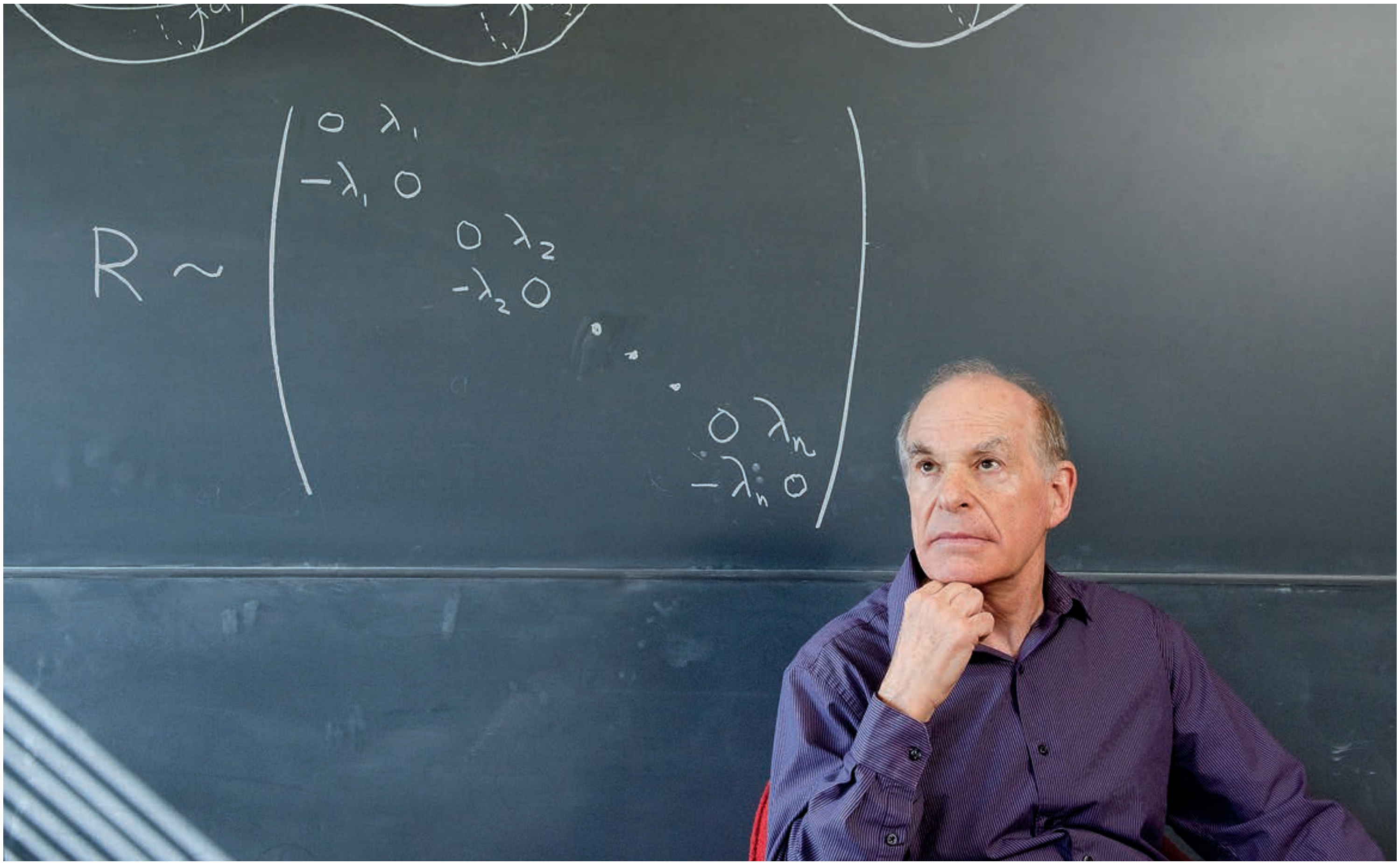
When Schwarz and Scherk published their results in 1974, no one seemed to pay attention. That didn't deter Schwarz, who, convinced that the mathematical beauty of string theory wasn't happenstance, pressed forward. He began working with Michael Green—now at Cambridge University in England—to fix some of the mathematical inconsistencies in string theory that prevented it from fully explaining all of the physics in the standard model. Ooguri credits Caltech and, in particular, Murray Gell-Mann for supporting Schwarz in his lonesome—and rather risky—quest. When Schwarz and Green eventually succeeded, in 1984, string theory became a bona fide candidate for the title of unified theory. And this time, physicists the world over took notice.

Among them was Ooguri, who had just started graduate school in Japan. "I heard a rumor that there was some great discovery made in the United States at Caltech," he says. Looking into it further, he realized that it provided a base from which the properties of all elementary particles could be derived—something that the standard model, a rather ad hoc theory, does not do. When Ooguri realized that string theory provided these so-called first principles, he was amazed. "I thought it was beautiful," he says.

SEARCHING FOR STRINGS

Beautiful, but mathematically and conceptually complicated. And that, at least in part, is due to one of the hallmarks of string theory: it requires (at least) *nine* dimensions of space.

Below: Caltech physicist John Schwarz is one of the founders of string theory.



Above: Hirosi Ooguri is one of Caltech's leading string theorists.

That's six more than the three we're all acquainted with: up/down, left/right, and forward/backward. How could there be another six that we can't see or experience? String theory says those extra dimensions are so curled up and thus so small we don't even notice them. To get an idea of what that means, imagine a box that's placed far away from you. Although you know the box is three-dimensional—with length, width, and depth—from where you're standing it appears so small that it looks like a point, with no dimensions at all. Analogously, these extra dimensions would be too tiny for us to experience them.

Trying to imagine six curled-up extra dimensions gives most people a headache; now imagine the math needed to describe them. One major hurdle was in computing the distance between two points in six dimensions—a basic task without which you can't calculate much in a theory that requires so many dimensions. "I took that as a challenge," says Ooguri, who spent the 10 years after Schwarz and Green's breakthrough tackling it. Although today's physicists and mathematicians still don't know how to compute distances in the higher number of dimensions used in string theory, Ooguri and other scientists successfully developed mathematical tools that can be used to circumvent the problem and make physical sense of the math.

As physicists continue to delve deeper into string theory, developing more mathematical tools and ideas, the field has progressed rapidly. But there remains a major problem: there is no experimental or observational evidence to support string theory, other than the existence of gravity itself.

Which is not to say no one has tried. Indeed, much of the current scientific effort around string theory is focused on figuring out ways to test it. One possibility would be to observe strings that originated in the early universe. The strings by now would be so stretched by the universe's expansion that they should span the entire cosmos. They'd be extremely thin, sure, but they'd also be dense enough to create noticeable ripples in space and time, bend light, or produce other effects detectable by astronomers. And yet, so far, no one has been able to observe them.

Another way to find evidence for strings is to probe nature at its deepest and most fundamental levels—to access phenomena at increasingly tiny scales. And to reach those extreme scales, you need to slam particles together with extreme energies.

Which is why so many physicists—including those hoping to find hints of string theory—flock to the LHC, the most powerful particle accelerator in the world. By colliding particles at near-light speeds, physicists at the LHC can create matter that's as hot and dense as the universe was immediately after the Big Bang. The hope is that those collisions will reveal signs of extra dimensions—or that they will provide evidence to bolster an idea called supersymmetry, which Schwarz helped originate as an essential feature of string theory.

All particles can be categorized as either bosons or fermions, and supersymmetry is a type of symmetry that relates the two. All of the normal matter in the universe is composed of fermions (such as electrons and quarks); the force-carrying particles are bosons (such as photons and gluons). Every particle has a hypothetical "superpartner" that's of the opposite type; for example, an electron's superpartner is a boson called a "selectron." None of these superpartners have been discovered, however, and they're thought to be extremely massive and unstable—disappearing almost as soon as they're created. The only way to see if they exist is to be watching when they're created—and the only way to create them is by smashing other particles together at places like the LHC.

"If there were any experimental evidence of that sort, it would be extremely exciting," Schwarz says.

Unfortunately, no one has seen anything like an extra dimension or evidence of supersymmetry at the LHC yet, although physicists—including a Caltech team led by Harvey Newman and Maria Spiropulu—are still on the hunt. Schwarz and his colleagues aren't worried: it's still early, physicists say, and the LHC is now in the middle of an upgrade that will double its energy for its next experimental run, planned for December 2014. There's a fair chance that at those higher energies, the LHC will be able to detect supersymmetric particles, Schwarz says, and that would be highly encouraging for string theory.

The chances the LHC will be able to find extra dimensions, however, are a lot smaller. That's because, as Schwarz explains, the amount of energy likely needed to find evidence for extra dimensions may be beyond the reach of the LHC—even the souped-up version.

That's not too surprising since, if you compute the energy at which phenomena predicted by a unified theory would definitely occur, the answer you get is a number that's a *thousand trillion* times higher than what's possible at the LHC. "That's where you're going to find the characteristic phenomena of any relativistic quantum theory of gravity—whether it's string theory or any competing idea," Schwarz notes. "But such phenomena are inaccessible."

THE QUEST CONTINUES

If there's no experimental evidence for string theory—and if any potential evidence is more or less out of reach—then why are so many physicists still clinging to it? For one thing, there just aren't many good replacement theories. But more importantly, physicists say, recent mathematical developments in this area are just too compelling to ignore, as theorists uncover relationships that connect and unify seemingly disparate mathematical objects, structures, and concepts that are part of string theory.

"The bottom line is, people who work on string theory have developed a sense that they're dealing with a mathematical structure that has some extraordinarily deep features that are absolutely fascinating," Schwarz says.

Plus, string theory seems to have everything that's needed for a unified theory. "Because it consists of just one structure—a string—and it has the basic ingredients to describe everything we know about nature, we're optimistic that somewhere in this framework the theory can make contact with the real world," Schwarz says.

"If string theory were not promising, and if we were not making progress, talented people wouldn't come to this area and push this forward," Ooguri adds. And they are definitely coming. In the early days, Caltech's string theory group—which was one of the most active in the world—consisted of Schwarz and maybe a couple of visitors or students. Today, Caltech's group includes about a dozen graduate students and postdocs. In addition to Schwarz and Ooguri, theoretical physicists Anton Kapustin and Sergei Gukov also do research relating to string theory.

Of course, even if string theorists are on the right track, they may still be decades from unveiling a full-fledged unified theory. After all, they have to invent entirely new branches of mathematics to describe their theory. "We want to identify the fundamental laws that—in principle—mathematically explain everything," Ooguri says. "That's a very ambitious undertaking. It's not something you can hope to achieve in just a decade or two."

Even if string theory fails to be crowned as *the* unified theory, many feel its mathematical spin-offs alone will have made it worthwhile. In the last few years, for example, physicists have used mathematical tools that were developed for string theory to describe the strange quantum states of new kinds of materials such as high-temperature superconductors.

And so, despite its challenges, physicists press on toward a theory of everything with hope and optimism. The scientific method demands diligent exploration, after all, and to a scientist such a quest is never futile.

"It's never pointless when you're trying to figure out what the laws of nature are—even if it ends up that they're not found in the direction you were pursuing," Mark Wise says. "I mean, that's what physics is about. It's high risk, high reward. And we certainly want to take the risk." e&s

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