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- Group 4: The Classified

HYPERSPACE

A Scientific Odyssey Through Parallel Universes, Time Warps, and the Tenth Dimension

Michio Kaku

Illustrations by Robert O'Keefe

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The nature of my world was beyond their comprehension. I was intrigued that I could sit only a few inches from the carp, yet be separated from them by an immense chasm. The carp and I spent our lives in two distinct universes, never entering each other's world, yet were separated by only the thinnest barrier, the water's surface.

I once imagined that there may be carp "scientists" living among the fish. They would, I thought, scoff at any fish who proposed that a parallel world could exist just above the lilies. To a carp "scientist," the only things that were real were what the fish could see or touch. The pond was everything. An unseen world beyond the pond made no scientific sense.

Once I was caught in a rainstorm. I noticed that the pond's surface was bombarded by thousands of tiny raindrops. The pond's surface became turbulent, and the water lilies were being pushed in all directions by water waves. Taking shelter from the wind and the rain, I wondered how all this appeared to the carp. To them, the water lilies would appear to be moving around by themselves, without anything pushing them. Since the water they lived in would appear invisible, much like the air and space around us, they would be baffled that the water lilies could move around by themselves.

Their "scientists," I imagined, would concoct a clever invention called a "force" in order to hide their ignorance. Unable to comprehend that there could be waves on the unseen surface, they would conclude that lilies could move without being touched because a mysterious, invisible entity called a force acted between them. They might give this illusion impressive, lofty names (such as action-at-a-distance, or the ability of the lilies to move without anything touching them).

Once I imagined what would happen if I reached down and lifted one of the carp "scientists" out of the pond. Before I threw him back into the water, he might wiggle furiously as I examined him. I wondered how this would appear to the rest of the carp. To them, it would be a truly unsettling event. They would first notice that one of their "scientists" had disappeared from their universe. Simply vanished, without leaving a trace. Wherever they would look, there would be no evidence of the missing carp in their universe. Then, seconds later, when I threw him back into the pond, the "scientist" would abruptly reappear out of nowhere. To the other carp, it would appear that a miracle had happened.

After collecting his wits, the "scientist" would tell a truly amazing story. "Without warning," he would say, "I was somehow lifted out of the universe (the pond) and hurled into a mysterious nether world, with blinding lights and strangely shaped objects that I had never seen before. The strangest of all was the creature who held me prisoner, who did not resemble a fish in the slightest. I was shocked to see that it had no fins whatsoever, but nevertheless could move without them. It struck me that the familiar laws of nature no longer applied in this nether world. Then, just as suddenly, I found myself thrown back into our universe." (This story, of course, of a journey beyond the universe would be so fantastic that most of the carp would dismiss it as utter poppycock.)

I often think that we are like the carp swimming contentedly in that pond. We live out our lives in our own "pond," confident that our universe consists of only those things we can see or touch. Like the carp, our universe consists of only the familiar and the visible. We smugly refuse to admit that parallel universes or dimensions can exist next to ours, just beyond our grasp. If our scientists invent concepts like forces, it is only because they cannot visualize the invisible vibrations that fill the empty space around us. Some scientists sneer at the mention of higher dimensions because they cannot be conveniently measured in the laboratory.

Ever since that time, I have been fascinated by the possibility of other dimensions. Like most children, I devoured adventure stories in which time travelers entered other dimensions and explored unseen parallel universes, where the usual laws of physics could be conveniently suspended. I grew up wondering if ships that wandered into the Bermuda Triangle mysteriously vanished into a hole in space; I marveled at Isaac Asimov's Foundation Series, in which the discovery of hyperspace travel led to the rise of a Galactic Empire.

A second incident from my childhood also made a deep, lasting impression on me. When I was 8 years old, I heard a story that would stay with me for the rest of my life. I remember my schoolteachers telling the class about a great scientist who had just died. They talked about him with great reverence, calling him one of the greatest scientists in all history. They said that very few people could understand his ideas, but that his discoveries changed the entire world and everything around us. I didn't understand much of what they were trying to tell us, but what most intrigued me about this man was that he died before he could complete his greatest discovery. They said he spent years on this theory, but he died with his unfinished papers still sitting on his desk.

I was fascinated by the story. To a child, this was a great mystery. What was his unfinished work? What was in those papers on his desk? What problem could possibly be so difficult and so important that such a great scientist would dedicate years of his life to its pursuit? Curious, I

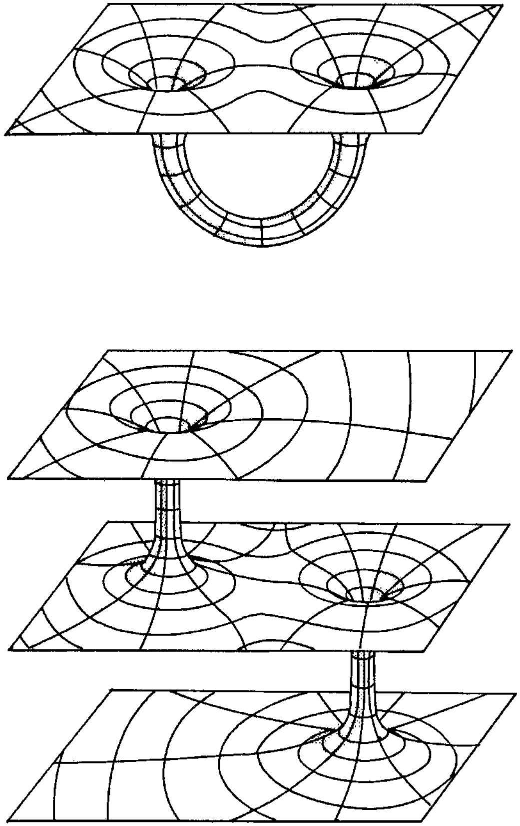

Figure 1.2. Wormholes may connect a universe with itself, perhaps providing a means of interstellar travel. Since wormholes may connect two different time eras, they may also provide a means for time travel. Wormholes may also connect an infinite series of parallel universes. The hope is that the hyperspace theory will be able to determine whether wormholes are physically possible or merely a mathematical curiosity.

Field Theory: The Language of Physics

Fields were first introduced by the great nineteenth-century British scientist Michael Faraday. The son of a poor blacksmith, Faraday was a self-taught genius who conducted elaborate experiments on electricity and magnetism. He visualized "lines of force" that, like long vines spreading from a plant, emanated from magnets and electric charges in all directions and filled up all of space. With his instruments, Faraday could measure the strength of these lines of force from a magnetic or an electric charge at any point in his laboratory. Thus he could assign a series of numbers (the strength and direction of the force) to that point (and any point in space). He christened the totality of these numbers at any point in space, treated as a single entity, a field. (There is a famous story concerning Michael Faraday. Because his fame had spread far and wide, he was often visited by curious bystanders. When one asked what his work was good for, he answered, "What is the use of a child? It grows to be a man." One day, William Gladstone, then Chancellor of the Exchequer, visited Faraday in his laboratory. Knowing nothing about science, Gladstone sarcastically asked Faraday what use the huge electrical contraptions in his laboratory could possibly have for England. Faraday replied, "Sir, I know not what these machines will be used for, but I am sure that one day you will tax them." Today, a large portion of the total wealth of England is invested in the fruit of Faraday's labors.)

Simply put, a *field* is a collection of numbers defined at every point in space that completely describes a force at that point. For example, three numbers at each point in space can describe the intensity and direction of the magnetic lines of force. Another three numbers everywhere in space can describe the electric field. Faraday got this concept when he thought of a "field" plowed by a farmer. A farmer's field occupies a two-dimensional region of space. At each point in the farmer's field, one can assign a series of numbers (which describe, for example, how many seeds there are at that point). Faraday's field, however, occupies a three-dimensional region of space. At each point, there is a series of six numbers that describes both the magnetic and electric lines of force.

What makes Faraday's field concept so powerful is that all forces of nature can be expressed as a field. However, we need one more ingredient before we can understand the nature of any force: We must be able to write down the equations that these fields obey. The progress of the past hundred years in theoretical physics can be succinctly summarized as the search for the *field equations* of the forces of nature.

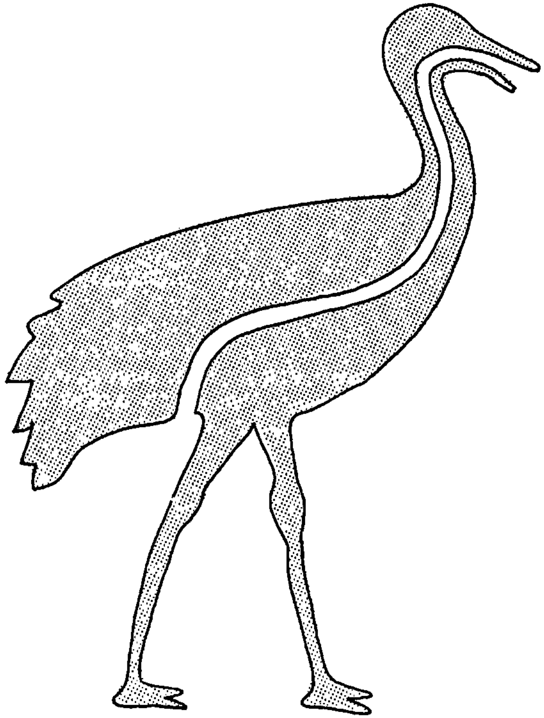

Figure 2.5. A two-dimensional being cannot eat. Its digestive tract necessarily divides it into two distinct pieces, and the being falls apart.

popularizing the idea for the general public. Hermann von Helmholtz, perhaps the most famous German physicist of his generation, was deeply affected by Riemann's work and wrote and spoke extensively to the general public about the mathematics of intelligent beings living on a ball or sphere.

According to Helmholtz, these creatures, with reasoning powers similar to our own, would independently discover that all of Euclid's pos-

tulates and theorems were useless. On a sphere, for example, the sums of the interior angles of a triangle do not add up to 180 degrees. The "bookworms" first talked about by Gauss now found themselves inhabiting Helmholtz's two-dimensional spheres. Helmholtz wrote that "geometrical axioms must vary according to the kind of space inhabited by beings whose powers of reasoning are quite in conformity with ours."[9] However, in his *Popular Lectures of Scientific Subjects* (1881), Helmholtz warned his readers that it is impossible for us to visualize the fourth dimension. In fact, he said "such a 'representation' is as impossible as the 'representation' of colours would be to one born blind."[10]

Some scientists, marveling at the elegance of Riemann's work, tried to find physical applications for such a powerful apparatus.[11] While some scientists were exploring the applications of higher dimension, other scientists asked more practical, mundane questions, such as: How does a two-dimensional being eat? In order for Gauss's two-dimensional people to eat, their mouths would have to face to the side. But if we now draw their digestive tract, we notice that this passageway completely bisects their bodies (Figure 2.5). Thus if they eat, their bodies will split into two pieces. In fact, any tube that connects two openings in their bodies will separate them into two unattached pieces. This presents us with a difficult choice. Either these people eat like we do and their bodies break apart, or they obey different laws of biology.

Unfortunately, the advanced mathematics of Riemann outstripped the relatively backward understanding of physics in the nineteenth century. There was no physical principle to guide further research. We would have to wait another century for the physicists to catch up with the mathematicians. But this did not stop nineteenth-century scientists from speculating endlessly about what beings from the fourth dimension would look like. Soon, they realized that such a fourth-dimensional being would have almost God-like powers.

To Be a God

Imagine being able to walk through walls.

You wouldn't have to bother with opening doors; you could pass right through them. You wouldn't have to go around buildings; you could enter them through their walls and pillars and out through the back wall. You wouldn't have to detour around mountains; you could step right into them. When hungry, you could simply reach through the

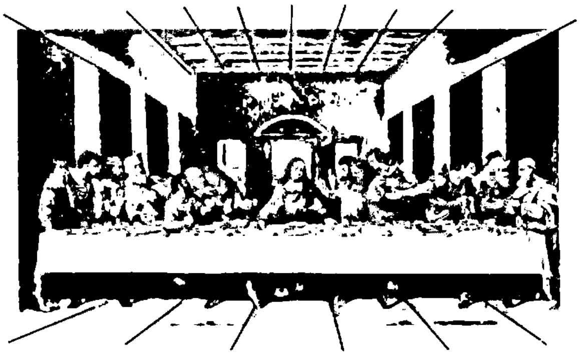

Figure 3.4. During the Renaissance, painters discovered the third dimension. Pictures were painted with perspective and were viewed from the vantage point of a single eye, not God's eye. Note that all the lines in Leonardo da Vinci's fresco The Last Supper *converge to a point at the horizon. (Bettmann Archive)*

nous comet soaring overhead in April 1066, convinced that it is an omen of impending defeat. (Six centuries later, the same comet would be christened Halley's comet.) Harold subsequently lost the crucial Battle of Hastings to William the Conqueror, who was crowned the king of England, and a new chapter in English history began. However, the Bayeux Tapestry, like other medieval works of art, depicts Harold's soldiers' arms and faces as flat, as though a plane of glass had been placed over their bodies, compressing them against the tapestry.

Renaissance art was a revolt against this flat God-centered perspective, and man-centered art began to flourish, with sweeping landscapes and realistic, three-dimensional people painted from the point of view of a person's eye. In Leonardo da Vinci's powerful studies on perspective, we see the lines in his sketches vanishing into a single point on the horizon. Renaissance art reflected the way the eye viewed the world, from the singular point of view of the observer. In Michelangelo's frescoes or in da Vinci's sketch book, we see bold, imposing figures jumping out of the second dimension. In other words, Renaissance art discovered the third dimension (Figure 3.4).

With the beginning of the machine age and capitalism, the artistic world revolted against the cold materialism that seemed to dominate

industrial society. To the Cubists, positivism was a straitjacket that confined us to what could be measured in the laboratory, suppressing the fruits of our imagination. They asked: Why must art be clinically "realistic"? This Cubist "revolt against perspective" seized the fourth dimension because it touched the third dimension from all possible perspectives. Simply put, Cubist art embraced the fourth dimension.

Picasso's paintings are a splendid example, showing a clear rejection of the perspective, with women's faces viewed simultaneously from several angles. Instead of a single point of view, Picasso's paintings show multiple perspectives, as though they were painted by someone from the fourth dimension, able to see all perspectives simultaneously (Figure 3.5).

Picasso was once accosted on a train by a stranger who recognized him. The stranger complained: Why couldn't he draw pictures of people the way they actually were? Why did he have to distort the way people looked? Picasso then asked the man to show him pictures of his family. After gazing at the snapshot, Picasso replied, "Oh, is your wife really that small and flat?" To Picasso, any picture, no matter how "realistic," depended on the perspective of the observer.

Abstract painters tried not only to visualize people's faces as though painted by a four-dimensional person, but also to treat time as the fourth dimension. In Marcel Duchamp's painting *Nude Descending a Staircase,* we see a blurred representation of a woman, with an infinite number of her images superimposed over time as she walks down the stairs. This is how a four-dimensional person would see people, viewing all time sequences at once, if time were the fourth dimension.

In 1937, art critic Meyer Schapiro summarized the influence of these new geometries on the art world when he wrote, "Just as the discovery of non-Euclidean geometry gave a powerful impetus to the view that mathematics was independent of existence, so abstract painting cut at the roots of the classic ideas of artistic imitation." Or, as art historian Linda Henderson has said, "the fourth dimension and non-Euclidean geometry emerge as among the most important themes unifying much of modern art and theory."[5]

Bolsheviks and the Fourth Dimension

The fourth dimension also crossed over into Czarist Russia via the writings of the mystic P. D. Ouspensky, who introduced Russian intellectuals to its mysteries. His influence was so pronounced that even Fyodor Doslike an accordion. The train, I imagine, would be a flattened slab of metal 1 foot thick, barreling down the tracks. And everyone inside the subway cars would be as thin as paper. They would also be virtually frozen in time, as though they were motionless statues. However, as the train comes to a grinding halt, it suddenly expands, until this slab of metal gradually fills the entire station.

As absurd as these distortions might appear, the passengers inside the train would be totally oblivious to these changes. Their bodies and space itself would be compressed along the direction of motion of the train; everything would appear to have its normal shape. Furthermore, their brains would have slowed down, so that everyone inside the train would act normally. Then when the subway train finally comes to a halt, they are totally unaware that their train, to someone on the platform, appears to miraculously expand until it fills up the entire platform. When the passengers depart from the train, they are totally oblivious to the profound changes demanded by special relativity.*

The Fourth Dimension and High-School Reunions

There have been, of course, hundreds of popular accounts of Einstein's theory, stressing different aspects of his work. However, few accounts capture the essence behind the theory of special relativity, which is that time is the fourth dimension and that the laws of nature are simplified and unified in higher dimensions. Introducing time as the fourth dimension overthrew the concept of time dating all the way back to Aristotle. Space and time would now be forever dialectically linked by special relativity. (Zollner and Hinton had assumed that the next dimension to be discovered would be the fourth spatial dimension. In this respect, they were wrong and H. G. Wells was correct. The next dimension to be discovered would be time, a fourth temporal dimension. Progress in understanding the fourth spatial dimension would have to wait several more decades.)

To see how higher dimensions simplify the laws of nature, we recall that any object has length, width, and depth. Since we have the freedom

*Similarly, passengers riding in the train would think that the train was at rest and that the subway station was coming toward the train. They would see the platform and everyone standing on it compressed like an accordian. Then this leads us to a contradiction, that people on the train and in the station each think that the other has been compressed. The resolution of this paradox is a bit delicate.[3]

to rotate an object by 90 degrees, we can turn its length into width and its width into depth. By a simple rotation, we can interchange any of the three spatial dimensions. Now if time is the fourth dimension, then it is possible to make "rotations" that convert space into time and vice versa. These four-dimensional "rotations" are precisely the distortions of space and time demanded by special relativity. In other words, space and time have mixed in an essential way, governed by relativity. The meaning of time as being the fourth dimension is that time and space can rotate into each other in a mathematically precise way. From now on, they must be treated as two aspects of the same quantity: space–time. Thus adding a higher dimension helped to unify the laws of nature.

Newton, writing 300 years ago, thought that time beat at the same rate everywhere in the universe. Whether we sat on the earth, on Mars, or on a distant star, clocks were expected to tick at the same rate. There was thought to be an absolute, uniform rhythm to the passage of time throughout the entire universe. Rotations between time and space were inconceivable. Time and space were two distinct quantities with no relationship between them. Unifying them into a single quantity was unthinkable. However, according to special relativity, time can beat at different rates, depending on how fast one is moving. Time being the fourth dimension means that time is intrinsically linked with movement in space. How fast a clock ticks depends on how fast it is moving in space. Elaborate experiments done with atomic clocks sent into orbit around the earth have confirmed that a clock on the earth and a clock rocketing in outer space tick at different rates.

I was graphically reminded of the relativity principle when I was invited to my twentieth high-school reunion. Although I hadn't seen most of my classmates since graduation, I assumed that all of them would show the same telltale signs of aging. As expected, most of us at the reunion were relieved to find that the aging process was universal: It seemed that all of us sported graying temples, expanding waistlines, and a few wrinkles. Although we were separated across space and time by several thousand miles and 20 years, each of us had assumed that time had beat uniformly for all. We automatically assumed that each of us would age at the same rate.

Then my mind wandered, and I imagined what would happen if a classmate walked into the reunion hall looking *exactly* as he had on graduation day. At first, he would probably draw stares from his classmates. Was this the same person we knew 20 years ago? When people realized that he was, a panic would surge through the hall.

out any historical precedent. But their amazement is probably due to their unfamiliarity with the nonscientific work of the mystics, literati, and avante garde. A closer look at the cultural and historical setting shows that Kaluza's work was not such an unexpected development. As we have seen, because of Hinton, Zollner, and others, the possible existence of higher dimensions was perhaps the single most popular quasi-scientific idea circulating within the arts. From this larger cultural point of view, it was only a matter of time before some physicist took seriously Hinton's widely known idea that light is a vibration of the fourth spatial dimension. In this sense, the work of Riemann pollinated the world of arts and letters via Hinton and Zollner, and then probably cross-pollinated back into the world of science through the work of Kaluza. (In support of this thesis, it was recently revealed by Freund that Kaluza was actually not the first one to propose a five-dimensional theory of gravity. Gunnar Nordstrom, a rival of Einstein, actually published the first five-dimensional field theory, but it was too primitive to include both Einstein's and Maxwell's theories. The fact that both Kaluza and Nordstrom independently tried to exploit the fifth dimension indicates that the concepts widely circulating within popular culture affected their thinking.[13])

The Fifth Dimension

Every physicist receives quite a jolt when confronting the fifth dimension for the first time. Peter Freund remembers clearly the precise moment when he first encountered the fifth and higher dimensions. It was an event that left a deep impression on his thinking.

It was 1953 in Romania, the country of Freund's birth. Joseph Stalin had just died, an important event that led to a considerable relaxation of tensions. Freund was a precocious college freshman that year, and he attended a talk by George Vranceanu. He vividly remembers hearing Vranceanu discuss the important question: Why should light and gravity be so disparate? Then the lecturer mentioned an old theory that could contain both the theory of light and Einstein's equations of gravity. The secret was to use Kaluza–Klein theory, which was formulated in five dimensions.

Freund was shocked. Here was a brilliant idea that took him completely by surprise. Although only a freshman, he had the audacity to pose the obvious question: How does this Kaluza–Klein theory explain the other forces? He asked, "Even if you achieve a unification of light and gravity, you will not achieve anything because there is still the nuclear force." He realized that the nuclear force was outside Kaluza–Klein theory. (In fact, the hydrogen bomb, which hung like a sword over everyone on the planet at the height of the Cold War, was based on unleashing the nuclear force, not electromagnetism or gravity.)

The lecturer had no answer. In his youthful enthusiasm, Freund blurted out, "What about adding more dimensions?"

"But how many more dimensions?" asked the lecturer.

Freund was caught off guard. He did not want to give a low number of dimensions, only to be scooped by someone else. So he proposed a number that no one could possibly top: an infinite number of dimensions![14] (Unfortunately for this precocious physicist, an infinite number of dimensions does not seem to be physically possible.)

Life on a Cylinder

After the initial shock of confronting the fifth dimension, most physicists invariably begin to ask questions. In fact, Kaluza's theory raised more questions than it answered. The obvious question to ask Kaluza was: Where is the fifth dimension? Since all earthly experiments showed conclusively that we live in a universe with three dimensions of space and one of time, the embarrassing question still remained.

Kaluza had a clever response. His solution was essentially the same as that proposed by Hinton years before, that the higher dimension, which was not observable by experiment, was different from the other dimensions. It had, in fact, collapsed down to a circle so small that even atoms could not fit inside it. Thus the fifth dimension was not a mathematical trick introduced to manipulate electromagnetism and gravity, but a physical dimension that provided the glue to unite these two fundamental forces into one force, but was just too small to measure.

Anyone walking in the direction of the fifth dimension would eventually find himself back where he started. This is because the fifth dimension is topologically identical to a circle, and the universe is topologically identical to a cylinder.

Freund explains it this way:

> Think of some imaginary people living in Lineland, which consists of a single line. Throughout their history, they believed that their world was just a single line. Then, a scientist in Lineland proposed that their world was not just a one-dimensional line, but a two-dimensional world. When

fields. In one sentence, we have captured the essence of the past century of frustrating investigation into the subatomic realm. From this simple picture one can derive, from pure mathematics alone, all the myriad and baffling properties of matter. (Although it all seems so easy now, Nobel laureate Steven Weinberg, one of the creators of the Standard Model, once reflected on how tortuous the 50-year journey to discover the model had been. He wrote, "There's a long tradition of theoretical physics, which by no means affected everyone but certainly affected me, that said the strong interactions [were] too complicated for the human mind."[4])

Symmetry in Physics

The details of the Standard Model are actually rather boring and unimportant. The most interesting feature of the Standard Model is that it is based on symmetry. What has propelled this investigation into matter (wood) is that we can see the unmistakable sign of symmetry within each of these interactions. Quarks and leptons are not random, but occur in definite patterns in the Standard Model.

Symmetry, of course, is not strictly the province of physicists. Artists, writers, poets, and mathematicians have long admired the beauty that is to be found in symmetry. To the poet William Blake, symmetry possessed mystical, even fearful qualities, as expressed in the poem "Tyger! Tyger! burning bright":

> Tyger! Tyger! burning bright
> In the forests of the night
> What immortal hand or eye
> Could frame thy fearful symmetry?[5]

To mathematician Lewis Carroll, symmetry represented a familiar, almost playful concept. In the "The Hunting of the Snark," he captured the essence of symmetry when he wrote:

> You boil it in sawdust:
> You salt it in glue:
> You condense it with locusts in tape:
> Still keeping one principal object in view—
> To preserve its symmetrical shape.

In other words, symmetry is the preservation of the shape of an object even after we deform or rotate it. Several kinds of symmetries occur repeatedly in nature. The first is the symmetry of rotations and reflections. For example, a snowflake remains the same if we rotate it by 60 degrees. The symmetry of a kaleidoscope, a flower, or a starfish is of this type. We call these space–time symmetries, which are created by rotating the object through a dimension of space or time. The symmetry of special relativity is of this type, since it describes rotations between space and time.

Another type of symmetry is created by reshuffling a series of objects. Think of a shell game, where a huckster shuffles three shells with a pea hidden beneath one of them. What makes the game difficult is that there are many ways in which the shells can be arranged. In fact, there are six different ways in which three shells can be shuffled. Since the pea is hidden, these six configurations are identical to the observer. Mathematicians like to give names to these various symmetries. The name for the symmetries of a shell game is called S_3, which describes the number of ways that three identical objects may be interchanged.

If we replace the shells with quarks, then the equations of particle physics must remain the same if we shuffle the quarks among themselves. If we shuffle three colored quarks and the equations remain the same, then we say that the equations possess something called SU(3) symmetry. The 3 represents the fact that we have three types of colors, and the SU stands for a specific mathematical property of the symmetry.* We say that there are three quarks in a *multiplet.* The quarks in a multiplet can be shuffled among one another without changing the physics of the theory.

Similarly, the weak force governs the properties of two particles, the electron and the neutrino. The symmetry that interchanges these particles, yet leaves the equation the same, is called SU(2). This means that a multiplet of the weak force contains an electron and a neutrino, which can be rotated into each other. Finally, the electromagnetic force has U(1) symmetry, which rotates the components of the Maxwell field into itself.

Each of these symmetries is simple and elegant. However, the most controversial aspect of the Standard Model is that it "unifies" the three fundamental forces by simply splicing all three theories into one large symmetry, SU(3) × SU(2) × U(1), which is just the product of the

*SU stands for "special unitary" matrices—that is, matrices that have unit determinant and are unitary.

Kaluza–Klein theory, splitting off Einstein's field from the Yang–Mills field.

Apparently, one of the first physicists to perform this reduction was University of Texas physicist Bryce DeWitt, who has spent many years studying quantum gravity. Once this trick of splitting up the metric tensor was discovered, the calculation for extracting the Yang–Mills field is straightforward. DeWitt felt that extracting the Yang–Mills field from N-dimensional gravity theory was such a simple mathematical exercise that he assigned it as a homework problem at the Les Houches Physics Summer School in France in 1963. [Recently, it was revealed by Peter Freund that Oskar Klein had independently discovered the Yang–Mills field in 1938, preceding the work of Yang, Mills, and others by several decades. In a conference held in Warsaw titled "New Physical Theories," Klein announced that he was able to generalize the work of Maxwell to include a higher symmetry, O(3). Unfortunately, because of the chaos unleashed by World War II and because Kaluza–Klein theory was buried by the excitement generated by quantum theory, this important work was forgotten. It is ironic that Kaluza–Klein theory was killed by the emergence of quantum theory, which is now based on the Yang–Mills field, which was first discovered by analyzing Kaluza–Klein theory. In the excitement to develop quantum theory, physicists had ignored a central discovery coming from Kaluza–Klein theory.]

Extracting the Yang–Mills field out of Kaluza–Klein theory was only the first step. Although the symmetries of wood could now be seen as arising from the hidden symmetries of unseen dimensions, the next step was to create wood itself (made of quarks and leptons) entirely out of marble. This next step would be called supergravity.

Supergravity

Turning wood into marble still faced formidable problems because, according to the Standard Model, all particles are "spinning." Wood, for example, we now know is made of quarks and leptons. They, in turn, have ½ unit of quantum spin (measured in units of Planck's constant $\hbar$. Particles with half-integral spin (½, ³⁄₂, ⁵⁄₂, and so on) are called *fermions* (named after Enrico Fermi, who first investigated their strange properties). However, forces are described by quanta with integral spin. For example, the photon, the quantum of light, has one unit of spin. So does the Yang–Mills field. The graviton, the hypothetical packet of gravity, has two units of spin. They are called *bosons* (after the Indian physicist Satyendra Bose).

Traditionally, quantum theory kept fermions and bosons strictly apart. Indeed, any attempt to turn wood into marble would inevitably come to grips with the fact that fermions and bosons are worlds apart in their properties. For example, SU(N) may shuffle quarks among one another, but fermions and bosons were never supposed to mix. It came as a shock, therefore, when a new symmetry, called *supersymmetry*, was discovered, that did exactly that. Equations that are supersymmetric allow the interchange of a fermion with a boson and still keep the equations intact. In other words, one multiplet of supersymmetry consists of equal numbers of bosons and fermions. By shuffling the bosons and fermions within the same multiplet, the supersymmetric equations remain the same.

This gives us the tantalizing possibility of putting *all* the particles in the universe into one multiplet! As Nobel laureate Abdus Salam has emphasized, "Supersymmetry is the ultimate proposal for a complete unification of all particles."

Supersymmetry is based on a new kind of number system that would drive any schoolteacher insane. Most of the operations of multiplication and division that we take for granted fail for supersymmetry. For example, if a and b are two "super numbers," then $a \times b = -b \times a$. This, of course, is strictly impossible for ordinary numbers. Normally, any schoolteacher would throw these super numbers out the window, because you can show that $a \times a = -a \times a$, or, in other words, $a \times a = 0$. If these were ordinary numbers, then this means that $a = 0$, and the number system collapses. However, with super numbers, the system does not collapse; we have the rather astonishing statement that $a \times a = 0$ even when $a \neq 0$. Although these super numbers violate almost everything we have learned about numbers since childhood, they can be shown to yield a self-consistent and highly nontrivial system. Remarkably, an entirely new system of super calculus can be based on them.

Soon, three physicists (Daniel Freedman, Sergio Ferrara, and Peter van Nieuwenhuizen, at the State University of New York at Stony Brook) wrote down the theory of supergravity in 1976. Supergravity was the first realistic attempt to construct a world made entirely of marble. In a supersymmetric theory, all particles have super partners, called *sparticles*. The supergravity theory of the Stony Brook group contains just two fields: the spin-two graviton field (which is a boson) and its spin-3/2 partner, called the *gravitino* (which means "little gravity"). Since this is not enough particles to include the Standard Model, attempts were made to couple the theory to more complicated particles.

The simplest way to include matter is to write down the supergravity theory in 11-dimensional space. In order to write down the super

Intrigued by the program being initiated by KSV, I decided to try my luck at solving the problem. This was a bit difficult, because I was dodging machine-gun bullets at the time.

Boot Camp

I remember clearly when the KSV paper came out in 1969. KSV was proposing a program for future work, rather than giving precise details. I decided then to calculate all possible loops explicitly and complete the KSV program.

It's hard to forget those times. There was a war raging overseas, and the university campuses from Kent State to the University of Paris, were in a state of turmoil. I had graduated from Harvard the year before, when President Lyndon Johnson revoked deferments for graduate students, sending panic throughout graduate schools in the country. Chaos gripped the campuses. Suddenly, my friends were dropping out of college, teaching high school, packing their bags and heading to Canada, or trying to ruin their health in order to flunk the army physical.

Promising careers were being shattered. One of my good friends in physics from MIT vowed that he would go to jail rather than fight in Vietnam. He told us to send copies of the *Physical Review* to his jail cell so he could keep up with developments in the Veneziano model. Other friends, who quit college to teach in high schools rather than fight in the war, terminated promising scientific careers. (Many of them still teach in these high schools.)

Three days after graduation, I left Cambridge and found myself in the United States Army stationed at Fort Benning, Georgia (the largest infantry training center in the world), and later at Fort Lewis, Washington. Tens of thousands of raw recruits with no previous military training were being hammered into a fighting force and then shipped to Vietnam, replacing the 500 GIs who were dying every week.

One day, while throwing live grenades under the grueling Georgia sun and seeing the deadly shrapnel scatter in all directions, my thoughts began to wander. How many scientists throughout history had to face the punishing ravages of war? How many promising scientists were snuffed out by a bullet in the prime of their youth?

I remembered that Karl Schwarzschild had died in the kaiser's army on the Russian front during World War I just a few months after he found the basic solution to Einstein's equations used in every black hole calculation. (The Schwarzschild radius of a black hole is named in his honor. Einstein addressed the Prussian Academy in 1916 to commemorate Schwarzschild's work after his untimely death at the front lines.) And how many promising people were cut down even before they could begin their careers?

Infantry training, I discovered, is rigorous; it is designed to toughen the spirit and dull the intellect. Independence of thought is ground out of you. After all, the military does not necessarily want some wit who will question the sergeant's orders in the middle of a firefight. Understanding this, I decided to bring along some physics papers. I needed something to keep my mind active while peeling potatoes in KP or firing machine guns, so I brought along a copy of the KSV paper.

During night infantry training, I had to go past an obstacle course, which meant dodging live machine-gun bullets, froglegging under barbed wire, and crawling through thick brown mud. Because the automatic fire had tracers on them, I could see the beautiful crimson streaks made by thousands of machine-gun bullets sailing a few feet over my head. However, my thoughts kept drifting back to the KSV paper and how their program could be carried out.

Fortunately, the essential feature of the calculation was strictly topological. It was clear to me that these loops were introducing an entirely new language to physics, the language of topology. Never before in the history of physics had Möbius strips or Klein bottles been used in a fundamental way.

Because I rarely had any paper or pencils while practicing with machine guns, I forced myself to visualize in my head how strings could be twisted into loops and turned inside out. Machine-gun training was actually a blessing in disguise because it forced me to manipulate large blocks of equations in my head. By the time I finished the advanced machine-gun-training program, I was convinced that I could complete the program of calculating all loops.

Finally, I managed to squeeze time from the army to go to the University of California at Berkeley, where I furiously worked out the details that were racing in my head. I sank several hundred hours of intense thought into the question. This, in fact, became my Ph.D. dissertation.

By 1970, the final calculation took up several hundred densely filled notebook pages. Under the careful supervision of my adviser, Stanley Mandelstam, my colleague Loh-ping Yu and I successfully calculated an explicit expression for all possible loop diagrams known at that time. However, I wasn't satisfied with this work. The KSV program consisted of a hodge-podge of rules of thumb and intuition, not a rigorous set of basic principles from which these loops could be derived. String theory, supersymmetry and gravity can be combined in a totally self-consistent way.) And even though the potential discovery of sparticles will not prove the correctness of superstring theory, it will help to quiet the skeptics who have said that there is not one shred of physical evidence for superstring theory.

Signals from Outer Space

Since the SSC will never be built, and hence will never detect particles that are low-energy resonances of the superstring, then another possibility is to measure the energy of cosmic rays, which are highly energetic subatomic particles whose origin is still unknown, but must lie deep in outer space beyond our galaxy. For example, although no one knows where they come from, cosmic rays have energies much larger than anything found in our laboratories.

Cosmic rays, unlike the controlled rays produced in atom smashers, have unpredictable energies and cannot produce precise energies on demand. In some sense, it's like trying to put out a fire by either using hose water or waiting for a rainstorm. The hose water is much more convenient: We can turn it on any time we please, we can adjust the intensity of the water at will, and all the water travels at the same uniform velocity. Water from a fire hydrant therefore corresponds to producing controlled beams in atom smashers. However, water from a rainstorm may be much more intense and effective than water from a fire hydrant. The problem, of course, is that rainstorms, like cosmic rays, are unpredictable. You cannot regulate the rainwater, nor can you predict its velocity, which may fluctuate wildly.

Cosmic rays were first discovered 80 years ago in experiments performed by the Jesuit priest Theodor Wulf atop the Eiffel Tower in Paris. From the 1900s to the 1930s, courageous physicists sailed in balloons or scaled mountains to obtain the best measurements of cosmic rays. But cosmic-ray research began to fade during the 1930s, when Ernest Lawrence invented the cyclotron and produced controlled beams in the laboratory more energetic than most cosmic rays. For example, cosmic rays, which are as energetic as 100 million electron volts, are as common as rain drops; they hit the atmosphere of the earth at the rate of a few per square inch per second. However, Lawrence's invention spawned giant machines that could exceed that energy by a factor of 10 to 100.

Cosmic-ray experiments, fortunately, have changed dramatically since Father Wulf first placed electrified jars on the Eiffel Tower. Rockets

and even satellites can now send radiation counters high above the earth's surface, so that atmospheric effects are minimized. When a highly energetic cosmic ray strikes the atmosphere, it shatters the atoms in its wake. These fragments, in turn, create a shower of broken atoms, or ions, which can then be detected on the ground by this series of detectors. A collaboration between the University of Chicago and the University of Michigan has inaugurated the most ambitious cosmic-ray project yet, a vast array of 1,089 detectors scattered over about a square mile of desert, waiting for the cosmic-ray showers to trigger them. These detectors are located in an ideal, isolated area: the Dugway Proving Grounds, 80 miles southwest of Salt Lake City, Utah.

The Utah detector is sensitive enough to identify the point of origin of some of the most energetic cosmic rays. So far, Cygnus X-3 and Hercules X-1 have been identified as powerful cosmic-ray emitters. They are probably large, spinning neutron stars, or even black holes, that are slowly eating up a companion star, creating a large vortex of energy and spewing gigantic quantities of radiation (for example, protons) into outer space.

So far, the most energetic cosmic ray ever detected had an energy of 10^{20} electron volts. This figure is an incredible 10 million times the energy that would have been produced in the SSC. We do not expect to generate energies approaching this cosmic energy with our machines within the century. Although this fantastic energy is still 100 million times smaller than the energy necessary to probe the tenth dimension, we hope that energies produced deep within black holes in our galaxy will approach the Planck energy. With large, orbiting spacecraft, we should be able to probe deeper into the structure of these energy sources and detect energies even larger than this.

According to one favored theory, the largest energy source within our Milky Way galaxy—far beyond anything produced by Cygnus X-3 or Hercules X-1—lies at the center, which may consist of millions of black holes. So, because the SSC was canceled by Congress, we may find that the ultimate probe for exploring the tenth dimension may lie in outer space.

Testing the Untestable

Historically speaking, there have been many times when physicists have solemnly declared certain phenomena to be "untestable" or "unprovable." But there is another attitude that scientists can take concerning video screen and reappears on the other side of the screen, this corresponds to the rocket ship moving across the glued joint of the inner tube.

Vafa conjectures that our sister universe has the shape of some sort of twisted six-dimensional torus. Vafa and his colleagues have pioneered the concept that our sister universe can be described by what mathematicians call an *orbifold*. In fact, his proposal that our sister universe has the topology of an orbifold seems to fit the observed data rather well.[9]

To visualize an orbifold, think of moving 360 degrees in a circle. Everyone knows that we come back to the same point. In other words, if I dance 360 degrees around a May pole, I know that I will come back to the same spot. In an orbifold, however, if we move less than 360 degrees around the May pole, we will still come back to the same point. Although this may sound preposterous, it is easy to construct orbifolds. Think of Flatlanders living on a cone. If they move less than 360 degrees around the apex of the cone, they arrive at the same spot. Thus an orbifold is a higher-dimensional generalization of a cone (Figure 9.3).

To get a feel for orbifolds, imagine that some Flatlanders live on what is called a Z-orbifold, which is equivalent to the surface of a square bean bag (like those found at carnivals and country fairs). At first, nothing seems different from living in Flatland itself. As they explore the surface, however, they begin to find strange happenings. For example, if a Flatlander walks in any direction long enough, he returns to his original position as though he walked in a circle. However, Flatlanders also notice that there is something strange about certain points in their universe (the four points of the bean bag). When walking around any of these four points by 180 degrees (not 360 degrees), they return to the same place from which they started.

The remarkable thing about Vafa's orbifolds is that, with just a few assumptions, we can derive many of the features of quarks and other subatomic particles. (This is because, as we saw earlier, the geometry of space in Kaluza–Klein theory forces the quarks to assume the symmetry of that space.) This gives us confidence that we are on the right track. If the e orbifolds gave us totally meaningless results, then our intuition would tell us that there is something fundamentally wrong with this construction.

If none of the solutions of string theory contains the Standard Model, then we must throw away superstring theory as another promising but ultimately incorrect theory. However, physicists are excited by the fact that it is possible to obtain solutions that are tantalizingly close to the Standard Model.

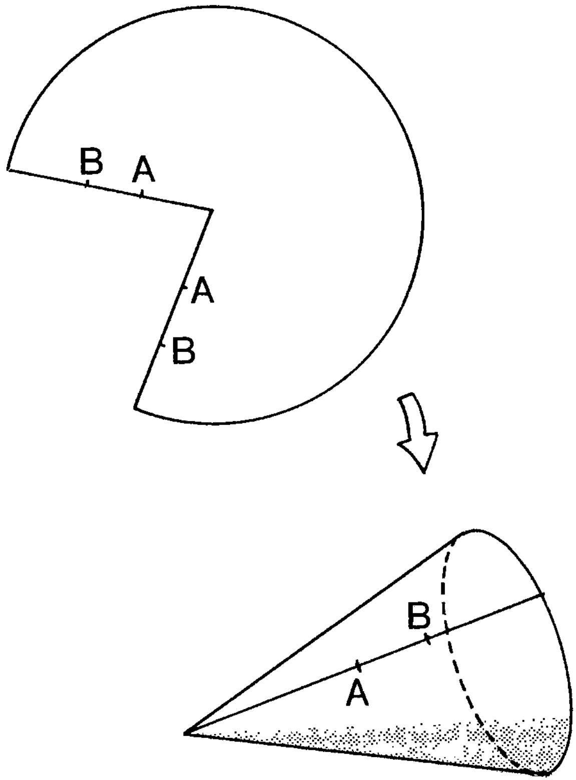

Figure 9.3. If we join points A and B, then we form a cone, which is the simplest example of an orbifold. In string theory, our four-dimensional universe may have a six-dimensional twin, which has the topology of an orbifold. However, the six-dimensional universe is so small that it is unobservable.

pedestrian point of view, the "force" between the star and a light beam is so great that its path is bent into a circle. Or one can take the Einsteinian point of view, in which case the "shortest distance between two points is a curved line." Bending a light beam into a full circle means that space itself has been bent full circle. This can happen only if the black hole has completely pinched a piece of space–time along with it, so the light beam is circulating in a hypersphere. This piece of space–time has now disconnected itself from the space–time around it. Space itself has now "ripped."

The Einstein–Rosen Bridge

The relativistic description of the black hole comes from the work of Karl Schwarzschild. In 1916, barely a few months after Einstein wrote down his celebrated equations, Schwarzschild was able to solve Einstein's equations exactly and calculate the gravitational field of a massive, stationary star.

Schwarzschild's solution has several interesting features. First, a "point of no return" surrounds the black hole. Any object that comes closer than this radius will inevitably be sucked into the black hole, with no possibility of escape. Inexorably, any person unfortunate enough to come within the Schwarzschild radius would be captured by the black hole and crushed to death. Today, this distance from the black hole is called the *Schwarzschild radius,* or the *horizon* (the farthest visible point).

Second, anyone who fell within the Schwarzschild radius would be aware of a "mirror universe" on the "other side" of space–time (Figure 10.2). Einstein was not worried about the existence of this bizarre mirror universe because communication with it was impossible. Any space probe sent into the center of a black hole would encounter infinite curvature; that is, the gravitational field would be infinite, and any material object would be crushed. The electrons would be ripped off atoms, and even the protons and neutrons within the nuclei themselves would be torn apart. Also, to penetrate through to the alternative universe, the probe would have to go faster than the speed of light, which is not possible. Thus although this mirror universe is mathematically necessary to make sense of the Schwarzschild solution, it could never be observed physically.

Consequently, the celebrated *Einstein–Rosen bridge* connecting these two universes (named after Einstein and his collaborator, Nathan Rosen) was considered a mathematical quirk. The bridge was necessary

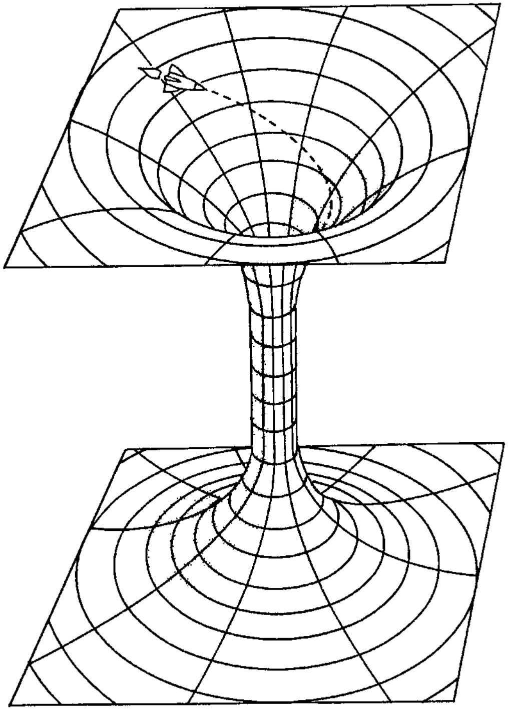

Figure 10.2. The Einstein–Rosen bridge connects two different universes. Einstein believed that any rocket that entered the bridge would be crushed, thereby making communication between these two universes impossible. However, more recent calculations show that travel through the bridge might be very difficult, but perhaps possible.

to have a mathematically consistent theory of the black hole, but it was impossible to reach the mirror universe by traveling through the Einstein–Rosen bridge. Einstein–Rosen bridges were soon found in other solutions of the gravitational equations, such as the Reissner–Nordstrom solution describing an electrically charged black hole. However, the Einthe universe. The topology of a Newman–Unti–Tamburino universe might be compared to living on a spiral staircase. If we move 360 degrees around the staircase, we do not arrive at the same point at which we started, but on another landing of the staircase. Living in such a universe would surpass our worst nightmare, with common sense being completely thrown out the window. In fact, this bizarre universe was so pathological that it was quickly coined the NUT universe, after the initials of its creators.

At first, relativists dismissed the NUT solution in the same way they had dismissed the Gödel solution; that is, our universe didn't seem to evolve in the way predicted by these solutions, so they were arbitrarily discarded for experimental reasons. However, as the decades went by, there was a flood of such bizarre solutions to Einstein's equations that allowed for time travel. In the early 1970s, Frank J. Tipler at Tulane University in New Orleans reanalyzed an old solution to Einstein's equations found by W. J. van Stockum in 1936, even before Gödel's solution. This solution assumed the existence of an infinitely long, rotating cylinder. Surprisingly enough, Tipler was able to show that this solution also violated causality.

Even the Kerr solution (which represents the most physically realistic description of black holes in outer space) was shown to allow for time travel. Rocket ships that pass through the center of the Kerr black hole (assuming they are not crushed in the process) could violate causality.

Soon, physicists found that NUT-type singularities could be inserted into any black hole or expanding universe. In fact, it now became possible to cook up an infinite number of pathological solutions to Einstein's equations. For example, every wormhole solution to Einstein's equations could be shown to allow some form of time travel.

According to relativist Frank Tipler, "solutions to the field equations can be found which exhibit virtually any type of bizarre behavior."[3] Thus an explosion of pathological solutions to Einstein's equations was discovered that certainly would have horrified Einstein had he still been alive.

Einstein's equations, in some sense, were like a Trojan horse. On the surface, the horse looks like a perfectly acceptable gift, giving us the observed bending of starlight under gravity and a compelling explanation of the origin of the universe. However, inside lurk all sorts of strange demons and goblins, which allow for the possibility of interstellar travel through wormholes and time travel. The price we had to pay for peering into the darkest secrets of the universe was the potential downfall of some of our most commonly held beliefs about our world—that its space is simply connected and its history is unalterable.

But the question still remained: Could these CTCs be dismissed on purely experimental grounds, as Einstein did, or could someone show that they were theoretically possible and then actually build a time machine?

To Build a Time Machine

In June 1988, three physicists (Kip Thorne and Michael Morris at the California Institute of Technology and Ulvi Yurtsever at the University of Michigan) made the first serious proposal for a time machine. They convinced the editors of *Physical Review Letters*, one of the most distinguished publications in the world, that their work merited serious consideration. (Over the decades, scores of crackpot proposals for time travel have been submitted to mainstream physics journals, but all have been rejected because they were not based on sound physical principles or Einstein's equations.) Like experienced scientists, they presented their arguments in accepted field theoretical language and then carefully explained where their weakest assumptions were.

To overcome the skepticism of the scientific community, Thorne and his colleagues realized that they would have to overcome the standard objections to using wormholes as time machines. First, as mentioned earlier, Einstein himself realized that the gravitational forces at the center of a black hole would be so enormous that any spacecraft would be torn apart. Although wormholes were mathematically possible, they were, in practice, useless.

Second, wormholes might be unstable. One could show that small disturbances in wormholes would cause the Einstein–Rosen bridge to collapse. Thus a spaceship's presence inside a black hole would be sufficient to cause a disturbance that would close the entrance to the wormhole.

Third, one would have to go faster than the speed of light actually to penetrate the wormhole to the other side.

Fourth, quantum effects would be so large that the wormhole might close by itself. For example, the intense radiation emitted by the entrance to the black hole not only would kill anyone who tried to enter the black hole, but also might close the entrance.

Fifth, time slows down in a wormhole and comes to a complete stop at the center. Thus wormholes have the undesirable feature that as seen by someone on the earth, a space traveler appears to slow down and come to a total halt at the center of the black hole. The space traveler looks like he or she is frozen in time. In other words, it takes an infinite theory was based on single particles, with no possibility of communication between different universes as they fissioned. However, Hawking's theory, although related, goes much further: It is based on an infinite number of self-contained universes (and not just particles) and postulates the possibility of tunneling (via wormholes) between them.

Hawking has even undertaken the daunting task of calculating the solution to the wave function of the universe. He is confident that his approach is correct partly because the theory is well defined (if, as we mentioned, the theory is ultimately defined in ten dimensions). His goal is to show that the wave function of the universe assumes a large value near a universe that looks like ours. Thus our universe is the most likely universe, but certainly not the only one.

By now, there have been a number of international conferences on the wave function of the universe. However, as before, the mathematics involved in the wave function of the universe is beyond the calculational ability of any human on this planet, and we may have to wait years before any enterprising individual can find a rigorous solution to Hawking's equations.

Parallel Worlds

A major difference between Everett's many-worlds theory and Hawking's wave function of the universe is that Hawking's theory places wormholes that connect these parallel universes at the center of his theory. However, there is no need to wonder whether you will someday walk home from work, open the door, enter a parallel universe, and discover that your family never heard of you. Instead of rushing to meet you after a hard day's work, your family is thrown into a panic, scream about an intruder, and have you thrown in jail for illegal entry. This kind of scenario happens only on television or in the movies. In Hawking's approach, the wormholes do, in fact, constantly connect our universe with billions upon billions of parallel universes, but the size of these wormholes, on the average, is extremely small, about the size of the Planck length (about a 100 billion billion times smaller than a proton, too small for human travel). Furthermore, since large quantum transitions between these universes are infrequent, we may have to wait a long time, longer than the lifetime of the universe, before such an event takes place.

Thus it is perfectly consistent with the laws of physics (although *highly* unlikely) that someone may enter a twin universe that is precisely like

our universe except for one small crucial difference, created at some point in time when the two universes split apart.

This type of parallel world was explored by John Wyndham in the story "Random Quest." Colin Trafford, a British nuclear physicist, is almost killed in 1954 when a nuclear experiment blows up. Instead of winding up in the hospital, he wakes up, alone and unhurt, in a remote part of London. He is relieved that everything appears normal, but soon discovers that something is very wrong. The newspaper headlines are all impossible. World War II never took place. The atomic bomb was never discovered.

World history has been twisted. Furthermore, he glances at a store shelf and notices his own name, with his picture, as the author of a best-selling book. He is shocked. An exact counterpart of himself exists in this parallel world as an author instead of a nuclear physicist!

Is he dreaming all this? Years ago, he once thought of becoming a writer, but instead he chose to become a nuclear physicist. Apparently in this parallel universe, different choices were made in the past.

Trafford scans the London telephone book and finds his name listed, but the address is wrong. Shaking, he decides to visit "his" home.

Entering "his" apartment, he is shocked to meet "his" wife—someone he has never seen before—a beautiful woman who is bitter and angry over "his" numerous affairs with other women. She berates "him" for his extramarital indiscretions, but she notices that her husband seems confused. His counterpart, Trafford finds out, is a cad and a womanizer. However, he finds it difficult to argue with a beautiful stranger he has never seen before, even if she happens to be "his" wife. Apparently, he and his counterpart have switched universes.

He gradually finds himself falling in love with "his" own wife. He cannot understand how his counterpart could ever have treated his lovely wife in such a despicable manner. The next few weeks spent together are the best of their lives. He decides to undo all the harm his counterpart inflicted on his wife over the years. Then, just as the two are rediscovering each other, he is suddenly wrenched back into his own universe, leaving "his" love behind. Thrown back into his own universe against his will, he begins a frantic quest to find "his" wife. He has discovered that most, but not all, people in his universe have a counterpart in the other. Surely, he reasons, "his" wife must have a counterpart in his own world.

He becomes obsessed, tracking down all the clues that he remembers from the twin universe. Using all his knowledge of history and physics, he concludes that two worlds diverged from each other because of some lets the computer evolve the disk until small, rocky masses begin to coalesce out of the dust. Much to his pleasant surprise, he found that planets of approximately the size of the earth were easy to evolve out of these rocky cores. Most of the time, in fact, earth-size planets spontaneously coalesced with masses between 80% and 130% of the earth's distance from the sun. (Curiously, he also found that the formation of Jupiter-size planets far from the sun was important for the evolution of the earth-size planets. The Jupiter-size planets were essential to sweep out swarms of comets and debris that would eventually strike the earthlike planet, extinguishing any primitive life forms on it. Wetherill's computer simulations show that without a Jupiter-like planet to clean out these comets with its gigantic gravitational pull, these comets would hit the earthlike planet about 1,000 times more frequently than they do in reality, making a life-destroying impact every 100,000 years or so.)

Thus it is a compelling (but certainly not rigorous) conclusion that the laws of probability favor the presence of other intelligence within the galaxy. The fact that our galaxy is perhaps 10 billion years old means that there has been ample time for scores of intelligent life forms to have flourished within it. Type II and III civilizations, broadcasting for several hundred to several thousand years, should be sending out an easily detectable sphere of electromagnetic radiation measuring several hundred to several thousand light-years in diameter. Yet we see no signs of intelligent life forms in the heavens.

Why?

Several speculative theories have been advanced to explain why we have been unable to detect signs of intelligent life out to 100 light-years of our planet. None of them is particularly satisfying, and the final truth may be a combination of all of them.

One theory holds that Drake's equation may give us rough probabilities of how many planets contain intelligent life, but tells us nothing about when these planets attain this level of development. Given the astronomical time scales involved, perhaps Drake's equation predicts intelligent life forms that existed millions of years before us, or will exist millions of years after us.

For example, our solar system is approximately 4.5 billion years old. Life started on the earth about 3 to 4 billion years ago, but only within the past million years has intelligent life developed on the planet (and only within the past few decades has this civilization built radio stations capable of sending signals into outer space). However, 1 million years, on the time scale of billions of years, is but an instant of time. It is reasonable to assume that thousands of advanced civilizations existed before our distant ancestors even left the forest and have since perished, or that thousands more civilizations will develop long after ours has died. Either way, we would not be able to detect them via our instruments.

The second theory holds that the galaxy is, in fact, teeming with advanced forms of civilizations, but they are advanced enough to conceal their existence from our prying instruments. We would mean nothing to them because they are so many millions of years ahead of us. For example, if we stumble on an ant colony while walking in a field, our first impulse is certainly not to make contact with the ants, ask to see their leader, wave trinkets before their eyes, and offer them unparalleled prosperity and the fruits of our advanced technology. More likely, our first temptation is to ignore them (or perhaps even step on a few of them).

Puzzled by these long-standing questions, I asked Dyson if he thought we would soon be making contact with extraterrestrial life forms. His answer rather surprised me. He said, "I hope not." I thought it was strange that someone who had spent decades speculating about intelligent civilizations in outer space should have reservations about actually meeting them. Knowing British history, however, he must have had good reasons for not rushing in to embrace other civilizations. British civilization was probably only several hundred years more advanced than many of the civilizations, such as the Indian and the African, conquered by the British army and navy.

Although most science-fiction writers bewail the limitations on space exploration placed by the speed of light, Dyson takes the unorthodox view that perhaps this is a good thing. Viewing the often bloody history of colonialism throughout our own world history, perhaps it is a blessing in disguise, he muses, that various Type II civilizations will be separated by large distances and that the Planck energy is inaccessible. Looking at the bright side, he quipped, "At least, one can evade the tax collector."

Unfortunately, the meeting of two unequal civilizations has often had catastrophic implications for the weaker one. For example, the Aztec civilization had risen over thousands of years to great prominence in central Mexico. In some areas, its mastery of science, art, and technology rivaled the achievements of Europe. However, in the area of gunpowder and warships, the Aztecs were perhaps several centuries behind the Spanish. The sudden clash between a small, ragged band of 400 conquistadors and the advanced civilizations of the Aztecs ended in tragedy in 1521. Within a brief period of time, the Aztec people, with a population numbering in the millions, were systematically crushed and enslaved to work in the mines. Their treasuries were looted, their history of hidden, undetectable "missing mass" or "dark matter," which is not luminous but has weight. Even if we include an approximate value for the mass of nonluminous interstellar gas, Newton's laws predict that the galaxy is far heavier than the value calculated by counting stars.

Until astronomers resolve the question of this missing mass or dark matter, we cannot resolve the question of whether the universe will contract and collapse into a fiery ball or will expand forever.

Entropy Death

Assume, for the moment, that the average density of the universe is less than the critical value. Since the matter–energy content determines the curvature of space–time, we find that there is not enough matter–energy to make the universe recollapse. It will then expand limitlessly until its temperature reaches almost absolute zero. This increases *entropy* (which measures the total amount of chaos or randomness in the universe). Eventually, the universe dies in an entropy death.

The English physicist and astronomer Sir James Jeans wrote about the ultimate death of the universe, which he called the "heat death," as early as the turn of the century: "The second law of thermodynamics predicts that there can be but one end to the universe—a 'heat death' in which [the] temperature is so low as to make life impossible."[3]

To understand how entropy death occurs, it is important to understand the three laws of thermodynamics, which govern all chemical and nuclear processes on the earth and in the stars. The British scientist and author C. P. Snow had an elegant way of remembering the three laws:

1. *You cannot win* (that is, you cannot get something for nothing, because matter and energy are conserved).
2. *You cannot break even* (you cannot return to the same energy state, because there is always an increase in disorder; entropy always increases).
3. *You cannot get out of the game* (because absolute zero is unattainable).

For the death of the universe, the most important is the Second Law, which states that any process creates a net increase in the amount of disorder (entropy) in the universe. The Second Law is actually an integral part of our everyday lives. For example, consider pouring cream into a cup of coffee. Order (separate cups of cream and coffee) has naturally changed into disorder (a random mixture of cream and coffee). However, reversing entropy, extracting order from disorder, is exceedingly difficult. "Unmixing" the liquid back into separate cups of cream and coffee is impossible without an elaborate chemistry laboratory. Also, a lighted cigarette can fill an empty room with wisps of smoke, increasing entropy in that room. Order (tobacco and paper) has again turned into disorder (smoke and charcoal). Reversing entropy—that is, forcing the smoke back into the cigarette and turning the charcoal back into unburned tobacco—is impossible even with the finest chemistry laboratory on the planet.

Similarly, everyone knows that it's easier to destroy than to build. It may take a year to construct a house, but only an hour or so to destroy it in a fire. It took almost 5,000 years to transform roving bands of hunters into the great Aztec civilization, which flourished over Mexico and Central America and built towering monuments to its gods. However, it only took a few months for Cortez and the conquistadors to demolish that civilization.

Entropy is relentlessly increasing in the stars as well as on our planet. Eventually, this means that the stars will exhaust their nuclear fuel and die, turning into dead masses of nuclear matter. The universe will darken as the stars, one by one, cease to twinkle.

Given our understanding of stellar evolution, we can paint a rather dismal picture of how the universe will die. All stars will become black holes, neutron stars, or cold dwarf stars (depending on their mass) within 10^{24} years as their nuclear furnaces shut down. Entropy increases as stars slide down the curve of binding energy, until no more energy can be extracted by fusing their nuclear fuel. Within 10^{32} years, all protons and neutrons in the universe will probably decay. According to the GUTs, the protons and neutrons are unstable over that vast time scale. This means that eventually all matter as we know it, including the earth and the solar system, will dissolve into smaller particles, such as electrons and neutrinos. Thus intelligent beings will have to face the unpleasant possibility that the protons and neutrons in their bodies will disintegrate. The bodies of intelligent organisms will no longer be made of the familiar 100 chemical elements, which are unstable over that immense period of time. Intelligent life will have to find ways of creating new bodies made of energy, electrons, and neutrinos.

After a fantastic 10^{100} (a googol) years, the universe's temperature will reach near absolute zero. Intelligent life in this dismal future will face the prospect of extinction. Unable to huddle next to stars, they will freeze to death. But even in a desolate, cold universe at temperatures ingless. However, with the coming of the ten-dimensional theory, the meaning of the wave function of the entire universe becomes a relevant concept once again. Calculations with the wave function of the universe can appeal to the fact that the theory is ultimately a ten-dimensional theory, and is hence renormalizable.

This partial solution to the question of observation once again takes the best of both philosophies. On the one hand, this picture is reductionist because it adheres closely to the standard quantum-mechanical explanation of reality, without recourse to consciousness. On the other hand, it is also holistic because it begins with the wave function of the entire universe, which is the ultimate holistic expression! This picture does not make the distinction between the observer and the observed. In this picture, everything, including all objects and their observers, is included in the wave function.

This is still only a partial solution because the cosmic wave function itself, which describes the entire universe, does not live in any definite state, but is actually a composite of all possible universes. Thus the problem of indeterminacy, first discovered by Heisenberg, is now extended to the entire universe.

The smallest unit that one can manipulate in these theories is the universe itself, and the smallest unit that one can quantize is the space of all possible universes, which includes both dead cats and live cats. Thus in one universe, the cat is indeed dead; but in another, the cat is alive. However, both universes reside in the same home: the wave function of the universe.

A Child of *S*-Matrix Theory

Ironically, in the 1960s, the reductionist approach looked like a failure; the quantum theory of fields was hopelessly riddled with divergences found in the perturbation expansion. With quantum physics in disarray, a branch of physics called *S*-matrix (scattering matrix) theory broke off from the mainstream and began to germinate. Originally founded by Heisenberg, it was further developed by Geoffrey Chew at the University of California at Berkeley. *S*-matrix theory, unlike reductionism, tried to look at the scattering of particles as an inseparable, irreducible whole.

In principle, if we know the *S* matrix, we know everything about particle interactions and how they scatter. In this approach, how particles bump into one another is everything; the individual particle is nothing. *S*-matrix theory said that the self-consistency of the scattering matrix,

and *self-consistency alone,* was sufficient to determine the *S* matrix. Thus fundamental particles and fields were banished forever from the Eden of *S*-matrix theory. In the final analysis, only the *S* matrix had any physical meaning.

As an analogy, let us say that we are given a complex, strange-looking machine and are asked to explain what it does. The reductionist will immediately get a screw driver and take the machine apart. By breaking down the machine to thousands of tiny pieces, the reductionist hopes to find out how the machine functions. However, if the machine is too complicated, taking it apart only makes matters worse.

The holists, however, do not want to take the machine apart for several reasons. First, analyzing thousands of gears and screws may not give us the slightest hint of what the overall machine does. Second, trying to explain how each tiny gear works may send us on a wild-goose chase. The correct way, they feel, is to look at the machine as a whole. They turn the machine on and ask how the parts move and interact with one another. In modern language, this machine is the *S* matrix, and this philosophy became the *S*-matrix theory.

In 1971, however, the tide shifted dramatically in favor of reductionism with Gerard 't Hooft's discovery that the Yang–Mills field can provide a self-consistent theory of subatomic forces. Suddenly, each of the particle interactions came tumbling down like huge trees in a forest. The Yang–Mills field gave uncanny agreement with the experimental data from atom smashers, leading to the establishment of the Standard Model, while *S*-matrix theory became entangled in more and more obscure mathematics. By the late 1970s, it seemed like a total, irreversible victory of reductionism over holism and the *S*-matrix theory. The reductionists began to declare victory over the prostrate body of the holists and the *S* matrix.

The tide, however, shifted once again in the 1980s. With the failure of the GUTs to yield any insight into gravitation or yield any experimentally verifiable results, physicists began to look for new avenues of research. This departure from GUTs began with a new theory, which owed its existence to the *S*-matrix theory.

In 1968, when *S*-matrix theory was in its heyday, Veneziano and Suzuki were deeply influenced by the philosophy of determining the *S* matrix in its entirety. They hit on the Euler beta function because they were searching for a mathematical representation of the entire *S* matrix. If they had looked for reductionist Feynman diagrams, they never would have stumbled on one of the great discoveries of the past several decades.

Twenty years later, we see the flowering of the seed planted by the