THE ELEGENT UNIVERSE,

by Brian Greene (1999)

Superstrings, Hidden Dimensions,
and the Quest for the Ultimate Theory

'M' Theory Stands for Magic, Matrix,

■ Some say it's like a computer dropped into the 19th century. No one can figure out how it works because the science behind it hasn't yet been invented.

By K.C. COLE
TIMES SCIENCE WRITER

The appeal of string theory among physicists is particularly astonishing in light of the fact that no one knows, as yet, exactly what 'it' is. It doesn't even have a proper name: The latest, most powerful, incarnation is cryptically called "M" theory—where M can stand for Magic, Mother, Mystery, Matrix or Membrane.

So why do physicists take it seriously? What makes it science rather than superstition or idle philosophizing akin to figuring out how many angels can dance on the head of a pin?

One answer is: String theory strikes many physicists as too beautiful not to be true.

"I think it's the most fantastic set of interconnected rules which has ever been known," said Harvard physicist Andrew Strominger. "Nobody in this field is clever enough to have invented something like that."

Since only nature is ingenious enough to devise such a theory, these physicists argue, it must be rooted in reality.

The more compelling answer is: It works. Over the last few years, string theory has produced a seemingly unending string of what physicists call "string theory miracles."

"It's as if some guys had set out to design a better can opener and wound up with an interstellar space ship," said Harvard physicist Sidney Coleman, one recent convert.

Since 1995, string theory has pulled off a series of spectacular successes that made even its staunchest critics take a second look.

Membrane, Mother or Mystery

For example, one complex paradox revolved around those empty pits of warped space-time known as black holes. Strominger and his colleagues showed that black holes could be constructed out of strings. Indeed, they showed that under the right conditions, black holes could transform into elementary particles, like water freezing into ice.

The result helped propel string theory to the forefront. "If you have a theory that can come to grips with a problem that's been around for 20 years, it builds confidence," said physicist David Gross, director of the Institute for Theoretical Physics at UC Santa Barbara.

In a second major coup, string theory vastly simplified mathematical tools for dealing with more traditional problems in four-dimensional space, including standard particle physics. Suddenly, the ethereal world of strings had real applications to problems involving known elementary particles.

"These were results other [non-string] physicists could relate to," said physicist Nathan Seiberg of the Institute for Advanced Studies. "It solved problems they'd been bothered by."

In other words, physicists put faith in string theory for the same reason the rest of us put faith in other things we don't understand, like jet planes and computers: They get us places we want to go.

The difference is that at least somebody understands the underlying science of planes and computers, and no one as yet understands what underlies string theory.

Columbia University physicist Brian Greene compares string theory to a computer dropped into the 19th century. It does seemingly miraculous things, but no one can figure out how, for the simple reason that the essential science behind it hasn't yet been invented.

Greene said: "Today's physicists are in possession of what may well be the Holy Grail of modern science, but they can't unleash its full predictive power until they succeed in writing the full instruction manual."

COLUMN ONE

Time, Space Obsolete in New View of Universe

■ Many physicists are embracing a revolutionary, still mysterious idea called string theory. The concept rejects several familiar notions and includes the existence of 11 dimensions.

By K.C. COLE
TIMES SCIENCE WRITER

Ever since early astronomers yanked Earth from center stage in the solar system some 500 years ago, scientists have been pulling the rug out from under people's basic beliefs.

"The history of physics," says Harvard physicist Andrew Strominger, "is the history of giving up cherished ideas."

No idea has been harder to give up, however—for physicists and laypeople alike—than everyday notions of space and time, the fundamental "where" and "when" of the universe and everything in it.

Einstein's unsettling insights more than 80 years ago showed that static space and fixed time were flimsy facades, thinly veiling a cosmos where seconds and meters ooze like mud and the rubbery fabric of space-time warps into an unseen fourth dimension. About the same time, the new "quantum mechanical" understanding of the atom revealed that space and time are inherently jittery and uncertain.

Now, some physicists are taking this revolutionary line of thinking one step further: If their theories are right, in the words of Edward Witten of the Institute for Advanced Study in Princeton, space and time may be "doomed."

Concurs physicist Nathan Seiberg, also of the Institute: "I am almost certain that space and time are illusions. These are primitive notions that will be replaced by something more sophisticated."

That conclusion may not affect anyone's morning commute. But it is rocking the foundations of physics—as well as causing metaphysical reverberations that inevitably follow major changes in our fundamental understanding of how the universe works.

The impetus behind this tumult is an idea that has become increasingly dominant in modern physics: string theory. According to string theory, the most basic ingredients in the universe are no longer pointlike particles, the familiar electrons and quarks. Instead, they are unimaginably small vibrating strings of some unknown fundamental stuff.

String theory suggests that different configurations of strings produce different harmonic chords—just as a piano produces a sound different from that of a flute. The

Please see THEORY, A22

OF SPACE, TIME AND STRINGS

Rocking the foundations of physics

■ First in a series

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vibrating string gives rise to the particles, and the way the string vibrates determines each particle's properties. This all takes place in a convoluted landscape of 11-dimensional space.

It is a concept so strange that even theoretical physicists struggle to understand it. String theory offers a universe bizarre beyond imagining: Under powerful enough magnification, every known particle in the universe would resemble a complex origami folded out of sheets or strings of the three familiar spatial dimensions, plus one dimension of time, plus seven extra dimensions of space.

While string theory is far from proven, or even well formulated, its consequences would be enormous. Among other things, it would:

- Reshape fundamental notions of space and time, energy and matter, expanding the number of dimensions to 11.
- Give the first comprehensive list of all the ingredients that make up the universe.
- Reveal that every tick of a clock, every barking dog, every dying star, can be described by one master mathematical equation.

Being Involved in a 'Scientific Revolution'

Which practical fruits will flow from the new view of the universe remain unknown. But in the past, fundamental revolutions in physics have—against everyone's wildest expectations—flowered into everything from cell phones to brain scans.

"I've been in physics for 35 years, and this is the first time I've felt I'm involved in a scientific revolution," said Stanford physicist Leonard Susskind. "In the last five or six years, I really have the feeling we're doing something as crazy, as interesting, as new as the revolution that Einstein wrought."

Perhaps most revolutionary of all, it appears that space and time aren't essential ingredients of a universe ruled by strings.

To grasp the extent of the current upheaval in physics, consider what has happened to our basic understanding of space and time over the past hundred years.

Until the early 20th century, scientists, like laypeople, assumed that space and time were fixed—like huge, metaphysical clocks and rulers in the firmament. Objects that moved in this unchanging background could be pinned down to definite positions.

"Everything was where it was when it was supposed to be, and that was all there was to it," said Strominger. "Space-time was out there. You could count on it."

Then, Einstein revealed that space and time were woven into a single fabric that deforms like so much Silly Putty; indeed, it is the warping of the fabric of space-time by massive objects that produces the force of gravity. We perceive gravity as a "force" only because we can't directly perceive the fourth dimension.

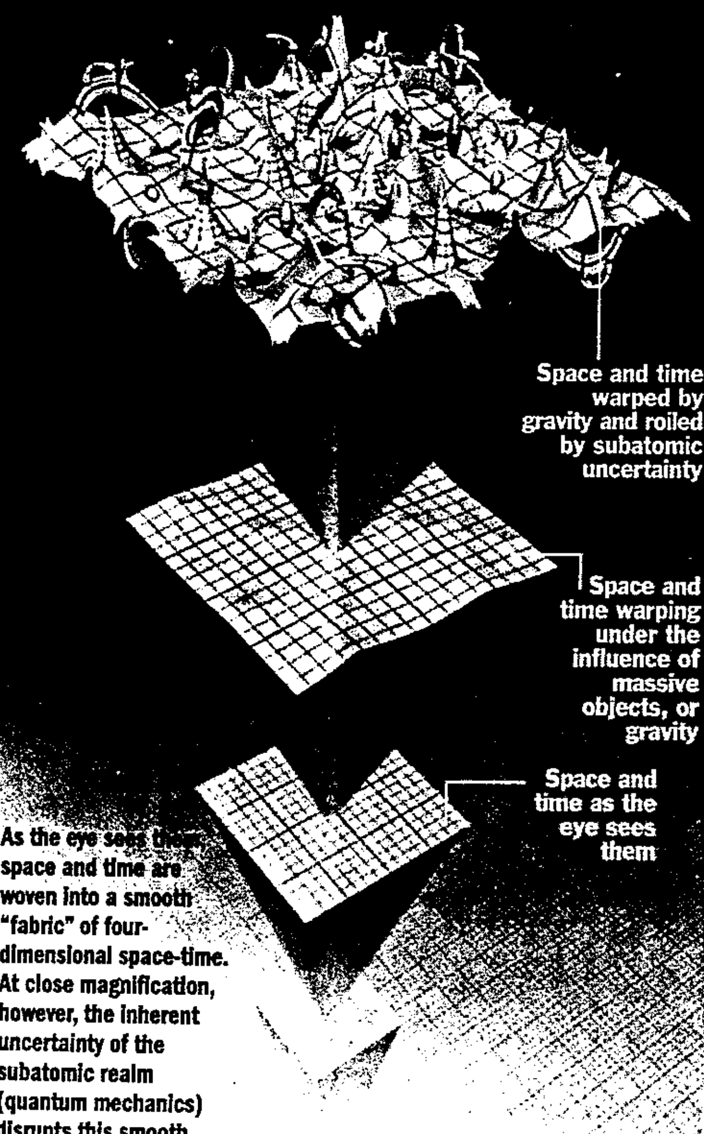
Because gravity affects everything, everything gets warped by its pervasive influence—including the clocks and rulers we use to measure time and space.

Even more unsettling, Einstein's now well-proven theories showed that the fabric of space-time, with its three dimensions of space and one of time, is not a passive backdrop for the events and objects in the universe. Space-time also creates objects and events.

Imagine the universe as a performance on a stage. The stage of space-time does not act like a static floor. It also pulls and pushes the actors around.

Quantum mechanics introduced even more uncertainty. In the subatomic realm, the entire concept of fixed particles in time and space fuzzes out into an ever-shifting haze of probabilities. Trying to pin down a subatomic particle's loca-

The Fabric of Space-Time



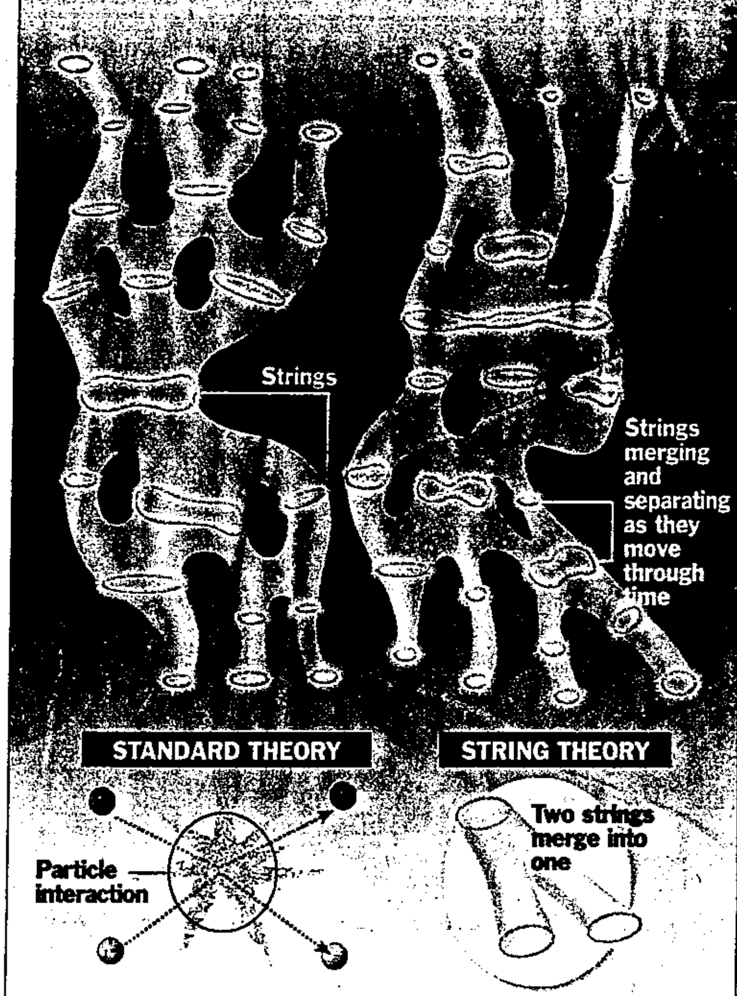
As the eye sees them, space and time are woven into a smooth "fabric" of four-dimensional space-time. At close magnification, however, the inherent uncertainty of the subatomic realm (quantum mechanics) disrupts this smooth landscape, creating submicroscopic chaos.

Source: The Elegant Universe by Brian Greene

Los Angeles Times

String Theory

According to string theory, unimaginably small vibrating strings form the building blocks of everything in the cosmos. This differs from prevailing theories of subatomic physics, in which particles meet and exchange energy at specific points in space and time. Under string theory, strings spread out these interactions over space and time. This "spreading out" eliminates the mathematical problems that crop up when infinitely small points collide.



Researched by NONA YATES/Los Angeles Times

REBECCA PERRY / Los Angeles Times

tion or motion is like trying to put your finger on a snowflake; the very act of measurement destroys the thing being measured.

"That means . . . space-time is an uncertain concept, so you've lost your firm footing," said Strominger. "And that is a deep conceptual issue we have not yet come to grips with."

Now string theory appears to be propelling this evolution one drastic, perhaps inevitable, step further.

Certain approaches to string theory dispense with the notion of space-time completely. Yet, they seem to produce the same set of results as string theories with normal space and time.

To some theorists, this strongly suggests that space and time are superfluous. Space and time as fundamental concepts may be about to disappear altogether—literally pulling the floor out from under physics.

"The notion of space-time is something we've cherished for thousands of years, and it's clearly something we're going to have to give up," said Strominger.

Even before string theory enjoyed its recent successes, physicists knew they would have to grapple again with the inadequacy of our understanding of space and time. The reason is a glaring mismatch between gravity, which rules large-scale events in the cosmos, and quantum mechanics, which rules small-scale happenings.

Both gravity and quantum theory are well understood and have survived decades of experimental tests. Quantum mechanics gave rise to lasers and computers; Einstein's theory of gravity predicted everything from black holes to the bending of light by stars, insights since proved by observations.

The problem is, the two theories are mutually exclusive. The space and time of quantum theory don't mesh with the space and time of Einstein's theory of gravity, or General Relativity. In the language of gravity, the quantum mechanical aspects of the universe turn into gobbledygook. And vice versa.

"We can describe the world that we see and experience completely," said UC Santa Barbara physicist Sean Carroll, "but the explanations are internally inconsistent."

Some Things Don't Affect Everyday Life

Until recently, physicists found it easy to sweep this unpleasantness under the rug—in part because they didn't know how to deal with it, in part because it doesn't make a difference in our everyday lives.

The inherently uncertain behavior of subatomic particles affects only things as small as atoms, not everyday objects like chairs; the warping of space and time shapes the orbits of planets, but is too diluted to make itself felt on the scale of our own backyards.

Where the large-scale fabric of space-time gets tangled in the inner lives of atoms, however, chaos erupts; space and time fail to make sense. And increasingly, physicists find themselves face to face with situations where quantum mechanics and the extreme warping of space-time collide.

For example, physicists won't be able to understand either the innards of black holes or the origins of the universe until they come to grips with how gravity behaves at extremely small scales. Indeed, the ultimate laboratory for studying the collision of these two opposing realms is the infinitely compressed dollop of space-time that gave rise to the Big Bang.

That cataclysmic speck, physicists believe, contained everything now in our universe, so it would have packed a huge gravitational wallop. At the same time, it would have been small enough to behave according to quantum mechanical laws.

Because physicists can't study the Big Bang directly, they wind back the clock with equations and thought experiments—imagining what might happen, for example, if time really reversed.

The results are disturbing: As the universe gets smaller and smaller, the warping of space-time gets stronger and quantum uncertainties get progressively larger. Finally, the uncertainty becomes larger than any time interval that could possibly be measured. Measurement becomes meaningless.

Time at the first moment dissolves into nonsense.

"If you ask questions about what happened at very early times," said Harvard physicist Sidney Coleman, "and you compute the answer, the [real] answer is: Time doesn't mean anything."

Or consider what happens inside a black hole—a region where gravity is so strong that space-time curls in on itself, in effect, shutting out the rest of the universe. Black holes are swirling pits of pure space-time. And according to Einstein's theory, their enormous gravity causes them to collapse to an infinite point of zero size—what physicists call singularity. Is there such a nonsensical thing as infinite density packed into zero size?

"I remember puzzling about that when I was a kid," said Gary Horowitz of the Institute for Theoretical Physics at UC Santa Barbara. "I thought when I went to college I would find out the answer . . . I'm still waiting."

In the pinched-off centers of black holes, space-time appears to simply stop. "The singularity acts like an edge," said Horowitz. "You run into it, and it's the end. There's no time after that; there's no space after that. But we don't think physics should end [there]. That's why we're trying to" find new laws of physics, which will describe what happens beyond that edge.

Black holes, said Princeton physicist John Archibald Wheeler, "[teach] us that space can be crumpled like a piece of paper into an infinitesimal dot, that time can be extinguished like a blown-out flame, and that the laws of physics that we regard as 'sacred,' as immutable, are anything but."

Space, Time May Be Doomed as Concepts

String theory has emerged as the only viable candidate to reconcile the differences between gravity and quantum mechanics. It does so by eliminating the notion of infinitely small particles. The loop of string is the smallest allowable size.

"You never get to the point where the disasters happen," said Seiberg of the Institute for Advanced Study. "String theory prevents it."

But rather than rescuing space and time, string theory only seems to make their doom as fundamental concepts more imminent.

When they are incorporated into string theory, "space and time get confused," said Seiberg. "It's telling us that the traditional understanding of space and time will evaporate and there will be a more interesting and subtle result."

Some string theorists believe that space and time somehow emerged in the early universe out of the disorganized, 11-dimensional strings. The strings are "shards" of space and time, said physicist Brian Greene of Columbia University.

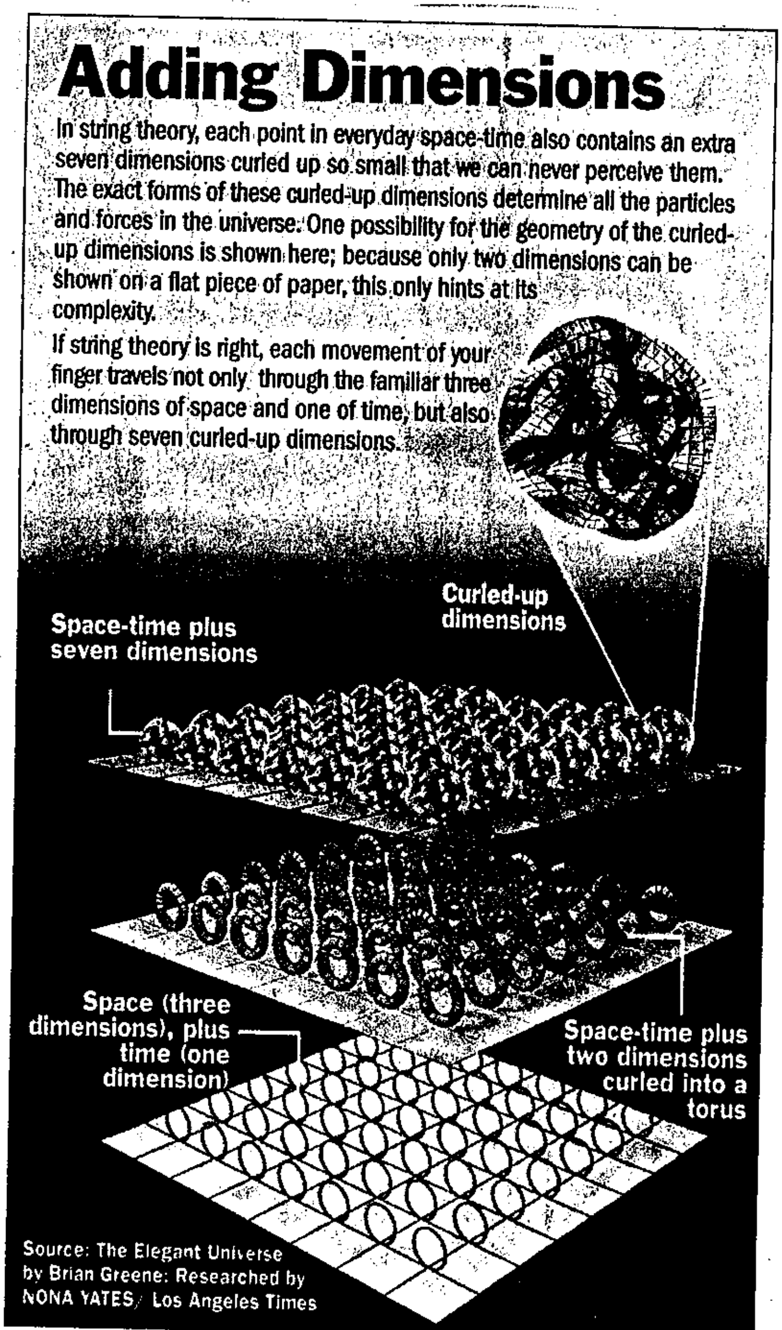
Imagine grains of sand on the surface of a drum. If you tap the surface over and over at the same place, the sand falls into patterns—like iron filings around a magnet.

Did space and time emerge in the same way, as resonant patterns of vibrating strings?

Trying to make sense of such an idea is a struggle even for theorists.

"String theory has been giving us a lot of clues," said Strominger,

THEORY: Bizarre Concept Could Explain Universe



REBECCA PERRY / Los Angeles Times

"but we haven't been able to put them together into a unified picture."

Even philosophically, the challenge of replacing space and time is daunting. What does it mean to inhabit a spaceless, timeless universe? Clocks and rulers not only measure hours and inches; they tell us where we've been and where we're going.

"When we talk about space and time, we think there is something there, and we live in it," said David Gross, director of the Institute for Theoretical Physics. The idea that space and time might be illusions, he said, "is very disturbing. Where are we? When are we?"

The almost unfathomable scenario of a universe without space and time in turn calls into question the very connection between cause and effect. If time can break down, how can one event be placed clearly "before" or "after" another?

Hypothetically, if there is no clear difference between now and the instant after, how can we say whether the gunshot caused death—or death caused the gunshot?

"We normally think of causality as a basic property," said Horowitz. "Something effects something else. But when you're getting rid of space and time . . . are we sure that causality is going to be preserved?"

New views of time could lead to even more bizarre consequences—for instance, more than two dimensions of time, a theory being worked on by USC physicist Itzhak Bars, among others.

Whatever the outcome of these efforts, it's clear, said Greene, that "space is undergoing a drastic rearrangement of its basic pieces; we will not understand string theory until we make a major breakthrough in notions of space and time."

If Greene and his colleagues are right, expanding the universe into 11 dimensions and looping it into strings are only the beginning. On the horizon looms a new kind of physics, where space and time melt down completely.

"The real change that's around the corner [is] in the way we think about space and time," said Gross. "We haven't come to grips with what Einstein taught us. But that's coming. And that will make the world around us seem much stranger than any of us can imagine."

Next: Caltech's savior of string theory

How Faith in the Fringe Paid Off for One Scientist

■ **Research:** When others bailed out, Caltech professor stuck by string theory, now firmly in mainstream of physics.

By K.C. COLE
TIMES SCIENCE WRITER

It's not every day that a revolution in physics is announced by a ranting and raving guy who gets carried off by two men in white coats. Yet that's more or less what happened to Caltech physicist John Schwarz in the summer of 1984.

To be fair, the ravings were a prearranged part of a physics "cabaret" put on as pure entertainment at the Aspen Center for Physics in Colorado. But Schwarz used the opportunity to announce a newly discovered mathematical "miracle" that set off a revolution in string theory—sparking a renaissance that continues to this day.

"Within weeks [string theorists] went from an intellectual backwater to the mainstream of theoretical physics," said Schwarz.

Certainly, string theory—which views everything in the universe as

OF SPACE, TIME AND STRINGS

Rocking the foundations of physics

■ Second in a series

the combined harmonies of strings vibrating in 11 dimensions—has not been proved. At best, it's far from complete.

But today it's considered a profoundly important work in progress that is almost sure to play a major

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STRING: One Man's Persistence Pays Off

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role in revamping physics.

This current matter-of-fact acceptance is amazing to Schwarz, who labored for years on the theory in near obscurity, sometimes facing outright hostility. He takes special satisfaction in displaying an editorial that appeared in the Los Angeles Times in 1988, taking sides with an eminent critic who pondered whether string theorists should even be "paid by universities and be permitted to pervert impressionable students."

The theory's newfound acceptance "has come as a shock to me," Schwarz said in his office at Caltech, where he very belatedly attained the rank of professor in 1985—13 years after he signed on as a researcher.

Before his 1984 discovery, Schwarz did give occasional talks on his work at scientific meetings. However, they didn't have much impact on the leaders of the theoretical physics community. "I suspect most of them don't remember I was there," he said.

Problems Seemed Overwhelming

String theory, after all, did not look very promising at the start. After an initial burst of enthusiasm for the new idea in the early 1970s, the problems seemed overwhelming.

For one thing, the theory predicted the existence of a particle that traveled faster than light—an impossibility. For another, it did not include particles of matter, but only particles that transmit forces.

And it didn't help that the theory at first seemed to require 26 dimensions. "For all these reasons, it looked a little crazy," Schwarz said. Besides, string theory was discovered by accident during efforts to understand how nuclear particles bind together inside atoms.

Physicists stumbled upon the equations almost by chance. They didn't know what the theory meant or what it was good for. In the mid-1970s, a far simpler theory came along that solved the particle problem without getting tangled in 26-dimensional strings.

Most physicists left the field of string theory. "They stopped for good reasons," Schwarz said. But "I felt [that] such a beautiful mathematical structure had to lead someplace." So he persisted.

"John Schwarz led the effort to keep string theory alive," said Columbia physicist Brian Greene recently during a lecture at Caltech.

Even in the theory's "dark ages" Schwarz made big strides, working first with French physicists Andre Neveu and Joel Scherk, and later with English physicist Michael Green. They figured out how to incorporate the matter particles into the theory, got rid of the faster-than-light particle and brought the number of dimensions down to 10.

But they still faced a major problem. The theory predicted the existence of another strange particle that didn't make any sense. Try as they might, they couldn't get rid of it.

"Eventually, we decided to stop trying to get rid of the thing and take it seriously," Schwarz said. In a classic case of looking at what everyone else had seen, but thinking what no one else had thought, he recognized the problem particle as a graviton—a "particle" of gravity.

Suddenly, string theory wasn't just an ill-fitting theory of subnuclear interactions. Once it included gravity, it had the potential to become a theory of all the forces and particles in the universe.

If string theory is right, Schwarz will have gone Newton one better. While Newton discovered the laws of gravity, and Einstein discovered how gravity works, string theory tells us why gravity exists at all. Gravity appears from the equations of string theory as naturally as chickens hatch from eggs.

Still, few physicists paid much attention. "The plus was [that] there was no competition," said Schwarz. "The minus was that nobody was interested in what we were doing."

Schwarz's 1984 breakthrough changed all that. (Although far too technical to be understood by laypeople, the mathematical discovery was considered a major advance by string theorists.)

From then on, he had a lot of company (and competition) from many top physicists, attracted by string theory's newfound potential.

Still, he remains a leader in the field. By 1987, he'd won not only a professorship, but a MacArthur Fellowship. And his work had set off what became known as the First Superstring Revolution.

Schwarz, 57, seems surprisingly normal compared to the theory that's driven much of his professional life. He likes to ride his bike, and hike; his office is clean and uncluttered.

After getting his bachelor's degree in math from Harvard, he received his doctorate from Berkeley in 1966, but watched the politics from the sidelines. He spent the next several years at Princeton as an assistant professor but never got tenure.

"I would like to say they made a mistake," he said. "But if you look at who they chose instead of me, they did pretty well," he said, naming several top physicists in the field.

Every summer for 30 years, Schwarz has gone to Aspen, hiking in the mountains, talking strings. "Theoretical physics is a very portable activity, which is nice," he said.

In contrast to all this seeming predictability, Schwarz's wife, Patricia, who received a PhD in physics from Caltech last year, is a self-described activist. She combines feminism and physics in a lively Web site *(www.superstringtheory.com)* devoted to string theory, its history and the science behind it.

The site "was an act of love," she said. "There's nothing more revolutionary you can do than to get people to love physics."

The two don't talk physics much at home, she said. She's interested in geometrical approaches to space and time, and he thinks algebraically. "When he starts talking about [exotic kinds of] algebras, I just think, 'Yuuuccckk.' "

'A Lot of It's Guesswork'

Today, Schwarz works much as he always did. A lot of it, he says, is simply inspired fooling around. "A lot of it's guesswork," he said, laughing. "Of course, we never say 'guesswork.' We say 'conjectures.'"

That approach fits string theory well, because unlike other areas of physics, it doesn't begin with a well formulated theory that can be

LORI SHEPLER Los Angeles Times

Physicists Brian Greene, Edward Witten and John Schwarz, from left, discuss some scientific models.

REBECCA PERRY / Los Angeles Times

mathematically explored. Moreover, strings are much too small to see directly, and string theorists haven't yet figured out ways to detect their presence indirectly in experiments.

That's a problem for theorists, because experiments can't provide the essential reality check of their work. "Usually, there's a back and forth between theory and experiment," Schwarz said. "But [string theory is] so far removed, we have to sort of go it on our own."

This year Schwarz has some high-level company at Caltech. Edward Witten of the Institute for Advanced Study at Princeton—perhaps the mostly highly respected figure in string theory—is spending the year in the office adjoining Schwarz's.

Meanwhile, Witten's wife, physicist Chiara Nappi, is teaching at USC. It's all part of a master plan to link Caltech and USC in a new Center for Theoretical Physics. USC already has a strong group of "stringy" physicists.

"Our goal is to turn Los Angeles into a center for theoretical physics—focusing on string theory," said USC string theorist Itzhak Bars.

Dismissed by Some as Pretty Mathematics

Because many critics have dismissed string theory as so much pretty mathematics, Schwarz and his colleagues are anxious to prove them wrong by finding places where the theory can solve real-world physical problems.

"String theory has held out great promise ever since it came on the scene," said Case Western Reserve University physicist Lawrence Krauss. "But it's not at all clear that it has absolutely anything to do with the real world."

The problem at the top of almost everyone's list is why empty space seems to be bubbling over with energy yet has little noticeable effect on the cosmos at large.

String theory should have a good shot at finding a way out of the paradox, say Schwarz and others, but so far it hasn't produced much.

"If I knew how [to solve that paradox], I would do it," Schwarz said. "You just try to think of whatever good ideas you can."

On the experimental front, Schwarz and others believe that indirect evidence for string theory might show up within a few years if

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a new family of particles is discovered either at the Fermi National Accelerator Laboratory (known as Fermilab) outside Chicago or the Large Hadron Collider, now under construction in Europe.

The family—if it exists—consists of the "supersymmetric" partners of regular particles. Known as "sparticles," they include squarks (which pair with quarks), selectrons (partners of electrons) and so forth.

Since supersymmetry is an essential aspect of string theory, the discovery of one or more "sparticles" would be a major milestone.

In fact, Schwarz has said—only somewhat in jest—that it would be more important than the discovery of life on Mars.

Meanwhile, string theory continues to grow and evolve. In 1995, Witten sparked the latest revolution, introducing vibrating sheets called membranes and bringing the total number of new dimensions to 11. Known as M theory, the new approach allows not only strings and membranes, but also "blobs" of many dimensions, and a whole zoo of extra-elementary objects—including zero-dimensional points known as zero branes.

Before M theory came along, there were at least five separate string theories with different configurations of dimensions, and each seemed to have little in common with the others. M Theory showed that all five theories were part of a grander scheme. In doing so, it tied together string theory in a way that gave it credibility.

The situation is strikingly similar to the state of physics before the discovery of quantum theory—when light seemed to be either waves or particles. Later, it was shown that light—like matter—has characteristics of both waves and particles. Both are different aspects of the same entity—just as vapor and ice are aspects of water.

In the same way, all the different string theories appear to be aspects of each other—the same theory viewed through different lenses.

"Eventually, the subject won't be called string theory anymore," Schwarz said. "We don't know what the right name will be."

One name he hates, however, is "the theory of everything," a term some physicists and most journalists use routinely.

"That's a phrase I detest," said Schwarz, dismissing it as arrogant.

More important, he said, it's misleading. Even if string theory turns out to be right, "it still wouldn't make us any wiser about all the other phenomena in the world."

Roses and clouds and war will remain immune to the explanatory power of strings.

Still, he'd like to know where the theory is heading. Ultimately, that's what drives him—the sense of going "where no person has gone before." He says "person" quite deliberately.

"Other species in other solar systems have undoubtedly done it many times," he said, without a trace of irony.

"When people say, 'So and so was the first to discover this or that,' I say, 'Baloney!' It's probably been done millions of times."

Next: The Soap-Bubble Universe (In Thursday's Science File, Page B2)

Los Angeles Times

Unseen Dimensions Hold Theory Aloft

■ Skeptics have scoffed at a radical new view of the universe, saying its vibrating 11-dimensional strings are too small to be verified. But backers say confirmation through experiments may not be out of the question after all.

By K.C. COLE
TIMES SCIENCE WRITER

String theory—the notion that everything in the universe is woven in a tapestry of 11 dimensional vibrating strings—has seduced an increasing number of physicists over the past 20 years with its sheer mathematical beauty and power to solve difficult problems.

At the same time, skeptics have found it easy to dismiss these successes as so much theoretical smoke. After all, critics argue, the vibrating strings and unseen dimensions that hold them are too tiny ever to be seen in experiments. And a theory that can't be tested is about as relevant to a physicist as a bicycle is to a fish.

But what if the unseen dimensions were much larger than previously thought, big enough to see in relatively simple experiments? "You cannot rule out that possibility," says Harvard physicist Andrew Strominger. "That's astonishing."

In fact, the idea that the strings might be big enough to perceive is rapidly gaining attention, if not outright respect, among many scientists.

If true, it would mean that "string theory is just out of reach of experiment," according to physicist Joseph Lykken of

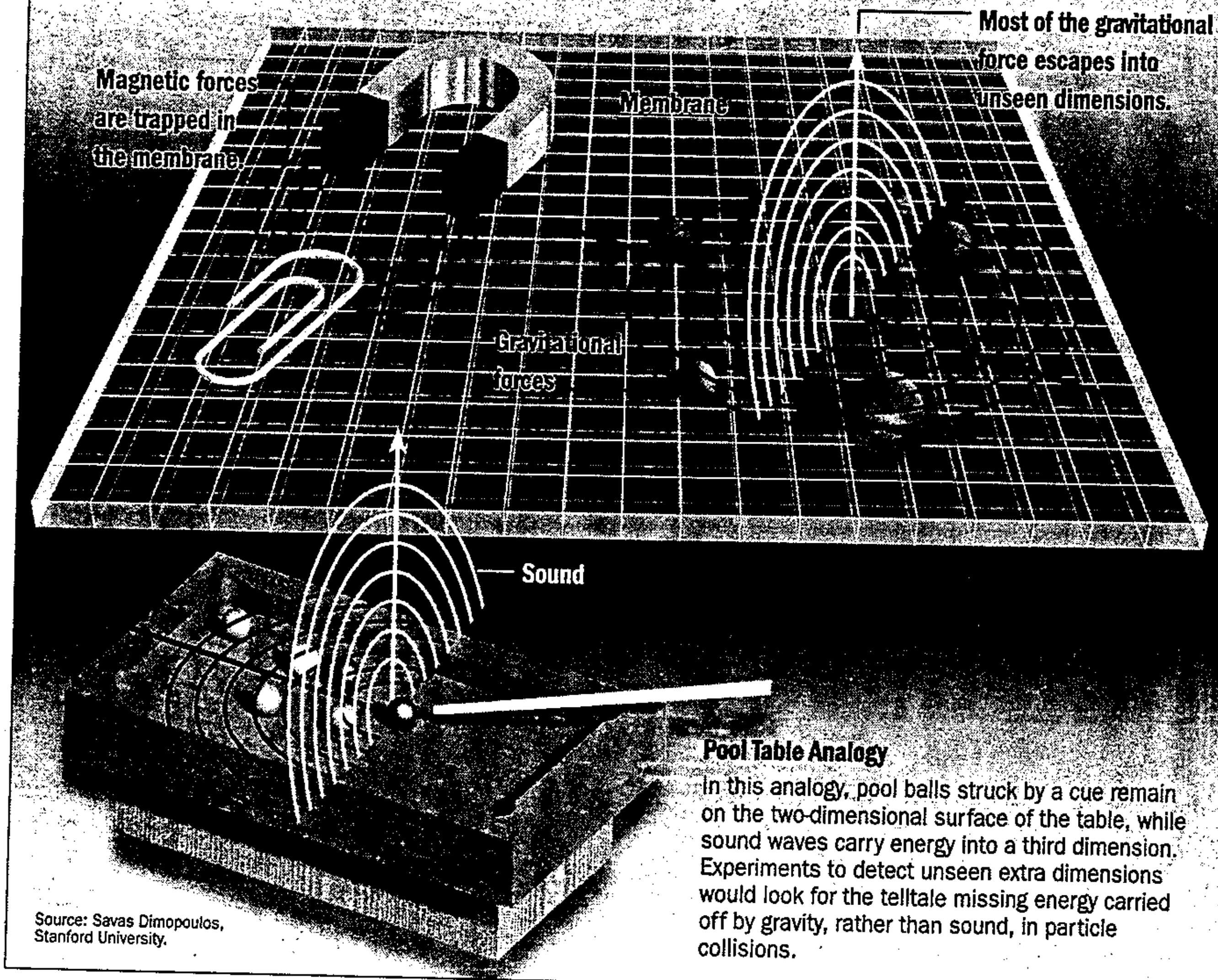
OF SPACE, TIME AND STRINGS

Rocking the foundations of physics

■ Third in a series

A Universe on a Membrane

According to some radical new theories, our universe is trapped entirely on a very thin membrane that is part of a much larger universe of extra dimensions. Electric, magnetic and nuclear forces are stuck inside the membrane, while gravity leaks out. If true, this theory would explain why gravity is so weak compared with the other forces.



Pool Table Analogy

In this analogy, pool balls struck by a cue remain on the two-dimensional surface of the table, while sound waves carry energy into a third dimension. Experiments to detect unseen extra dimensions would look for the telltale missing energy carried off by gravity, rather than sound, in particle collisions.

Source: Savas Dimopoulos, Stanford University.

REBECCA PERRY / Los Angeles Times

the Fermi National Accelerator Laboratory in Batavia, Ill. Even more important, it would mean a whole new way of solving a host of thus-far elusive mysteries—ranging from the unexplainable weakness of gravity to the unaccountable existence of matter in the universe at all.

According to this new scenario, the everyday, three-dimensional universe we live in is trapped on a thin membrane—something like the world inhabited by characters playing out their lives within the confines of a movie screen. Unknown to these shallow, two-dimensional players, a larger universe spreads into numerous extra dimensions, like theaters in a multiplex.

Making Better Sense of Gravity's Disparity

And while we are stuck as firmly in our membrane as Rhett and Scarlett are stuck on the screen, certain aspects of our universe can ooze off—leaving behind experimentally detectable tracks.

In fact, Stanford physicist Savas Dimopoulos speculates (not entirely tongue in cheek) that Bill Gates might figure out how to make a profit in the universe beyond our membrane. "There is extra space out there," he said recently during a workshop at the Aspen Institute for Physics. "Maybe you can store things. This is a possibility that hasn't been investigated."

Of course, these ideas are wildly speculative, to put it mildly. But the general idea that our universe is but a thin sliver of a larger reality offers multiple advantages to theorists.

For example, one of the thorniest problems in physics is the vast disparity between the relative weakness of gravity and the strength of all the other forces, such as electricity, magnetism and nuclear forces. A tiny magnet is powerful enough to lift a paper clip off a table in defiance of the gravitational pull of every atom in the entire Earth.

Such a huge difference just doesn't make sense.

However, it would make perfect sense, according to Dimopoulos and his colleagues, if gravity were weak only because it alone could leak off our membrane into the larger universe.

Imagine our three-dimensional universe as the skin of a soap bubble floating in a larger world. Electricity, magnetism and nuclear forces are stuck inside the skin.

In contrast, the gravitational attraction of the paper clip to the Earth gets diluted as most of the gravity oozes out of our membrane into other dimensions.

"The reason why gravity is weak is that [most of it] lives far away from us," says Dimopoulos. "In a way, it's a very simple idea."

Taking another tack, MIT's Lisa Randall and her colleagues are exploring the possibility that gravity changes strength dramatically in various parts of this higher-dimensional world; we just happen to live on a slice of it where gravity is weak.

And gravity is only the tip of the iceberg. After you introduce the idea that our three-dimensional universe is simply a slice of life in a larger world, it's only natural to assume that other membranes lurk out there as well. Signals from these other membranes could affect our universe just as gusts of wind can deform the skin of a bubble.

In our universe, the energy infiltrating our area of the cosmos from other membranes might show up as puzzling new particles—or perhaps some unexplained property of matter. Because these other forces are extremely diluted, however—living as they do mostly in that larger, extra-dimensional universe—they would have very weak effects.

As such, they would enable scientists to explain many quantities in physics that snuggle up puzzlingly close to zero, but don't quite amount to exactly nothing. Among them: the mass of a barely there particle called the neutrino, the exceedingly slight excess of matter over antimatter that allows us to exist, and the "weight" of empty space.

The extra dimensions also provide a logical hiding place for the long-sought "dark matter" that gravitationally pulls on clusters of galaxies but has remained otherwise frustratingly invisible.

"It's just mind-boggling," said Randall. "There are some hard problems out there that we haven't been able to get at. Maybe there's something lurking here which will help us solve some of these problems."

Answers Could Come Within a Few Years

Physicists won't have to wait forever to find out if these ideas have any basis in fact. Dimopoulos' latest work predicts that previously unknown forces reaching us from membranes far beyond could be a million times stronger than gravity, and therefore even easier to detect. Energy oozing out of our membrane might show up as missing energy in particle experiments in a new accelerator now under construction in Europe, the Large Hadron Collider.

Or, new families of particles created from extra-dimensional vibrations might pop out of these experiments. If the physicists get very, very lucky, the first signs of higher dimensions could materialize at Fermilab within the next few years.

Even more imminent, if more speculative, are pending results from several tabletop experiments at Stanford and the University of Colorado to sense "large" extra dimensions. Because measuring gravity is the only way to perceive these dimensions—and gravity is uncannily weak—finding evidence will be difficult.

Moreover, it's known that at most, these extra dimensions could be the width of a grain of rice. (Gravity has been well tested down to scales as small as a millimeter, and no evidence of extra dimensions has shown up yet.)

In Dimopoulos' scenario, the two extra dimensions are curled up into tiny tubes, like cocktail straws, about a millimeter in diameter. An experiment sensitive enough to probe on that tiny scale could witness a dramatic change in Newton's familiar laws of gravity.

Of course, physicists will have to explain the geometry of these extra dimensional landscapes, as well as the way they evolved: Why should three dimensions spread out while two roll up? Why a millimeter and not a yard?

The range of possibilities is almost endless. But so are the opportunities.

Indeed, the very fact that these scenarios are not impossible has stoked much excitement among string theorists. It is as if, said Strominger, humans are like water bugs skipping over the surface of a deep ocean. Everything we know is so much foam and flotsam stuck to the surface. But there may be a whole undiscovered world waiting underneath.

"This kind of structure never occurred to anybody before, but it turns out it's very natural," he said. "It tells us that our imagination has been very limited. It shows how little we know about the universe beyond that which we've actually measured."

In upcoming Science Files: Physics' Biggest Mysteries; and Experimenting on the Universe.

Preface

During the last thirty years of his life, Albert Einstein sought relentlessly for a so-called unified field theory—a theory capable of describing nature's forces within a single, all-encompassing, coherent framework. Einstein was not motivated by the things we often associate with scientific undertakings, such as trying to explain this or that piece of experimental data. Instead, he was driven by a passionate belief that the deepest understanding of the universe would reveal its truest wonder: the simplicity and power of the principles on which it is based. Einstein wanted to illuminate the workings of the universe with a clarity never before achieved, allowing us all to stand in awe of its sheer beauty and elegance.

Einstein never realized this dream, in large part because the deck was stacked against him: In his day, a number of essential features of matter and the forces of nature were either unknown or, at best, poorly understood. But during the past half-century, physicists of each new generation—through fits and starts, and diversions down blind alleys—have been building steadily on the discoveries of their predecessors to piece together an ever fuller understanding of how the universe works. And now, long after Einstein articulated his quest for a unified theory but came up empty-handed, physicists believe they have finally found a framework for stitching these insights together into a seamless whole—a single theory that, in principle, is capable of describing all physical phenomena. The theory, *superstring theory,* is the subject of this book.

I wrote *The Elegant Universe* in an attempt to make the remarkable insights emerging from the forefront of physics research accessible to a broad spectrum of readers, especially those with no training in mathematics or physics. Through public lectures on superstring theory I have given over the past few years, I have witnessed a widespread yearning to understand what current research says about the fundamental laws of the universe, how these laws require a monumental restructuring of our conception of the cosmos, and what challenges lie ahead in the ongoing quest for the ultimate theory. I hope that, by explaining the major achievements of physics going back to Einstein and Heisenberg, and describing how their discoveries have grandly flowered through the breakthroughs of our age, this book will both enrich and satisfy this curiosity.

I also hope that *The Elegant Universe* will be of interest to readers who do have some scientific background. For science students and teachers, I hope this book will crystallize some of the foundational material of modern physics, such as special relativity, general relativity, and quantum mechanics, while conveying the contagious excitement of researchers closing in on the long-sought unified theory. For the avid reader of popular science, I have tried to explain many of the exhilarating advances in our understanding of the cosmos that have come to light during the last decade. And for my colleagues in other scientific disciplines, I hope this book will give an honest and balanced sense of why string theorists are so enthusiastic about the progress being made in the search for the ultimate theory of nature.

Superstring theory casts a wide net. It is a broad and deep subject that draws on many of the central discoveries in physics. Since the theory unifies the laws of the large and of the small, laws that govern physics out to the farthest reaches of the cosmos and down to the smallest speck of matter, there are many avenues by which one can approach the subject. I have chosen to focus on our evolving understanding of space and time. I find this to be an especially gripping developmental path, one that cuts a rich and fascinating swath through the essential new insights. Einstein showed the world that space and time behave in astoundingly unfamiliar ways. Now, cutting-edge research has integrated his discoveries into a quantum universe with numerous hidden dimensions coiled into the fabric of the cosmos—dimensions whose lavishly entwined geometry may well hold the key to some of the most profound questions ever posed. Although some of these concepts are subtle, we will see that they can be grasped through down-to-earth analogies. And when these ideas are understood, they provide a startling and revolutionary perspective on the universe.

Throughout this book, I have tried to stay close to the science while giving the reader an intuitive understanding—often through analogy and metaphor—of how scientists have reached the current conception of the cosmos. Although I avoid technical language and equations, because of the radically new concepts involved the reader may need to pause now and then, to mull over a section here or ponder an explanation there, in order to follow the progression of ideas fully. A few sections of Part IV (focusing on the most recent developments) are a bit more abstract than the rest; I have taken care to forewarn the reader about these sections and to structure the text so that they can be skimmed or skipped with minimal impact on the book's logical flow. I have included a glossary of scientific terms for an easy and accessible reminder of ideas introduced in the main text. Although the more casual reader may wish to skip the endnotes completely, the more diligent reader will find in the notes amplifications of points made in the text, clarifications of ideas that have been simplified in the text, as well as a few technical excursions for those with mathematical training.

I owe thanks to many people for their help during the writing of this book. David Steinhardt read the manuscript with great care and generously provided sharp editorial insights and invaluable encouragement. David Morrison, Ken Vineberg, Raphael Kasper, Nicholas Boles, Steven Carlip, Arthur Greenspoon, David Mermin, Michael Popowits, and Shani Offen read the manuscript closely and offered detailed reactions and suggestions that greatly enhanced the presentation. Others who read all or part of the manuscript and offered advice and encouragement are Paul Aspinwall, Persis Drell, Michael Duff, Kurt Gottfried, Joshua Greene, Teddy Jefferson, Marc Kamionkowski, Yakov Kanter, Andras Kovacs, David Lee, Megan McEwen, Nari Mistry, Hasan Padamsee, Ronen Plesser, Massimo Poratti, Fred Sherry, Lars Straeter, Steven Strogatz, Andrew Strominger, Henry Tye, Cumrun Vafa, and Gabriele Veneziano. I owe special thanks

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For agreeing to be interviewed and to lend their personal perspectives on various topics covered I thank Howard Georgi, Sheldon Glashow, Michael Green, John Schwarz, John Wheeler, Edward Witten, and, again, Andrew Strominger, Cumrun Vafa, and Gabriele Veneziano.

I am happy to acknowledge the penetrating insights and invaluable suggestions of Angela Von der Lippe and the sharp sensitivity to detail of Traci Nagle, my editors at W. W. Norton, both of whom significantly enhanced the clarity of the presentation. I also thank my literary agents, John Brockman and Katinka Matson, for their expert guidance in shepherding the book from inception to publication.

For generously supporting my research in theoretical physics for more than a decade and a half, I gratefully acknowledge the National Science Foundation, the Alfred P. Sloan Foundation, and the U.S. Department of Energy. It is perhaps not surprising that my own research has focused on the impact superstring theory has on our conception of space and time, and in a couple of the later chapters I describe some of the discoveries in which I had the fortune to take part. Although I hope the reader will enjoy reading these "inside" accounts, I realize that they may leave an exaggerated impression of the role I have played in the development of superstring theory. So let me take this opportunity to acknowledge the more than one thousand physicists around the world who are crucial and dedicated participants in the effort to fashion the ultimate theory of the universe. I

apologize to all whose work is not included in this account; this merely r flects the thematic perspective I have chosen and the length limitatio of a general presentation.

Finally, I owe heartfelt thanks to Ellen Archer for her unwavering lo and support, without which this book would not have been written.

Chapter 1

Tied Up with String

Calling it a cover-up would be far too dramatic. But for more than half a century—even in the midst of some of the greatest scientific achievements in history—physicists have been quietly aware of a dark cloud looming on a distant horizon. The problem is this: There are two foundational pillars upon which modern physics rests. One is Albert Einstein's general relativity, which provides a theoretical framework for understanding the universe on the largest of scales: stars, galaxies, clusters of galaxies, and beyond to the immense expanse of the universe itself. The other is quantum mechanics, which provides a theoretical framework for understanding the universe on the smallest of scales: molecules, atoms, and all the way down to subatomic particles like electrons and quarks. Through years of research, physicists have experimentally confirmed to almost unimaginable accuracy virtually all predictions made by each of these theories. But these same theoretical tools inexorably lead to another disturbing conclusion: As they are currently formulated, general relativity and quantum mechanics *cannot both be right.* The two theories underlying the tremendous progress of physics during the last hundred years—progress that has explained the expansion of the heavens and the fundamental structure of matter—are mutually incompatible.

If you have not heard previously about this ferocious antagonism you may be wondering why. The answer is not hard to come by. In all but the most extreme situations, physicists study things that are either small and light (like atoms and their constituents) or things that are huge and heavy (like stars and galaxies), but not both. This means that they need use only quantum mechanics *or* only general relativity and can, with a furtive glance, shrug off the barking admonition of the other. For fifty years this approach has not been quite as blissful as ignorance, but it has been pretty close.

But the universe *can* be extreme. In the central depths of a black hole an enormous mass is crushed to a minuscule size. At the moment of the big bang the whole of the universe erupted from a microscopic nugget whose size makes a grain of sand look colossal. These are realms that are tiny and yet incredibly massive, therefore requiring that both quantum mechanics and general relativity simultaneously be brought to bear. For reasons that will become increasingly clear as we proceed, the equations of general relativity and quantum mechanics, when combined, begin to shake, rattle, and gush with steam like a red-lined automobile. Put less figuratively, well-posed physical questions elicit nonsensical answers from the unhappy amalgam of these two theories. Even if you are willing to keep the deep interior of a black hole and the beginning of the universe shrouded in mystery, you can't help feeling that the hostility between quantum mechanics and general relativity cries out for a deeper level of understanding. Can it really be that the universe at its most fundamental level is divided, requiring one set of laws when things are large and a different, incompatible set when things are small?

Superstring theory, a young upstart compared with the venerable edifices of quantum mechanics and general relativity, answers with a resounding no. Intense research over the past decade by physicists and mathematicians around the world has revealed that this new approach to describing matter at its most fundamental level resolves the tension between general relativity and quantum mechanics. In fact, superstring theory shows more: Within this new framework, general relativity and quantum mechanics *require one another* for the theory to make sense. According to superstring theory, the marriage of the laws of the large and the small is not only happy but inevitable.

That's part of the good news. But superstring theory—string theory, for short—takes this union one giant step further. For three decades, Einstein sought a unified theory of physics, one that would interweave all of nature's forces and material constituents within a single theoretical tapestry.

He failed. Now, at the dawn of the new millennium, proponents of string theory claim that the threads of this elusive unified tapestry finally have been revealed. String theory has the potential to show that all of the wondrous happenings in the universe—from the frantic dance of subatomic quarks to the stately waltz of orbiting binary stars, from the primordial fireball of the big bang to the majestic swirl of heavenly galaxies—are reflections of one grand physical principle, one master equation.

Because these features of string theory require that we drastically change our understanding of space, time, and matter, they will take some time to get used to, to sink in at a comfortable level. But as shall become clear, when seen in its proper context, string theory emerges as a dramatic yet natural outgrowth of the revolutionary discoveries of physics during the past hundred years. In fact, we shall see that the conflict between general relativity and quantum mechanics is actually not the first, but the third in a sequence of pivotal conflicts encountered during the past century, each of whose resolution has resulted in a stunning revision of our understanding of the universe.

The Three Conflicts

The first conflict, recognized as far back as the late 1800s, concerns puzzling properties of the motion of light. Briefly put, according to Isaac Newton's laws of motion, if you run fast enough you can catch up with a departing beam of light, whereas according to James Clerk Maxwell's laws of electromagnetism, you can't. As we will discuss in Chapter 2, Einstein resolved this conflict through his theory of special relativity, and in so doing completely overturned our understanding of space and time. According to special relativity, no longer can space and time be thought of as universal concepts set in stone, experienced identically by everyone. Rather, space and time emerged from Einstein's reworking as malleable constructs whose form and appearance depend on one's state of motion.

The development of special relativity immediately set the stage for the second conflict. One conclusion of Einstein's work is that no object—in fact, no influence or disturbance of any sort—can travel faster than the speed of light. But, as we shall discuss in Chapter 3, Newton's experimentally successful and intuitively pleasing universal theory of gravitation involves influences that are transmitted over vast distances of space *instantaneously.* It was Einstein, again, who stepped in and resolved the conflict by offering a new conception of gravity with his 1915 general theory of relativity. Just as special relativity overturned previous conceptions of space and time, so too did general relativity. Not only are space and time influenced by one's state of motion, but they can warp and curve in response to the presence of matter or energy. Such distortions to the fabric of space and time, as we shall see, transmit the force of gravity from one place to another. Space and time, therefore, can no longer to be thought of as an inert backdrop on which the events of the universe play themselves out; rather, through special and then general relativity, they are intimate players in the events themselves.

Once again the pattern repeated itself: The discovery of general relativity, while resolving one conflict, led to another. Over the course of the three decades beginning in 1900, physicists developed quantum mechanics (discussed in Chapter 4) in response to a number of glaring problems that arose when nineteenth-century conceptions of physics were applied to the microscopic world. And as mentioned above, the third and deepest conflict arises from the incompatibility between quantum mechanics and general relativity. As we will see in Chapter 5, the gently curving geometrical form of space emerging from general relativity is at loggerheads with the frantic, roiling, microscopic behavior of the universe implied by quantum mechanics. As it was not until the mid-1980s that string theory offered a resolution, this conflict is rightly called the central problem of modern physics. Moreover, building on special and general relativity, string theory requires its own severe revamping of our conceptions of space and time. For example, most of us take for granted that our universe has three spatial dimensions. But this is not so according to string theory, which claims that our universe has many more dimensions than meet the eye—dimensions that are tightly curled into the folded fabric of the cosmos. So central are these remarkable insights into the nature of space and time that we shall use them as a guiding theme in all that follows. String theory, in a real sense, is the story of space and time since Einstein.

To appreciate what string theory actually is, we need to take a step back and briefly describe what we have learned during the last century about the microscopic structure of the universe.

The Universe at Its Smallest: What We Know about Matter

The ancient Greeks surmised that the stuff of the universe was made up of tiny "uncuttable" ingredients that they called *atoms*. Just as the enormous number of words in an alphabetic language is built up from the wealth of combinations of a small number of letters, they guessed that the vast range of material objects might also result from combinations of a small number of distinct, elementary building blocks. It was a prescient guess. More than 2,000 years later we still believe it to be true, although the identity of the most fundamental units has gone through numerous revisions. In the nineteenth century scientists showed that many familiar substances such as oxygen and carbon had a smallest recognizable constituent; following in the tradition laid down by the Greeks, they called them *atoms*. The name stuck, but history has shown it to be a misnomer, since atoms surely are "cuttable." By the early 1930s the collective works of J. J. Thomson, Ernest Rutherford, Niels Bohr, and James Chadwick had established the solar system–like atomic model with which most of us are familiar. Far from being the most elementary material constituent, atoms consist of a nucleus, containing protons and neutrons, that is surrounded by a swarm of orbiting electrons.

For a while many physicists thought that protons, neutrons, and electrons were the Greeks' "atoms." But in 1968 experimenters at the Stanford Linear Accelerator Center, making use of the increased capacity of technology to probe the microscopic depths of matter, found that protons and neutrons are not fundamental, either. Instead they showed that each consists of three smaller particles, called *quarks*—a whimsical name taken from a passage in James Joyce's *Finnegan's Wake* by the theoretical physicist Murray Gell-Mann, who previously had surmised their existence. The experimenters confirmed that quarks themselves come in two varieties, which were named, a bit less creatively, *up* and *down*. A proton consists of two up-quarks and a down-quark; a neutron consists of two down-quarks and an up-quark.

Everything you see in the terrestrial world and the heavens above appears to be made from combinations of electrons, up-quarks, and down-quarks. No experimental evidence indicates that any of these three particles is built up from something smaller. But a great deal of evidence indicates that the universe itself has additional particulate ingredients. In the mid-1950s, Frederick Reines and Clyde Cowan found conclusive experimental evidence for a fourth kind of fundamental particle called a *neutrino*—a particle whose existence was predicted in the early 1930s by Wolfgang Pauli. Neutrinos proved very difficult to find because they are ghostly particles that only rarely interact with other matter: an average-energy neutrino can easily pass right through many trillion miles of lead without the slightest effect on its motion. This should give you significant relief, because right now as you read this, billions of neutrinos ejected into space by the sun are passing through your body and the earth as well, as part of their lonely journey through the cosmos. In the late 1930s, another particle called a *muon*—identical to an electron except that a muon is about 200 times heavier—was discovered by physicists studying cosmic rays (showers of particles that bombard earth from outer space). Because there was nothing in the cosmic order, no unsolved puzzle, no tailor-made niche, that necessitated the muon's existence, the Nobel Prize–winning particle physicist Isidor Isaac Rabi greeted the discovery of the muon with a less than enthusiastic "Who ordered that?" Nevertheless, there it was. And more was to follow.

Using ever more powerful technology, physicists have continued to slam bits of matter together with ever increasing energy, momentarily recreating conditions unseen since the big bang. In the debris they have searched for new fundamental ingredients to add to the growing list of particles. Here is what they have found: four more quarks—*charm, strange, bottom,* and *top*—and another even heavier cousin of the electron, called a *tau,* as well as two other particles with properties similar to the neutrino (called the *muon-neutrino* and *tau-neutrino* to distinguish them from the original neutrino, now called the *electron-neutrino*). These particles are produced through high-energy collisions and exist only ephemerally; they are not constituents of anything we typically encounter. But even this is not quite the end of the story. Each of these particles has an *antiparticle* partner—a particle of identical mass but opposite in certain other respects such as its electric charge (as well as its charges with respect to other forces discussed below). For instance, the antiparticle of an electron is called a *positron*—it has exactly the same mass as an electron, but its electric charge is +1 whereas the electric charge of the electron is −1. When

in contact, matter and antimatter can annihilate one another to produce pure energy—that's why there is extremely little naturally occurring antimatter in the world around us.

Physicists have recognized a pattern among these particles, displayed in Table 1.1. The matter particles neatly fall into three groups, which are often called *families.* Each family contains two of the quarks, an electron or one of its cousins, and one of the neutrino species. The corresponding particle types across the three families have identical properties except for their mass, which grows larger in each successive family. The upshot is that physicists have now probed the structure of matter to scales of about a billionth of a billionth of a meter and shown that *everything* encountered to date—whether it occurs naturally or is produced artificially with giant atom-smashers—consists of some combination of particles from these three families and their antimatter partners.

A glance at Table 1.1 will no doubt leave you with an even stronger sense of Rabi's bewilderment at the discovery of the muon. The arrangement into families at least gives some semblance of order, but innumerable "whys" leap to the fore. Why are there so many fundamental particles, especially when it seems that the great majority of things in the world around us need only electrons, up-quarks, and down-quarks? Why are there three families? Why not one family or four families or any other number? Why do the particles have a seemingly random spread of masses—why, for in-

Family 1		Family 2		Family 3	
Particle	***Mass***	***Particle***	***Mass***	***Particle***	***Mass***
Electron	.00054	Muon	.11	Tau	1.9
Electron-neutrino	$< 10^{-8}$	Muon-neutrino	< .0003	Tau-neutrino	< .033
Up-quark	.0047	Charm Quark	1.6	Top Quark	189
Down-quark	.0074	Strange Quark	.16	Bottom Quark	5.2

Table 1.1 The three families of fundamental particles and their masses (in multiples of the proton mass). The values of the neutrino masses have so far eluded experimental determination.

stance, does the tau weigh about 3,520 times as much as an electron? Why does the top quark weigh about 40,200 times as much an up-quark? These are such strange, seemingly random numbers. Did they occur by chance, by some divine choice, or is there a comprehensible scientific explanation for these fundamental features of our universe?

The Forces, or, Where's the Photon?

Things only become more complicated when we consider the forces of nature. The world around us is replete with means of exerting influence: balls can be hit with bats, bungee enthusiasts can throw themselves earthward from high platforms, magnets can keep superfast trains suspended just above metallic tracks, Geiger counters can tick in response to radioactive material, nuclear bombs can explode. We can influence objects by vigorously pushing, pulling, or shaking them; by hurling or firing other objects into them; by stretching, twisting, or crushing them; or by freezing, heating, or burning them. During the past hundred years physicists have accumulated mounting evidence that all of these interactions between various objects and materials, as well as any of the millions upon millions of others encountered daily, can be reduced to combinations of four fundamental forces. One of these is the *gravitational force*. The other three are the *electromagnetic force*, the *weak force*, and the *strong force*.

Gravity is the most familiar of the forces, being responsible for keeping us in orbit around the sun as well as for keeping our feet firmly planted on earth. The mass of an object measures how much gravitational force it can exert as well as feel. The electromagnetic force is the next most familiar of the four. It is the force driving all of the conveniences of modern life—lights, computers, TVs, telephones—and underlies the awesome might of lightning storms and the gentle touch of a human hand. Microscopically, the electric charge of a particle plays the same role for the electromagnetic force as mass does for gravity: it determines how strongly the particle can exert as well as respond electromagnetically.

The strong and the weak forces are less familiar because their strength rapidly diminishes over all but subatomic distance scales; they are the nuclear forces. This is why these two forces were discovered only much more recently. The strong force is responsible for keeping quarks "glued"

together inside of protons and neutrons and keeping protons and neutrons tightly crammed together inside atomic nuclei. The weak force is best known as the force responsible for the radioactive decay of substances such as uranium and cobalt.

During the past century, physicists have found two features common to all these forces. First, as we will discuss in Chapter 5, at a microscopic level all the forces have an associated particle that you can think of as being the smallest packet or bundle of the force. If you fire a laser beam—an "electromagnetic ray gun"—you are firing a stream of *photons*, the smallest bundles of the electromagnetic force. Similarly, the smallest constituents of weak and strong force fields are particles called *weak gauge bosons* and *gluons*. (The name *gluon* is particularly descriptive: You can think of gluons as the microscopic ingredient in the strong glue holding atomic nuclei together.) By 1984 experimenters had definitively established the existence and the detailed properties of these three kinds of force particles, recorded in Table 1.2. Physicists believe that the gravitational force also has an associated particle—the graviton—but its existence has yet to be confirmed experimentally.

The second common feature of the forces is that just as mass determines how gravity affects a particle, and electric charge determines how the electromagnetic force affects it, particles are endowed with certain amounts of "strong charge" and "weak charge" that determine how they are affected by the strong and weak forces. (These properties are detailed in

Force	*Force particle*	*Mass*
Strong	Gluon	0
Electromagnetic	Photon	0
Weak	Weak gauge bosons	86, 97
Gravity	Graviton	0

Table 1.2 The four forces of nature, together with their associated force particles and their masses in multiples of the proton mass. (The weak force particles come in varieties with the two possible masses listed. Theoretical studies show that the graviton should be massless.)

the table in the endnotes to this chapter.[1]) But as with particle masses, beyond the fact that experimental physicists have carefully measured these properties, no one has any explanation of *why* our universe is composed of these particular particles, with these particular masses and force charges.

Notwithstanding their common features, an examination of the fundamental forces themselves serves only to compound the questions. Why, for instance, are there four fundamental forces? Why not five or three or perhaps only one? Why do the forces have such different properties? Why are the strong and weak forces confined to operate on microscopic scales while gravity and the electromagnetic force have an unlimited range of influence? And why is there such an enormous spread in the intrinsic strength of these forces?

To appreciate this last question, imagine holding an electron in your left hand and another electron in your right hand and bringing these two identical electrically charged particles close together. Their mutual gravitational attraction will favor their getting closer while their electromagnetic repulsion will try to drive them apart. Which is stronger? There is no contest: The electromagnetic repulsion is about a million billion billion billion billion (10^{42}) times stronger! If your right bicep represents the strength of the gravitational force, then your left bicep would have to extend beyond the edge of the known universe to represent the strength of the electromagnetic force. The only reason the electromagnetic force does not completely overwhelm gravity in the world around us is that most things are composed of an equal amount of positive and negative electric charges whose forces cancel each other out. On the other hand, since gravity is always attractive, there are no analogous cancellations—more stuff means greater gravitational force. But fundamentally speaking, gravity is an extremely feeble force. (This fact accounts for the difficulty in experimentally confirming the existence of the graviton. Searching for the smallest bundle of the feeblest force is quite a challenge.) Experiments also have shown that the strong force is about one hundred times as strong as the electromagnetic force and about one hundred thousand times as strong as the weak force. But where is the rationale—the raison d'être—for our universe having these features?

This is not a question borne of idle philosophizing about why certain details happen to be one way instead of another; the universe would be a vastly different place if the properties of the matter and force particles

were even moderately changed. For example, the existence of the stable nuclei forming the hundred or so elements of the periodic table hinges delicately on the ratio between the strengths of the strong and electromagnetic forces. The protons crammed together in atomic nuclei all repel one another electromagnetically; the strong force acting among their constituent quarks, thankfully, overcomes this repulsion and tethers the protons tightly together. But a rather small change in the relative strengths of these two forces would easily disrupt the balance between them, and would cause most atomic nuclei to disintegrate. Furthermore, were the mass of the electron a few times greater than it is, electrons and protons would tend to combine to form neutrons, gobbling up the nuclei of hydrogen (the simplest element in the cosmos, with a nucleus containing a single proton) and, again, disrupting the production of more complex elements. Stars rely upon fusion between stable nuclei and would not form with such alterations to fundamental physics. The strength of the gravitational force also plays a formative role. The crushing density of matter in a star's central core powers its nuclear furnace and underlies the resulting blaze of starlight. If the strength of the gravitational force were increased, the stellar clump would bind more strongly, causing a significant increase in the rate of nuclear reactions. But just as a brilliant flare exhausts its fuel much faster than a slow-burning candle, an increase in the nuclear reaction rate would cause stars like the sun to burn out far more quickly, having a devastating effect on the formation of life as we know it. On the other hand, were the strength of the gravitational force significantly decreased, matter would not clump together at all, thereby preventing the formation of stars and galaxies.

We could go on, but the idea is clear: the universe is the way it is because the matter and the force particles have the properties they do. But is there a scientific explanation for *why* they have these properties?

String Theory: The Basic Idea

String theory offers a powerful conceptual paradigm in which, for the first time, a framework for answering these questions has emerged. Let's first get the basic idea.

The particles in Table 1.1 are the "letters" of all matter. Just like their linguistic counterparts, they appear to have no further internal substructure. String theory proclaims otherwise. According to string theory, if we could examine these particles with even greater precision—a precision many orders of magnitude beyond our present technological capacity—we would find that each is not pointlike, but instead consists of a tiny one-dimensional *loop*. Like an infinitely thin rubber band, each particle contains a vibrating, oscillating, dancing filament that physicists, lacking Gell-Mann's literary flair, have named a *string*. In Figure 1.1 we illustrate this essential idea of string theory by starting with an ordinary piece of matter, an apple, and repeatedly magnifying its structure to reveal its ingredients on ever smaller scales. String theory adds the new microscopic layer of a vibrating loop to the previously known progression from atoms through protons, neutrons, electrons and quarks.[2]

Although it is by no means obvious, we will see in Chapter 6 that this simple replacement of point-particle material constituents with strings resolves the incompatibility between quantum mechanics and general relativity. String theory thereby unravels the central Gordian knot of contemporary theoretical physics. This is a tremendous achievement, but it is only part of the reason string theory has generated such excitement.

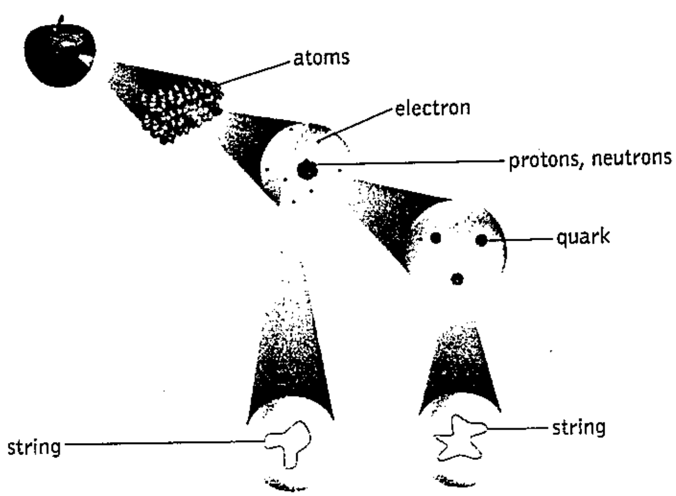

Figure 1.1 Matter is composed of atoms, which in turn are made from quarks and electrons. According to string theory, all such particles are actually tiny loops of vibrating string.

String Theory as the Unified Theory of Everything

In Einstein's day, the strong and the weak forces had not yet been discovered, but he found the existence of even two distinct forces—gravity and electromagnetism—deeply troubling. Einstein did not accept that nature is founded on such an extravagant design. This launched his thirty-year voyage in search of the so-called *unified field theory* that he hoped would show that these two forces are really manifestations of one grand underlying principle. This quixotic quest isolated Einstein from the mainstream of physics, which, understandably, was far more excited about delving into the newly emerging framework of quantum mechanics. He wrote to a friend in the early 1940s, "I have become a lonely old chap who is mainly known because he doesn't wear socks and who is exhibited as a curiosity on special occasions."[3]

Einstein was simply ahead of his time. More than half a century later, his dream of a unified theory has become the Holy Grail of modern physics. And a sizeable part of the physics and mathematics community is becoming increasingly convinced that string theory may provide the answer. From one principle—that everything at its most microscopic level consists of combinations of vibrating strands—string theory provides a single explanatory framework capable of encompassing all forces and all matter.

String theory proclaims, for instance, that the observed particle properties, the data summarized in Tables 1.1 and 1.2, are a reflection of the various ways in which a string can vibrate. Just as the strings on a violin or on a piano have resonant frequencies at which they prefer to vibrate—patterns that our ears sense as various musical notes and their higher harmonics—the same holds true for the loops of string theory. But we will see that, rather than producing musical notes, each of the preferred patterns of vibration of a string in string theory appears as a particle whose mass and force charges are determined by the string's oscillatory pattern. The electron is a string vibrating one way, the up-quark is a string vibrating another way, and so on. Far from being a collection of chaotic experimental facts, particle properties in string theory are the manifestation of one and the same physical feature: the resonant patterns of vibration—the music, so to speak—of fundamental loops of string. The same idea applies to the forces of nature as well. We will see that force particles are also associated with particular patterns of string vibration and hence everything, all matter and all forces, is unified under the same rubric of microscopic string oscillations—the "notes" that strings can play.

For the first time in the history of physics we therefore have a framework with the capacity to explain every fundamental feature upon which the universe is constructed. For this reason string theory is sometimes described as possibly being the "theory of everything" (T.O.E.) or the "ultimate" or "final" theory. These grandiose descriptive terms are meant to signify the deepest possible theory of physics—a theory that underlies all others, one that does not require or even allow for a deeper explanatory base. In practice, many string theorists take a more down-to-earth approach and think of a T.O.E. in the more limited sense of a theory that can explain the properties of the fundamental particles and the properties of the forces by which they interact and influence one another. A staunch reductionist would claim that this is no limitation at all, and that in principle absolutely everything, from the big bang to daydreams, can be described in terms of underlying microscopic physical processes involving the fundamental constituents of matter. If you understand everything about the ingredients, the reductionist argues, you understand everything.

The reductionist philosophy easily ignites heated debate. Many find it fatuous and downright repugnant to claim that the wonders of life and the universe are mere reflections of microscopic particles engaged in a pointless dance fully choreographed by the laws of physics. Is it really the case that feelings of joy, sorrow, or boredom are nothing but chemical reactions in the brain—reactions between molecules and atoms that, even more microscopically, are reactions between some of the particles in Table 1.1, which are really just vibrating strings? In response to this line of criticism, Nobel laureate Steven Weinberg cautions in *Dreams of a Final Theory*,

> At the other end of the spectrum are the opponents of reductionism who are appalled by what they feel to be the bleakness of modern science. To whatever extent they and their world can be reduced to a matter of particles or fields and their interactions, they feel diminished by that knowledge. . . . I would not try to answer these critics with a pep talk about the beauties of modern science. The reductionist worldview *is* chilling and impersonal. It has to be accepted as it is, not because we like it, but because that is the way the world works.[4]

Some agree with this stark view, some don't.

Others have tried to argue that developments such as chaos theory tel us that new kinds of laws come into play when the level of complexity o a system increases. Understanding the behavior of an electron or a quarl is one thing; using this knowledge to understand the behavior of a tornadc is quite another. On this point, most agree. But opinions diverge on whether the diverse and often unexpected phenomena that can occur in systems more complex than individual particles truly represent new physical principles at work, or whether the principles involved are derivative, relying, albeit in a terribly complicated way, on the physical principles governing the enormously large number of elementary constituents. My own feeling is that they do not represent new and independent laws of physics. Although it would be hard to explain the properties of a tornado in terms of the physics of electrons and quarks, I see this as a matter of calculational impasse, not an indicator of the need for new physical laws. But again, there are some who disagree with this view.

What is largely beyond question, and is of primary importance to the journey described in this book, is that even if one accepts the debatable reasoning of the staunch reductionist, principle is one thing and practice quite another. Almost everyone agrees that finding the T.O.E. would in no way mean that psychology, biology, geology, chemistry, or even physics had been solved or in some sense subsumed. The universe is such a wonderfully rich and complex place that the discovery of the final theory, in the sense we are describing here, would not spell the end of science. Quite the contrary: The discovery of the T.O.E.—the ultimate explanation of the universe at its most microscopic level, a theory that does not rely on any deeper explanation—would provide the firmest foundation on which to *build* our understanding of the world. Its discovery would mark a beginning, not an end. The ultimate theory would provide an unshakable pillar of coherence forever assuring us that the universe is a comprehensible place.

The State of String Theory

The central concern of this book is to explain the workings of the universe according to string theory, with a primary emphasis on the implications that these results have for our understanding of space and time. Unlike many other exposés of scientific developments, the one given here does not address itself to a theory that has been completely worked out, confirmed by vigorous experimental tests, and fully accepted by the scientific community. The reason for this, as we will discuss in subsequent chapters, is that string theory is such a deep and sophisticated theoretical structure that even with the impressive progress that has been made over the last two decades, we still have far to go before we can claim to have achieved full mastery.

And so string theory should be viewed as a work in progress whose partial completion has already revealed astonishing insights into the nature of space, time, and matter. The harmonious union of general relativity and quantum mechanics is a major success. Furthermore, unlike any previous theory, string theory has the capacity to answer primordial questions having to do with nature's most fundamental constituents and forces. Of equal importance, although somewhat harder to convey, is the remarkable elegance of both the answers and the framework for answers that string theory proposes. For instance, in string theory many aspects of nature that might appear to be arbitrary technical details—such as the number of distinct fundamental particle ingredients and their respective properties—are found to arise from essential and tangible aspects of the geometry of the universe. If string theory is right, the microscopic fabric of our universe is a richly intertwined multidimensional labyrinth within which the strings of the universe endlessly twist and vibrate, rhythmically beating out the laws of the cosmos. Far from being accidental details, the properties of nature's basic building blocks are deeply entwined with the fabric of space and time.

In the final analysis, though, nothing is a substitute for definitive, testable predictions that can determine whether string theory has truly lifted the veil of mystery hiding the deepest truths of our universe. It may be some time before our level of comprehension has reached sufficient

depth to achieve this aim, although, as we will discuss in Chapter 9, ex[illegible] perimental tests could provide strong circumstantial support for strin[illegible] theory within the next ten years or so. Moreover, in Chapter 13 we will se[illegible] that string theory has recently solved a central puzzle concerning blac[illegible] holes, associated with the so-called Bekenstein-Hawking entropy, that ha[illegible] stubbornly resisted resolution by more conventional means for more tha[illegible] twenty-five years. This success has convinced many that string theory i[illegible] in the process of giving us our deepest understanding of how the univers[illegible] works.

Edward Witten, one of the pioneers and leading experts in string theory, summarizes the situation by saying that "string theory is a part of twenty-first-century physics that fell by chance into the twentieth century," an assessment first articulated by the celebrated Italian physicist Danielle Amati.[5] In a sense, then, it is as if our forebears in the late nineteenth century had been presented with a modern-day supercomputer, without the operating instructions. Through inventive trial and error, hints of the supercomputer's power would have become evident, but it would have taken vigorous and prolonged effort to gain true mastery. The hints of the computer's potential, like our glimpses of string theory's explanatory power, would have provided extremely strong motivation for obtaining complete facility. A similar motivation today energizes a generation of theoretical physicists to pursue a full and precise analytic understanding of string theory.

Witten's remark and those of other experts in the field indicate that it could be decades or even centuries before string theory is fully developed and understood. This may well be true. In fact, the mathematics of string theory is so complicated that, to date, no one even knows the exact equations of the theory. Instead, physicists know only approximations to these equations, and even the approximate equations are so complicated that they as yet have been only partially solved. Nevertheless, an inspiring set of breakthroughs in the latter half of the 1990s—breakthroughs that have answered theoretical questions of hitherto unimaginable difficulty—may well indicate that complete quantitative understanding of string theory is much closer than initially thought. Physicists worldwide are developing powerful new techniques to transcend the numerous approximate methods so far used, collectively piecing together disparate elements of the string theory puzzle at an exhilarating rate.

Surprisingly, these developments are providing new vantage points for reinterpreting some of the basic aspects of the theory that have been in place for some time. For instance, a natural question that may have occurred to you in looking at Figure 1.1 is, Why strings? Why not little frisbee disks? Or microscopic bloblike nuggets? Or a combination of all of these possibilities? As we shall see in Chapter 12, the most recent insights show that these other kinds of ingredients *do* have an important role in string theory, and have revealed that string theory is actually part of an even grander synthesis currently (and mysteriously) named M-theory. These latest developments will be the subject of the final chapters of this book.

Progress in science proceeds in fits and starts. Some periods are filled with great breakthroughs; at other times researchers experience dry spells. Scientists put forward results, both theoretical and experimental. The results are debated by the community, sometimes they are discarded, sometimes they are modified, and sometimes they provide inspirational jumping-off points for new and more accurate ways of understanding the physical universe. In other words, science proceeds along a zig-zag path toward what we hope will be ultimate truth, a path that began with humanity's earliest attempts to fathom the cosmos and whose end we cannot predict. Whether string theory is an incidental rest stop along this path, a landmark turning point, or in fact the final destination we do not know. But the last two decades of research by hundreds of dedicated physicists and mathematicians from numerous countries have given us well-founded hope that we are on the right and possibly final track.

It is a telling testament of the rich and far-reaching nature of string theory that even our present level of understanding has allowed us to gain striking new insights into the workings of the universe. A central thread in what follows will be those developments that carry forward the revolution in our understanding of space and time initiated by Einstein's special and general theories of relativity. We will see that if string theory is correct, the fabric of our universe has properties that would likely have dazzled even Einstein.

Part II

The Dilemma of Space, Time, and the Quanta