BEYOND EINSTEIN

MICHIO KAKU & JENNIFER THOMPSON

The Cosmic Quest for the Theory of the Universe

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Michio Kaku
and Jennifer Thompson

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Introduction

The idea for this book dates back to the mid-1950s, when Michio was a child growing up in California and first heard about the unified field theory.

Michio was in fourth grade when he read about the death of a great scientist, Albert Einstein. He learned that Einstein had discovered many great things in his lifetime that made him world famous, but that he had died before he could finish his greatest work. Michio was fascinated by the story.

If the man was that great, the boy reasoned, then his unfinished project must have been wonderful—the crowning achievement in his illustrious career.

Curious, Michio combed the Palo Alto libraries to discover more about this unified field theory, but he couldn't find any books or articles on the subject. There were a few college texts on quantum mechanics, but at age eight Michio found them largely incomprehensible. Moreover, they didn't make even a passing reference to the unified field theory.

So Michio went to his teachers, who had no answers for him. Even physicists whom he later met would shrug their shoulders when he mentioned Einstein's last theory. Most physicists felt that it was premature, or downright presumptuous, to believe that man could unite the four forces in the universe.

Years later, while working on the string theory (which was being proposed as a theory of strong interactions), Michio too grew cynical, believing that perhaps the search for the unified field theory was a wild goose chase after all. No one took physicists John Schwarz and Joel Scherk seriously in the 1970s when they proclaimed that perhaps a sophisticated version of this string theory was the fabled unified field theory that had eluded Einstein and other physicists.

Finally, in 1984, a dramatic theoretical breakthrough was made that seemed to clinch it. "Superstrings," as Schwarz and Scherk had predicted years earlier, seemed the best (and only) candidate for the unified field theory.

Although the details of the theory are still being worked out, it was clear that this discovery was going to shake the world of physics. Michio and Jennifer Thompson had already coauthored a book, *Nuclear Power: Both Sides,* and it seemed natural to team up again and answer the question that had fascinated Michio thirty years earlier: "What is the unified field theory?"

Together we sought to produce a book that would serve as a guide for the curious layman. We wanted to write a book that covered the "superstring revolution" with the insight and scope that often only an insider can provide, and to present the subject in a lively, informative manner. We felt that our combined experience—as a theoretical physicist and as a writer—worked well in this regard.

We also wanted to provide a comprehensive glimpse of the world of physics, presenting the superstring theory in the context of the last three hundred years of science. Many books address one aspect of modern physics—be it relativity, quantum mechanics, or cosmology —but neglect the larger sweep of physics. *Beyond Einstein* is different; instead of dwelling on isolated areas of research, we focus on the entire scope of physics, pointing out where each particular theory fits into the larger picture. What does the unified field theory have to do with quantum mechanics? How does Newton's theory of gravity apply to the superstring theory? These are a few of the questions answered in *Beyond Einstein.*

In this book, we have stressed how superstring theory gives a unified description of *matter.* We have focused on the diverse properties of the subatomic particles, such as the quarks, leptons, Yang-Mills particles, gluons, and others, and how they can be viewed as different vibrations of the superstring. In a companion volume, *Hyperspace,* Michio focuses instead on the properties of *space and time,* especially the possibility of parallel universes, time warps, and the tenth dimension.

We're excited about the new breakthroughs in physics and we hope we've written a book that is both authoritative and interesting —in short, one that Michio would like to have read when he was young.

New York, N.Y. MICHIO KAKU
Williamstown, Ma. JENNIFER THOMPSON

Note to Oxford Paperback Edition

In an effort to convey the vigorous, fast-paced progress made in superstring theory, we have added a short afterword at the end of the book concerning M-theory, which is perhaps the most advanced version of superstring theory. This is the latest and perhaps most exciting development in superstring theory, which may be decisive in proving the correctness of the theory.

I

A Theory of the Universe

1

Superstrings: A Theory of Everything?

A NEW THEORY is rocking the foundations of modern physics, rapidly overturning cherished but obsolete notions about our universe and replacing them with new mathematics of breathtaking beauty and elegance. Although there are still some unresolved questions concerning this theory, the excitement among physicists is palpable; throughout the world, leading physicists are proclaiming that we are witnessing the genesis of a new physics.

This theory is called "superstrings," and a series of astonishing breakthroughs in physics within the last decade have culminated in its development, indicating that perhaps we are finally closing in on the unified field theory: a comprehensive, mathematical framework that would unite all known forces of the universe.

Advocates of superstrings even claim that the theory could be the ultimate "theory of the universe."

Although physicists are usually cautious in their approach to new ideas, Princeton physicist Edward Witten has claimed that the superstring theory will dominate the world of physics for the next fifty years. "Superstring theory is a miracle, through and through," he said recently. At one physics conference, he astonished his audience by declaring that we may be witnessing a revolution in physics as great as the birth of the quantum theory. He added, "It's probably going to lead to a new understanding of what space and time really are, the most dramatic [understanding] since general relativity.''[1]

Even *Science* magazine, always careful not to exaggerate the claims of scientists, compared the birth of the superstring theory to the discovery of the Holy Grail. This revolution, *Science* magazine claimed, may be ''no less profound than the transition from real numbers to complex numbers in mathematics.''[2]

Two of the theory's creators, John Schwarz of the California Institute of Technology and Michael Green of Queen Mary College in London, call it—a bit puckishly—a Theory of Everything (TOE).[3]

At the heart of this excitement is the realization that superstrings may provide a comprehensive theory that can explain *all* known physical phenomena—everything from the motion of galaxies down to the dynamics within the nucleus of the atom. The theory even makes startling predictions concerning the origin of the universe, the beginning of time, and the existence of multidimensional universes.

To a physicist, it is an intoxicating notion that the vast storehouse of information of our physical universe, painfully accumulated over several thousand years of careful investigation, can be summarized in one theory.

For example, German physicists have compiled an encyclopedia, the *Handbuch der Physik*, an exhaustive work that summarized the world's knowledge of physics. The *Handbuch,* which physically occupies an entire bookshelf of a library, represented the pinnacle of scientific learning. If the superstring theory is correct, then all the information contained in this encyclopedia can be derived (in principle) from *a single equation.*

Physicists are particularly excited about the superstring theory because it forces us to revise our understanding of the nature of matter. Since the time of the Greeks, scientists have assumed that the building blocks of the universe were tiny point particles. Democritus coined the word *atomos* to describe these ultimate, indestructible units of matter.

The superstring theory, however, assumes that the ultimate building blocks of nature consist of tiny vibrating strings. If correct, this means that the protons and neutrons in all matter, everything from our bodies to the farthest star, are ultimately made up of strings. Nobody has seen these strings because they are much too small to be observed. (They are about *100 billion billion* times smaller than a proton.) According to the superstring theory, our world only appears to be made of point particles, because our measuring devices are too crude to see these tiny strings.

At first it seems strange that such a simple concept—replacing point particles with strings—can explain the rich diversity of particles and forces (which are created by the exchange of particles) in nature. The superstring theory, however, is so elegant and comprehensive that it is able to explain simply why there can be billions upon billions of different types of particles and substances in the universe, each with astonishingly diverse characteristics.

The superstring theory can produce a coherent and all-inclusive picture of nature similar to the way a violin string can be used to "unite" all the musical tones and rules of harmony. Historically, the laws of music were formulated only after thousands of years of trial-and-error investigation of different musical sounds. Today, these diverse rules can be derived easily from a single picture—that is, a string that can resonate with different frequencies, each one creating a separate tone of the musical scale. The tones created by the vibrating string, such as C or B flat, are not in themselves any more fundamental than any other tone. What is fundamental, however, is the fact that a single concept, vibrating strings, can explain the laws of harmony.

Knowing the physics of a violin string, therefore, gives us a comprehensive theory of musical tones and allows us to predict new harmonies and chords. Similarly, in the superstring theory, the fundamental forces and various particles found in nature are nothing more than different modes of vibrating strings. The gravitational interaction, for example, is caused by the lowest vibratory mode of a circular string (a loop). Higher excitations of the string create different forms of matter. From the point of view of the superstring theory, no force or particle is more fundamental than any other. All particles are just different vibratory resonances of vibrating strings. Thus, a single framework—the superstring theory—can in principle explain why the universe is populated with such a rich diversity of particles and atoms.

The answer to the ancient question "What is matter?" is simply that matter consists of particles that are different modes of vibration of the string, such as the note G or F. The "music" created by the string is matter itself.

But the fundamental reason why the world's physicists are so excited by this new theory is that it appears to solve perhaps the most important scientific problem of the century: namely, how to unite the four forces of nature into one comprehensive theory. At the center of this upheaval is the realization that the four fundamental forces governing our universe are actually different manifestations of a single unifying force, governed by the superstring.

Four Forces

A force is anything that can move an object. Magnetism, for example, is a force because it can make a compass needle spin. Electricity is a force because it can make our hair stand on end. Over the last two thousand years, we gradually have realized that there are four fundamental forces: gravity, electromagnetism (light), and two types of nuclear forces, the weak and the strong. (Other forces identified by the ancients, such as fire and wind, can be explained in terms of the four forces.) One of the great scientific puzzles of our universe, however, has been why these four forces seemed so different. For the past fifty years, physicists have grappled with the problem of uniting them into a coherent picture.

To help you appreciate the excitement that the superstring theory is generating among physicists, we will take a minute to describe each force and show just how dissimilar they are.

Gravity is an attractive force that binds together the solar system, keeps the earth and the planets in their orbits, and prevents the stars from exploding. In our universe, gravity is the dominant force that extends trillions upon trillions of miles, out to the farthest stars; this force, which causes an apple to fall to the ground and keeps our feet on the floor, is the same force that guides the galaxies in their motions throughout the universe.

The electromagnetic force holds together the atom. It makes the electrons (with negative charge) orbit around the positively charged nucleus of the atom. Because the electromagnetic force determines the structure of the orbits of the electrons, it also governs the laws of chemistry.

On the earth, the electromagnetic force is often strong enough to overpower gravity. By rubbing a comb, for example, it is possible to pick up scraps of paper from a table. The electromagnetic force counteracts the downward force of gravity and dominates the other forces down to .000000000001 inch (roughly the size of a nucleus).

(Perhaps the most familiar form of the electromagnetic force is light. When the atom is disturbed, the motion of the electrons around the nucleus becomes irregular, and the electrons emit light and other forms of radiation. This is the purest form of electromagnetic radiation, in the form of X rays, radar, microwave, or light. Radio and television are simply different forms of the electromagnetic force.)

Within the nucleus of the atom, the electromagnetic force is overpowered by the weak and strong (nuclear) forces. The strong force, for example, is responsible for binding together the protons and neutrons in the nucleus. In any nucleus, all the protons are positively charged. Left to themselves, their repulsive electric force would tear apart the nucleus. The strong force, therefore, overcomes the repulsive force between the protons. Roughly speaking, only a few elements can maintain the delicate balance between the strong force (which tends to hold the nucleus together) and the repulsive electric force (which tends to rip apart the nucleus), which helps to explain why there are only about one hundred known elements in nature. Should a nucleus contain more than about a hundred protons, even the strong nuclear force would have difficulty containing the repulsive electric force between them.

When the strong nuclear force is unleashed, the effect can be catastrophic. For example, when the uranium nucleus in an atomic bomb is split deliberately, the enormous energies locked within the nucleus are released explosively in the form of a nuclear detonation. Pound for pound, a nuclear bomb releases over a million times the energy contained in dynamite. Indeed, the strong force can yield significantly more energy than a chemical explosive, which is governed by the electromagnetic force.

The strong force also explains the reason why stars shine. A star is basically a huge nuclear furnace in which the strong force within the nucleus is unleashed. If the sun's energy, for example, were created by burning coal instead of nuclear fuel, only a minuscule fraction of the sun's light would be produced. The sun would rapidly fizzle and turn into a cinder. Without sunlight, the earth would turn cold and life on it would eventually die. Without the strong force, therefore, the stars would not shine, there would be no sun, and life on earth would be impossible.

If the strong force were the only force at work inside the nucleus, then most nuclei would be stable. However, we know from experience that certain nuclei (such as uranium, with ninety-two protons) are so massive that they automatically break apart, releasing smaller fragments and debris, which we call radioactivity. In these elements the nucleus is unstable and disintegrates. Therefore, yet another, weaker force must be at work, one that governs radioactivity and is responsible for the disintegration of very heavy nuclei. This is the weak force.

The weak force is so fleeting and ephemeral that we do not experience it directly in our lives. However, we feel its indirect effects. When a Geiger counter is placed next to a piece of uranium, the clicks that we hear measure the radioactivity of the nuclei, which is caused by the weak force. The energy released by the weak force can also be used to create heat. For example, the intense heat found in the interior of the earth is partially caused by the decay of radioactive elements deep in the earth's core. This tremendous heat, in turn, can erupt in volcanic fury if it reaches the earth's surface. Similarly, the heat released by the core of a nuclear power plant, which can generate enough electricity to light up a city, also is caused by the weak force (as well as the strong force).

Without these four forces, life would be unimaginable: The atoms of our bodies would disintegrate, the sun would burst, and the atomic fires lighting the stars and galaxy would be snuffed out. The idea of forces, therefore, is an old and familiar one, dating back at least to Isaac Newton. What is new is the idea that these forces are nothing but different manifestations of a single force.

Everyday experience demonstrates the fact that an object can manifest itself in a variety of forms. Take a glass of water and heat it until it boils and turns into steam. Water, normally a liquid, can turn into steam, a gas, with properties quite unlike any liquid, but it is still water. Now freeze the glass of water into ice. By withdrawing heat, we can transform this liquid into a solid. But it is still water—

the same substance—merely turned into a new form under certain circumstances.

Another, more dramatic example is the fact that a rock can turn into light. Under specific conditions, a piece of rock can turn into vast quantities of energy, especially if that rock is uranium, and the energy manifests itself in an atomic bomb. Matter, then, can manifest itself in two forms—either as a material object (uranium) or as energy (radiation).

In much the same way, scientists have realized over the past hundred years that electricity and magnetism are manifestations of the same force. Only within the last twenty-five years, however, have scientists understood that even the weak force can be treated as a manifestation of the same force. The Nobel Prize in 1979 was awarded to three physicists (Steven Weinberg, Sheldon Glashow, and Abdus Salam) who showed how to unite the weak and the electromagnetic forces into one force, called the "electro-weak" force. Similarly, physicists now believe that another theory (called the GUT, or "grand unified theory") may unite the electro-weak force with the strong interactions.

But the final force—gravity—has long eluded physicists. In fact, gravity is so unlike the other forces that, for the past sixty years, scientists have despaired of uniting it with the others. Although quantum mechanics spectacularly united the other three forces, it failed dismally when applied to gravity.

The Missing Link

In the twentieth century, two great theories have towered above all others: quantum mechanics, with its resounding success in explaining the three subatomic forces, and Einstein's theory of gravity, called general relativity. In some sense, these two theories are opposites: While quantum mechanics is devoted to the world of the very small—such as atoms, molecules, protons, and neutrons—relativity governs the physics of the very large, on the cosmic scale of stars and galaxies.

To physicists, one of the great puzzles of this century has been that these two theories, from which we can in principle derive the sum total of human knowledge of our physical universe, should be so incompatible. In fact, merging quantum mechanics with general relativity has defied all attempts by the world's greatest minds in this century. Even Albert Einstein spent the last three decades of his life on a futile search for a unifying theory that would include gravity and light.

Each of these two theories, in its particular domain, has scored spectacular successes. Quantum mechanics, for example, has no rival in explaining the secrets of the atom. Quantum mechanics has unraveled the secrets of nuclear physics, unleashed the power of the hydrogen bomb, and explained the workings of everything from transistors to lasers. In fact, the theory is so powerful that, if we had enough time, we could predict all the properties of the chemical elements by computer, without ever having to enter a laboratory. However, although quantum mechanics has been undeniably successful in explaining the world of the atom, the theory fails when trying to describe the gravitational force.

On the other hand, general relativity has scored brilliant successes in its own domain: the cosmic scale of galaxies. The black hole, which physicists believe is the ultimate state of a massive, dying star, is a well-known prediction of general relativity. General relativity also predicts that the universe originally started in a Big Bang that sent the galaxies hurtling away from one another at enormous speeds. The theory of general relativity, however, cannot explain the behavior of atoms and molecules.

So, physicists were faced with two distinct theories, each employing a different set of mathematics, each making astonishingly accurate predictions within its own realm, each profoundly separate and distinct.

It's as if nature created someone with two hands, with the right hand looking entirely different and functioning totally independently from the left hand. For physicists, who believe that nature ultimately should be simple and elegant, it was a puzzle; they could not believe that nature could function in such a bizarre fashion.

This is where superstrings enter the picture, for they may solve the problem of how to embrace these two great theories. In fact, both halves—quantum mechanics and relativity—are *necessary* to make the superstring theory work. Superstrings are the first and *only* mathematical framework in which a quantum theory of gravity makes sense. It's as if scientists for the past six decades were trying to assemble a cosmic jigsaw puzzle and suddenly noticed that the missing piece were superstrings.

Stranger Than Science Fiction

Ordinarily, scientists are conservative. They are slow to accept new theories, especially those that make predictions that are the least bit strange. The superstring theory, however, makes some of the wildest predictions of any theory ever proposed. Any theory that has the ability to condense the essence of so much physics into one equation will have profound physical consequences, and this theory is no exception.

(In 1958, the great quantum physicist Niels Bohr attended a talk given by physicist Wolfgang Pauli. At the end of the talk, which the audience received unfavorably, Bohr remarked, "We all agree that your theory is crazy. The question which divides us is whether it is crazy enough." Superstring theory, because of its bizarre predictions, is certainly "crazy enough.")

Although these predictions are discussed fully in ensuing chapters, a few of them are touched on here, to provide a glimpse of what people mean when they say that superstrings suddenly make real physics look stranger than science fiction.

MULTIDIMENSIONAL UNIVERSES

In the 1920s, Einstein's general theory of relativity provided the best explanation of how our universe began. According to Einstein's theory, the universe was born approximately 10 to 20 billion years ago in a gigantic explosion called the Big Bang. All the matter in the universe, including the stars, galaxies, and planets, was originally concentrated in one superdense ball, which exploded violently, creating our current expanding universe. This theory explains the observed fact that all the stars and galaxies are currently moving away from the earth (propelled by the force of the Big Bang).

However, there were many gaps in Einstein's theory. Why did the universe explode? What happened before the Big Bang? Theologians as well as scientists have for years realized the incompleteness of the Big Bang theory, because it fails to explain the origin and nature of the Big Bang itself.

Incredibly, the superstring theory predicts what happened before the Big Bang. According to superstrings, the universe originally existed in ten dimensions, not the four dimensions (three space dimensions and one time dimension) of today. However, because the universe was unstable in ten dimensions, it "cracked" into two pieces, with a small, four-dimensional universe peeling off from the rest of the universe. By analogy, imagine a soap bubble that is vibrating slowly. If the vibrations become strong enough, the soap bubble becomes unstable and fissions into two or more smaller soap bubbles. Imagine that the original soap bubble represents the ten-dimensional universe, and that one of the smaller soap bubbles represents our universe.

If this theory is true, it means that our universe actually has a "sister universe" that coexists with our universe. It also means that the original fissioning of our universe was so violent that it created the explosion that we know as the Big Bang. The superstring theory, therefore, explains the Big Bang as a by-product of a much more violent transition, the cracking of the ten-dimensional universe into two pieces.

You do not have to worry, however, that one day as you are walking down the street you will "fall" into another other-dimensional universe as if in a science fiction novel. According to the superstring theory, the other multidimensional universe has shrunk to such an incredibly small size (about 100 billion billion times smaller than the nucleus of an atom) that it can never be reached by humans. Thus, it becomes an academic question what higher dimensions look like. In this sense, the prospect of traveling between higher dimensions was possible only at the origin of the universe, when the universe was ten-dimensional and interdimensional travel was physically possible.

DARK MATTER

In addition to multidimensional spaces, science fiction writers sometimes spice up their novels with talk of "dark matter," a mysterious form of matter with properties unlike any found in the universe.

Dark matter was predicted in the past, but wherever scientists trained their telescopes and instruments in the heavens, they found only the hundred or so familiar chemical elements existing on the earth. Even stars in the farthest reaches of the universe are made of ordinary hydrogen, helium, oxygen, carbon, et cetera. On one hand, this was reassuring; we knew that wherever we traveled in outer space, our rocket ships would encounter only the chemical elements found on the earth. On the other hand, it was a bit disappointing knowing that there would be no surprises in outer space.

The superstring theory might possibly change that, for the process of fissioning from a ten-dimensional universe down to smaller universes probably created a new form of matter. This dark matter has weight, like all matter, but is invisible (hence the name). Dark matter is also tasteless and has no smell. Even our most sensitive instruments cannot detect its presence. If you could hold this dark matter in your hand, it would feel heavy, but it would otherwise be undetectable. In fact, the only way to detect dark matter is by its weight: it has no other known interaction with other forms of matter.

Dark matter also may help to explain one of the puzzles of cosmology. If there is sufficient matter in the universe, then the gravitational attraction of the galaxies should slow down its expansion and even possibly reverse it, causing the universe to collapse. However, there is conflicting data as to whether there is enough matter in the universe to cause this reversal and eventual collapse. Astronomers who have tried to calculate the total amount of matter in the visible universe find that there is simply not enough matter in stars and galaxies to cause the universe to collapse. However, other calculations (based on calculating the red shifts and luminosities of stars) indicate that the universe might collapse. This is called the "missing mass" problem.

If the superstring theory is correct, then it may explain why astronomers fail to see this form of matter in their telescopes and instruments. Moreover, if the theory of dark matter is correct, dark matter may pervade the universe. (Indeed, there may be more dark matter than ordinary matter.) In this regard, the superstring theory not only clarifies what happened before the Big Bang but predicts what may happen at the death of the universe.

Super Skeptics

Of course, any theory that makes claims of this magnitude—to replace point particles with strings and a four-dimensional universe with a ten-dimensional one—invites skepticism. Although the superstring theory opens up a vista of mathematics that has startled even the mathematicians and has excited physicists from around the world, it may take years or even decades before we can build machines powerful enough to test the theory conclusively. Meanwhile, until there is irrefutable experimental proof, skeptics remain unconvinced of the superstring theory, despite its beauty, elegance, and uniqueness.

"Years of intense effort," complained Harvard physicist Sheldon Glashow, "by dozens of the best and the brightest have yielded not one verifiable prediction, nor should any soon be expected."[4]

World-renowned Dutch physicist Gerard 't Hooft, speaking at the Argonne National Laboratory outside Chicago, went so far as to compare the fanfare surrounding superstrings to "American television commercials"[5]—all advertisement and very little substance.

Indeed, as Princeton physicist Freeman Dyson once cautioned, referring in general to the search for a single mathematical model that would describe the unification of all four forces: "The ground of physics is littered with the corpses of unified theories."[6]

But superstrings' defenders point out that, although a decisive experiment that could prove the theory may be years away, there are no experiments that contradict the theory. No other theory can make that claim.

Indeed, the theory has no rival: There is no other way at the present time to marry the quantum and relativity theories consistently. Some physicists are skeptical of new attempts to find a unifying theory because so many attempts failed in the past, but these attempts failed because they could not unite gravity with quantum mechanics. The superstring theory, however, seems to accomplish this; it does not suffer from the disease that killed off its predecessors. Because of this, the superstring theory is by far the most promising candidate for a true unification of all forces.

THE SSC—LARGEST SCIENTIFIC MACHINE IN HISTORY

The world of physics, which is closing in on a unified description of the weak, the electromagnetic, the strong, and possibly the gravitational interactions, has spawned efforts to create powerful machines to test certain aspects of these theories. These theories are not matters of idle speculation but are the focal point of intense international interest.

For much of the 1980s, the U.S. government was committed to spending billions to build a colossal "atom smasher" or particle accelerator to probe deep into the atom's nucleus. This machine, called the Superconducting Super Collider (SSC), would have been the largest scientific machine ever built; however, the project was cancelled in 1993.

The primary mission of the SSC was to find new interactions and test the predictions of these unified theories, such as the electroweak theory, and possibly probe the fringers of the GUT and the superstring theory. This powerful machine would have focused on various aspects of the search for this fabled unification. Devouring enough energy to power a large metropolis, the SSC would have accelerated particles to trillions of electron volts in order to smash other subatomic particles. Physicists were hoping that locked deep within the nucleus of the atom was the crucial data necessary to verify some aspects of these theories.

The SSC, which would have dominated experimental high-energy physics into the next century, would still not have been large enough to test fully the consequences of the GUT theory, which unites the strong force with the electro-weak force, or the more ambitious superstring theory, which unites all known forces. Testing the predictions of both these theories would require machines vastly larger than the SSC. However, the SSC may have been able to probe the periphery of these theories and help us indirectly to verify or disprove various predictions of these theories.

With the collapse of the SSC, the hope of high energy physicists now rests with a smaller machine, the Large Hadron Collider (LHC), which is being built at CERN, outside Geneva, Switzerland, by a consortium of European nations. Although its financing is also a bit tenuous, physicists hope that, early in the next century, the LHC may be powerful enough to discover a new class of particles which would represent the lowest vibrations of the superstring. Although the discovery of these new particles would not be direct proof of the theory, it would provide perhaps the most compelling evidence for the correctness of superstring theory.

Experimentally, because the energies needed to probe the GUT and superstring theories are so fabulously large, the ultimate verification may come from the field of cosmology (the study of the origin of the universe). In fact, the energy scale in which this unification takes place can be found only at the beginning of time. In this sense solving the puzzle of the unified field theory may well solve the riddle of the origin of the universe.

But we are getting ahead of our story. Before one can build a house, one must first lay a foundation. So, too, in physics: Before we can explore in detail how the superstring theory unifies all forces, we must first answer some basic questions, such as: What is relativity? What is matter? Where did the idea of unification originate? These questions are the focus of the following two chapters.

2

The Quest for Unification

HISTORICALLY, science has developed rather disjointedly. The great contributions of Isaac Newton, for example, who computed the motions of the planets with his theory of gravitation, differ significantly from the works of Werner Heisenberg and Erwin Schrödinger, who revealed the workings of the atom with their quantum mechanics. Moreover, the mathematics and principles required for quantum mechanics seem dissimilar to Einstein's general theory of relativity, which describes space warps, black holes, and the Big Bang.

With developments in the unified field theory, however, it now becomes possible to assemble these disjointed pieces and view the whole as more than just the sum of its parts. Although the quest for unification is a recent one, with most of the pioneering work done in the past twenty years, in hindsight it is possible to reanalyze many of the great discoveries in science in terms of the coherent concept of unification.

Due to the momentum created by the unified field theory, the history of science is slowly being rewritten—beginning with the man who practically invented physics, Isaac Newton, and his discovery of the universal law of gravitation, easily the most significant scientific development in several millennia of human history.

Uniting the Heavens and the Earth

Newton lived in the late 1600s, when the church and scholars of the day believed in two distinct types of laws. The laws governing the heavens were perfect and harmonious, while mortals on earth lived under physical laws that were coarse and vulgar.

Anyone who insisted that the moon wasn't a perfect, polished sphere, or that the earth revolved around the sun, could be put to death by the church. Giordano Bruno was burned at the stake in 1600 in Rome for speculating that our sun was just another star and concluding that "there are then innumerable suns, and an infinite number of earths revolve around those suns. . . ."[1] A few decades later, the great astronomer and physicist Galileo Galilei had to recant, on pain of death, his heretical statements that the earth moved around the sun. (Even as he was forced to repudiate his scientific findings at his trial, he is said to have muttered under his breath, "But the earth does move!")

All this began to change when Isaac Newton, a twenty-three-year-old student, was sent home from Cambridge University because the dreaded Black Plague was sweeping the land and had closed down most of the universities and other institutions in Europe. With plenty of time on his hands, Newton observed the motion of objects that fall to the earth and then, in a stroke of brilliance, conceived of his famous theory, which governs the path of all falling objects.

Newton was led to his theory by asking himself such revolutionary questions as: Does the moon also fall?

According to the church, the moon stayed in the sky because it obeyed heavenly laws that were beyond the reach of earthly laws that forced objects to fall to the ground. Newton's revolutionary observation was to extend the law of gravitation into the heavens itself. An immediate conclusion of this heretical idea was that the moon was a satellite of the earth, held in the sky not by the motion of imaginary celestial spheres but by the laws of his gravitation theory.

Perhaps, Newton thought, the moon is continually falling, guided by the same laws that make a rock fall to the earth, but the moon never crashes to the earth because the earth's receding curvature cancels the falling motion. In his masterpiece, *Principia,* Newton wrote down the laws that govern the motion of satellites orbiting the earth and planets orbiting the sun.

Newton drew a simple picture that explained this idea of the falling moon being an earth satellite. Imagine standing on a high mountaintop and throwing a rock, which eventually falls to the earth. The faster you throw the rock, the farther it goes before it falls to the earth. In fact, argued Newton, if the rock were thrown with sufficient velocity, it would circle the earth and hit you in the back of your head. Like a rock circling the earth, the moon is simply a satellite continually falling to the earth.

This elegant picture conceived by Newton predated the launching of artificial satellites by three centuries. Today, the stunning achievements of our space probes, which have landed on Mars and flown past Uranus and Neptune, owe their success to the laws written down by Newton in the late 1600s.

In a rapid series of insights, Newton discovered that his equations allowed him, in principle, to estimate roughly the distance from the earth to the moon and the distance from the earth to the sun. While the church was still teaching that the earth stood still in the heavens, Isaac Newton was calculating the basic dimensions of the solar system.

In retrospect, we can appreciate Newton's discovery of the law of gravitation as the first "unification" in the history of science, uniting the laws of heaven and earth. The same force of gravitation, which acts instantaneously between any two bodies on the earth, linked the destiny of humans with the stars. After Newton's discovery, the motion of the entire solar system could be calculated with almost perfect accuracy.

Furthermore, Newton's diagram showing how even terrestrial rocks can orbit the earth without needing celestial spheres demonstrated that he was able to isolate the essential principles of his theory pictorially. Interestingly, all the great breakthroughs in science, especially those showing the unification of forces, can be displayed graphically. Although the mathematics may be obscure and tedious, the essence of unification is always pictorially quite simple.

Maxwell's Discovery

The next great leap in our understanding of unification—that of electricity and magnetism—took place two hundred years later, in the mid-1860s, during the American Civil War. While the United States was thrown into chaos by that devastating war, across the Atlantic the world of science was also in a period of great turmoil. Experiments being performed in Europe pointed to the unmistakable fact that magnetism, under certain circumstances, can turn into an electric field, and vice versa.

For centuries it was thought that magnetism, the force that guides the compass needles of navigators while at sea, and electricity, the force that creates everything from lightning bolts to the shock upon touching a doorknob after walking across a carpet, were distinct forces. However, by the mid-1800s, this rigid separation was falling apart as scientists realized that vibrating electric fields could create magnetic ones, and vice versa.

This effect can be demonstrated easily. For example, simply by shoving a bar magnet into a coil of wire we can generate a small electric current within the wire. Thus, a changing magnetic field has created an electric field. Similarly, we can reverse this demonstration by running an electric current through this coil of wire, thereby producing a magnetic field around the coil. Thus, a changing electric field has now created a magnetic field.

This same principle—that changing electric fields can produce magnetic fields and vice versa—is the reason why we have electricity in our homes. In a hydroelectric plant, water falling over a dam rotates a huge wheel connected to a turbine. The turbine contains large wire coils that spin rapidly in a magnetic field. Electricity is created by the spinning motion of these coils as they move in the magnetic field. This electricity, in turn, is sent over hundreds of miles of wires into our homes. Thus, a changing magnetic field (created by the dam) is transformed into an electric field (which brings electricity into our homes through our wall sockets).

In 1860, however, this effect was understood poorly. An obscure thirty-year-old Scottish physicist at Cambridge University, James Clerk Maxwell, challenged the prevailing thinking of the day and

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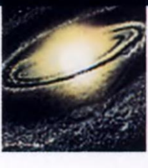

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