Michio Kaku

Bestselling Author of HYPERSPACE

Parallel Worlds

A Journey Through Creation, Higher Dimensions, and the Future of the Cosmos

"A wonderful tour, with an expert guide, of a cosmos whose comprehension forces us to stretch to the very limits of imagination."
—Brian Greene, author of THE ELEGANT UNIVERSE

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PREFACE

Cosmology is the study of the universe as a whole, including its birth and perhaps its ultimate fate. Not surprisingly, it has undergone many transformations in its slow, painful evolution, an evolution often overshadowed by religious dogma and superstition.

The first revolution in cosmology was ushered in by the introduction of the telescope in the 1600s. With the aid of the telescope, Galileo Galilei, building on the work of the great astronomers Nicolaus Copernicus and Johannes Kepler, was able to open up the splendor of the heavens for the first time to serious scientific investigation. The advancement of this first stage of cosmology culminated in the work of Isaac Newton, who finally laid down the fundamental laws governing the motion of the celestial bodies. Instead of magic and mysticism, the laws of heavenly bodies were now seen to be subject to forces that were computable and reproducible.

A second revolution in cosmology was initiated by the introduction of the great telescopes of the twentieth century, such as the one at Mount Wilson with its huge 100-inch reflecting mirror. In the 1920s, astronomer Edwin Hubble used this giant telescope to overturn centuries of dogma, which stated that the universe was static and eternal, by demonstrating that the galaxies in the heavens are moving away from the earth at tremendous velocities—that is, the universe is expanding. This confirmed the results of Einstein's theory of general relativity, in which the architecture of space-time, instead of being flat and linear, is dynamic and curved. This gave the first plausible explanation of the origin of the universe, that the universe began with a cataclysmic explosion called the "big bang," which sent the stars and galaxies hurtling outward in space. With the pioneering work of George Gamow and his colleagues on the big bang theory and Fred Hoyle on the origin of the elements, a scaffolding was emerging giving the broad outlines of the evolution of the universe.

A third revolution is now under way. It is only about five years old. It has been ushered in by a battery of new, high-tech instruments, such as space satellites, lasers, gravity wave detectors, X-ray telescopes, and high-speed supercomputers. We now have the most authoritative data yet on the nature of the universe, including its age, its composition, and perhaps even its future and eventual death.

Astronomers now realize that the universe is expanding in a runaway mode, accelerating without limit, becoming colder and colder with time. If this continues, we face the prospect of the "big freeze," when the universe is plunged into darkness and cold, and all intelligent life dies out.

This book is about this third great revolution. It differs from my earlier books on physics, *Beyond Einstein* and *Hyperspace*, which helped to introduce to the public the new concepts of higher dimensions and superstring theory. In *Parallel Worlds*, instead of focusing on space-time, I concentrate on the revolutionary developments in cosmology unfolding within the last several years, based on new evidence from the world's laboratories and the outermost reaches of space, and new breakthroughs in theoretical physics. It is my intention that it can be read and grasped without any previous introduction to physics or cosmology.

In part 1 of the book, I focus on the study of the universe, summarizing the advances made in the early stages of cosmology, culminating in the theory called "inflation," which gives us the most advanced formulation to date of the big bang theory. In part 2, I focus specifically on the emerging theory of the multiverse—a world made up of multiple universes, of which ours is but one—and discuss the possibility of wormholes, space and time warps, and how higher dimensions might connect them. Superstring theory and M-theory have given us the first major step beyond Einstein's original theory; they give further evidence that our universe may be but one of many. Finally, in part 3, I discuss the big freeze and what scientists now see as the end of our universe. I also give a serious, though speculative, discussion of how an advanced civilization in the distant future might use the laws of physics to leave our universe trillions of years from now and enter another, more hospitable universe to begin the process of rebirth, or to go back in time when the universe was warmer.

With the flood of new data we are receiving today, with new tools such as space satellites which can scan the heavens, with new gravity wave detectors, and with new city-size atom smashers nearing completion, physicists feel that we are entering what may be the golden age of cosmology. It is, in short, a great time to be a physicist and a voyager on this quest to understand our origins and the fate of the universe.

PART ONE

THE UNIVERSE

CHAPTER ONE

Baby Pictures of the Universe

The poet only asks to get his head into the heavens. It is the logician who seeks to get the heavens into his head. And it is his head that splits.

—G. K. Chesterton

When I was a child, I had a personal conflict over my beliefs. My parents were raised in the Buddhist tradition. But I attended Sunday school every week, where I loved hearing the biblical stories about whales, arks, pillars of salt, ribs, and apples. I was fascinated by these Old Testament parables, which were my favorite part of Sunday school. It seemed to me that the parables about great floods, burning bushes, and parting waters were so much more exciting than Buddhist chanting and meditation. In fact, these ancient tales of heroism and tragedy vividly illustrated deep moral and ethical lessons which have stayed with me all my life.

One day in Sunday school we studied Genesis. To read about God thundering from the heavens, "Let there be Light!" sounded so much more dramatic than silently meditating about Nirvana. Out of naïve curiosity, I asked my Sunday school teacher, "Did God have a mother?" She usually had a snappy answer, as well as a deep moral lesson to offer. This time, however, she was taken aback. No, she replied hesitantly, God probably did not have a mother. "But then where did God come from?" I asked. She mumbled that she would have to consult with the minister about that question.

I didn't realize that I had accidentally stumbled on one of the great questions of theology. I was puzzled, because in Buddhism, there is no God at all, but a timeless universe with no beginning or end. Later, when I began to study the great mythologies of the world, I learned that there were two types of cosmologies in religion, the first based on a single moment when God created the universe, the second based on the idea that the universe always was and always will be.

They couldn't both be right, I thought.

Later, I began to find that these common themes cut across many other cultures. In Chinese mythology, for example, in the beginning there was the cosmic egg. The infant god P'an Ku resided for almost an eternity inside the egg, which floated on a formless sea of Chaos. When it finally hatched, P'an Ku grew enormously, over ten feet per day, so the top half of the eggshell became the sky and the bottom half the earth. After 18,000 years, he died to give birth to our world: his blood became the rivers, his eyes the sun and moon, and his voice the thunder.

In many ways, the P'an Ku myth mirrors a theme found in many other religions and ancient mythologies, that the universe sprang into existence *creatio ex nihilo* (created from nothing). In Greek mythology, the universe started off in a state of Chaos (in fact, the word "chaos" comes from the Greek word meaning "abyss"). This featureless void is often described as an ocean, as in Babylonian and Japanese mythology. This theme is found in ancient Egyptian mythology, where the sun god Ra emerged from a floating egg. In Polynesian mythology, the cosmic egg is replaced by a coconut shell. The Mayans believed in a variation of this story, in which the universe is born but eventually dies after five thousand years, only to be resurrected again and again to repeat the unending cycle of birth and destruction.

These *creatio ex nihilo* myths stand in marked contrast to the cosmology according to Buddhism and certain forms of Hinduism. In these mythologies, the universe is timeless, with no beginning or end. There are many levels of existence, but the highest is Nirvana, which is eternal and can be attained only by the purest meditation. In the Hindu *Mahapurana*, it is written, "If God created the world, where was He before Creation? . . . Know that the world is uncreated, as time itself is, without beginning and end."

These mythologies stand in marked contradiction to each other, with no apparent resolution between them. They are mutually exclusive: either the universe had a beginning or it didn't. There is, apparently, no middle ground.

Today, however, a resolution seems to be emerging from an entirely new direction—the world of science—as the result of a new generation of powerful scientific instruments soaring through outer space. Ancient mythology relied upon the wisdom of storytellers to expound on the origins of our world. Today, scientists are unleashing a battery of space satellites, lasers, gravity wave detectors, interferometers, high-speed supercomputers, and the Internet, in the process revolutionizing our understanding of the universe, and giving us the most compelling description yet of its creation.

What is gradually emerging from the data is a grand synthesis of these two opposing mythologies. Perhaps, scientists speculate, Genesis occurs repeatedly in a timeless ocean of Nirvana. In this new picture, our universe may be compared to a bubble floating in a much larger "ocean," with new bubbles forming all the time. According to this theory, universes, like bubbles forming in boiling water, are in continual creation, floating in a much larger arena, the Nirvana of eleven-dimensional hyperspace. A growing number of physicists suggest that our universe did indeed spring forth from a fiery cataclysm, the big bang, but that it also coexists in an eternal ocean of other universes. If we are right, big bangs are taking place even as you read this sentence.

Physicists and astronomers around the world are now speculating about what these parallel worlds may look like, what laws they may obey, how they are born, and how they may eventually die. Perhaps these parallel worlds are barren, without the basic ingredients of life. Or perhaps they look just like our universe, separated by a single quantum event that made these universes diverge from ours. And a few physicists are speculating that perhaps one day, if life becomes untenable in our present universe as it ages and grows cold, we may be forced to leave it and escape to another universe.

The engine driving these new theories is the massive flood of data that is pouring from our space satellites as they photograph remnants of creation itself. Remarkably, scientists are now zeroing in on what happened a mere 380,000 years after the big bang, when the "afterglow" of creation first filled the universe. Perhaps the most compelling picture of this radiation from creation is coming from a new instrument called the WMAP satellite.

THE WMAP SATELLITE

"Incredible!" "A milestone!" were among the words uttered in February 2003 by normally reserved astrophysicists as they described the precious data harvested from their latest satellite. The WMAP (Wilkinson microwave anisotropy probe), named after pioneering cosmologist David Wilkinson and launched in 2001, has given scientists, with unprecedented precision, a detailed picture of the early universe when it was a mere 380,000 years old. The colossal energy left over from the original fireball that gave birth to stars and galaxies has been circulating around our universe for billions of years. Today, it has finally been captured on film in exquisite detail by the WMAP satellite, yielding a map never seen before, a photo of the sky showing with breathtaking detail the microwave radiation created by the big bang itself, what has been called the "echo of creation" by *Time* magazine. Never again will astronomers look at the sky in the same way again.

The findings of the WMAP satellite represent "a rite of passage for cosmology from speculation to precision science," declared John Bahcall of the Institute for Advanced Study at Princeton. For the first time, this deluge of data from this early period in the history of the universe has allowed cosmologists to answer precisely the most ancient of all questions, questions that have puzzled and intrigued humanity since we first gazed at the blazing celestial beauty of the night sky. How old is the universe? What is it made of? What is the fate of the universe?

(In 1992, a previous satellite, the COBE [Cosmic Background Explorer satellite] gave us the first blurry pictures of this background radiation filling the sky. Although this result was revolutionary, it was also disappointing because it gave such an out-of-focus picture of the early universe. This did not prevent the press from excitedly dubbing this photograph "the face of God." But a more accurate description of the blurry pictures from COBE would be that they represented a "baby picture" of the infant universe. If the universe today is an eighty-year-old man, the COBE, and later the WMAP, pictures showed him as a newborn, less than a day old.)

The reason the WMAP satellite can give us unprecedented pictures of the infant universe is that the night sky is like a time machine. Because light travels at a finite speed, the stars we see at night are seen as they once were, not as they are today. It takes a little over a second for light from the Moon to reach Earth, so when we gaze at the Moon we actually see it as it was a second earlier. It takes about eight minutes for light to travel from the Sun to Earth. Likewise, many of the familiar stars we see in the heavens are so distant that it takes from 10 to 100 years for their light to reach our eyes. (In other words, they lie 10 to 100 light-years from Earth. A light-year is roughly 6 trillion miles, or the distance light travels in a year.) Light from the distant galaxies may be hundreds of millions to billions of light-years away. As a result, they represent "fossil" light, some emitted even before the rise of the dinosaurs. Some of the farthest objects we can see with our telescopes are called quasars, huge galactic engines generating unbelievable amounts of power near the edge of the visible universe, which can lie up to 12 to 13 billion light-years from Earth. And now, the WMAP satellite has detected radiation emitted even before that, from the original fireball that created the universe.

To describe the universe, cosmologists sometimes use the example of looking down from the top of the Empire State Building, which soars more than a hundred floors above Manhattan. As you look down from the top, you can barely see the street level. If the base of the

Empire State Building represents the big bang, then, looking down from the top, the distant galaxies would be located on the tenth floor. The distant quasars seen by Earth telescopes would be on the seventh floor. The cosmic background measured by the WMAP satellite would be just half an inch above the street. And now the WMAP satellite has given us the precise measurement of the age of the universe to an astonishing 1 percent accuracy: 13.7 billion years.

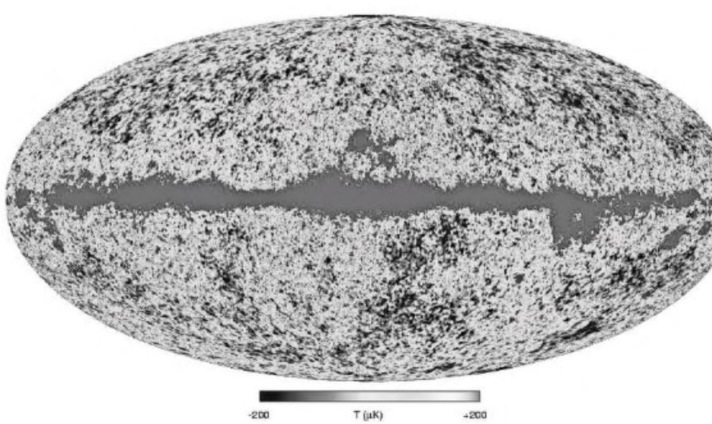
The WMAP mission is the culmination of over a decade of hard work by astrophysicists. The concept of the WMAP satellite was first proposed to NASA in 1995 and was approved two years later. On June 30, 2001, NASA sent the WMAP satellite aboard a Delta II rocket into a solar orbit perched between Earth and the Sun. The destination was carefully chosen to be the Lagrange point 2 (or L2, a special point of relative stability near Earth). From this vantage point, the satellite always points away from the Sun, Earth, and Moon and hence has a totally unobstructed view of the universe. It completely scans the entire sky every six months.

Its instrumentation is state-of-the-art. With its powerful sensors, it can detect the faint microwave radiation left over from the big bang that bathes the universe, but is largely absorbed by our atmosphere. The aluminum-composite satellite measures 3.8 meters by 5 meters (about 11.4 feet by 15 feet) and weighs 840 kilograms (1,850 pounds). It has two back-to-back telescopes that focus the microwave radiation from the surrounding sky, and eventually it radios the data back to Earth. It is powered by just 419 watts of electricity (the power of five ordinary lightbulbs). Sitting a million miles from Earth, the WMAP satellite is well above Earth's atmospheric disturbances, which can mask the faint microwave background, and it is able to get continuous readings of the entire sky.

The satellite completed its first observation of the full sky in April 2002. Six months later, the second full sky observation was made. Today, the WMAP satellite has given us the most comprehensive, detailed map of this radiation ever produced. The background microwave radiation the WMAP detected was first predicted by George Gamow and his group in 1948, who also noted that this radiation has a temperature associated with it. The WMAP measured this temperature to be just above absolute zero, or between 2.7249 to 2.7251 degrees Kelvin.

To the unaided eye, the WMAP map of the sky looks rather uninteresting; it is just a collection of random dots. However, this collection of dots has driven some astronomers almost to tears, for they represent fluctuations or irregularities in the original, fiery cataclysm of the big bang shortly after the universe was created. These tiny fluctuations are like "seeds" that have since expanded enormously as the universe itself exploded outward. Today, these tiny seeds have blossomed into the galactic clusters and galaxies we see lighting up the heavens. In other words, our own Milky Way galaxy and all the galactic clusters we see around us were once one of these tiny fluctuations. By measuring the distribution of these fluctuations, we see the origin of the galactic clusters, like dots painted on the cosmic tapestry that hangs over the night sky.

Today, the volume of astronomical data is outpacing scientists' theories. In fact, I would argue that we are entering a golden age of cosmology. (As impressive as the WMAP satellite is, it will likely be



This is a "baby picture" of the universe, as it was when it was only 380,000 years old, taken by the WMAP satellite. Each dot most likely represents a tiny quantum fluctuation in the afterglow of creation that has expanded to create the galaxies and galactic clusters we see today.

dwarfed by the Planck satellite, which the Europeans are launching in 2007; the Planck will give astronomers even more detailed pictures of this microwave background radiation.) Cosmology today is finally coming of age, emerging from the shadows of science after languishing for years in a morass of speculation and wild conjecture. Historically, cosmologists have suffered from a slightly unsavory reputation. The passion with which they proposed grandiose theories of the universe was matched only by the stunning poverty of their data. As Nobel laureate Lev Landau used to quip, "cosmologists are often in error but never in doubt." The sciences have an old adage: "There's speculation, then there's more speculation, and then there's cosmology."

As a physics major at Harvard in the late 1960s, I briefly toyed with the possibility of studying cosmology. Since childhood, I've always had a fascination with the origin of the universe. However, a quick glance at the field showed that it was embarrassingly primitive. It was not an experimental science at all, where one can test hypotheses with precise instruments, but rather a collection of loose, highly speculative theories. Cosmologists engaged in heated debates about whether the universe was born in a cosmic explosion or whether it has always existed in a steady state. But with so little data, the theories quickly outpaced the data. In fact, the less the data, the fiercer the debate.

Throughout the history of cosmology, this paucity of reliable data also led to bitter, long-standing feuds between astronomers, which often raged for decades. (For example, just before astronomer Allan Sandage of the Mount Wilson Observatory was supposed to give a talk about the age of the universe, the previous speaker announced sarcastically, "What you will hear next is all wrong." And Sandage, hearing of how a rival group had generated a great deal of publicity, would roar, "That's a bunch of hooey. It's war—it's war!")

THE AGE OF THE UNIVERSE

Astronomers have been especially keen to know the age of the universe. For centuries, scholars, priests, and theologians have tried to estimate the age of the universe using the only method at their disposal: the genealogy of humanity since Adam and Eve. In the last century, geologists have used the residual radiation stored in rocks to give the best estimate of the age of Earth. In comparison, the WMAP satellite today has measured the echo of the big bang itself to give us the most authoritative age of the universe. The WMAP data reveals that the universe was born in a fiery explosion that took place 13.7 billion years ago.

(Over the years, one of the most embarrassing facts plaguing cosmology has been that the age of the universe was often computed to be younger than the age of the planets and stars, due to faulty data. Previous estimates for the age of the universe were as low as 1 to 2 billion years, which contradicted the age of Earth [4.5 billion years] and the oldest stars [12 billion years]. These contradictions have now been eliminated.)

The WMAP has added a new, bizarre twist to the debate over what the universe is made of, a question that the Greeks asked over two thousand years ago. For the past century, scientists believed that they knew the answer to this question. After thousands of painstaking experiments, scientists had concluded that the universe was basically made of about a hundred different types of atoms, arranged in an orderly periodic chart, beginning with elemental hydrogen. This forms the basis of modern chemistry and is, in fact, taught in every high school science class. The WMAP has now demolished that belief.

Confirming previous experiments, the WMAP satellite showed that the visible matter we see around us (including the mountains, planets, stars, and galaxies) makes up a paltry 4 percent of the total matter and energy content of the universe. (Of that 4 percent, most of it is in the form of hydrogen and helium, and probably only 0.03 percent takes the form of the heavy elements.) Most of the universe is actually made of mysterious, invisible material of totally unknown origin. The familiar elements that make up our world constitute only 0.03 percent of the universe. In some sense, science is being thrown back centuries into the past, before the rise of the atomic hypothesis, as physicists grapple with the fact that the universe is dominated by entirely new, unknown forms of matter and energy.

According to the WMAP, 23 percent of the universe is made of a strange, undetermined substance called dark matter, which has weight, surrounds the galaxies in a gigantic halo, but is totally invisible. Dark matter is so pervasive and abundant that, in our own Milky Way galaxy, it outweighs all the stars by a factor of 10. Although invisible, this strange dark matter can be observed indirectly by scientists because it bends starlight, just like glass, and hence can be located by the amount of optical distortion it creates.

Referring to the strange results obtained from the WMAP satellite, Princeton astronomer John Bahcall said, "We live in an implausible, crazy universe, but one whose defining characteristics we now know."

But perhaps the greatest surprise from the WMAP data, data that sent the scientific community reeling, was that 73 percent of the universe, by far the largest amount, is made of a totally unknown form of energy called dark energy, or the invisible energy hidden in the vacuum of space. Introduced by Einstein himself in 1917 and then later discarded (he called it his "greatest blunder"), dark energy, or the energy of nothing or empty space, is now re-emerging as the driving force in the entire universe. This dark energy is now believed to create a new antigravity field which is driving the galaxies apart. The ultimate fate of the universe itself will be determined by dark energy.

No one at the present time has any understanding of where this "energy of nothing" comes from. "Frankly, we just don't understand it. We know what its effects are [but] we're completely clueless . . . everybody's clueless about it," admits Craig Hogan, an astronomer at the University of Washington at Seattle.

If we take the latest theory of subatomic particles and try to compute the value of this dark energy, we find a number that is off by 10^{120} (that's the number 1 followed by 120 zeros). This discrepancy between theory and experiment is far and away the largest gap ever found in the history of science. It is one of our greatest embarrassments—our best theory cannot calculate the value of the largest source of energy in the entire universe. Surely, there is a shelf full of Nobel Prizes waiting for the enterprising individuals who can unravel the mystery of dark matter and dark energy.

INFLATION

Astronomers are still trying to wade through this avalanche of data from the WMAP. As it sweeps away older conceptions of the universe, a new cosmological picture is emerging. "We have laid the cornerstone of a unified coherent theory of the cosmos," declares Charles L. Bennett, who led an international team that helped to build and analyze the WMAP satellite. So far, the leading theory is the "inflationary universe theory," a major refinement of the big bang theory, first proposed by physicist Alan Guth of MIT. In the inflationary scenario, in the first trillionth of a trillionth of a second, a mysterious antigravity force caused the universe to expand much faster than originally thought. The inflationary period was unimaginably explosive, with the universe expanding much faster than the speed of light. (This does not violate Einstein's dictum that nothing can travel faster than light, because it is empty space that is expanding. For material objects, the light barrier cannot be broken.) Within a fraction of a second, the universe expanded by an unimaginable factor of 10^{50}.

To visualize the power of this inflationary period, imagine a balloon that is being rapidly inflated, with the galaxies painted on the surface. The universe that we see populated by the stars and galaxies all lies on the surface of this balloon, rather than in the interior. Now draw a microscopic circle on the balloon. This tiny circle represents the visible universe, everything we can see with our telescopes. (By comparison, if the entire visible universe were as small as a subatomic particle, then the actual universe would be much larger than the visible universe that we see around us.) In other words, the inflationary expansion was so intense that there are whole regions of the universe beyond our visible universe that will forever be beyond our reach.

The inflation was so enormous, in fact, that the balloon seems flat in our vicinity, a fact that has been experimentally verified by the WMAP satellite. In the same way that the earth appears flat to us because we are so small compared to the radius of Earth, the universe appears flat only because it is curved on a much larger scale.

By assuming that the early universe underwent this process of inflation, one can almost effortlessly explain many of the puzzles concerning the universe, such as why it appears to be flat and uniform. Commenting on the inflation theory, physicist Joel Primack has said, "No theory as beautiful as this has ever been wrong before."

THE MULTIVERSE

The inflationary universe, although it is consistent with the data from the WMAP satellite, still does not answer the question: what caused inflation? What set off this antigravity force that inflated the universe? There are over fifty proposals explaining what turned on inflation and what eventually terminated it, creating the universe we see around us. But there is no universal consensus. Most physicists rally around the core idea of a rapid inflationary period, but there is no definitive proposal to answer what the engine behind inflation is.

Because no one knows precisely how inflation started, there is always the possibility that the same mechanism can take place again—that inflationary explosions can happen repeatedly. This is the idea proposed by Russian physicist Andrei Linde of Stanford University—that whatever mechanism caused part of the universe to suddenly inflate is still at work, perhaps randomly causing other distant regions of the universe to inflate as well.

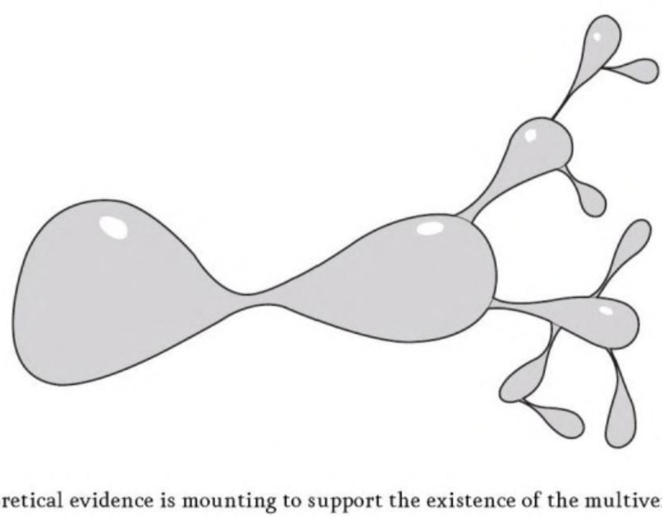
According to this theory, a tiny patch of a universe may suddenly inflate and "bud," sprouting a "daughter" universe or "baby" universe, which may in turn bud another baby universe, with this budding process continuing forever. Imagine blowing soap bubbles into the air. If we blow hard enough, we see that some of the soap bubbles split in half and generate new soap bubbles. In the same way, universes may be continually giving birth to new universes. In this scenario, big bangs have been happening continually. If true, we may live in a sea of such universes, like a bubble floating in an ocean of other bubbles. In fact, a better word than "universe" would be "multiverse" or "megaverse."

Linde calls this theory eternal, self-reproducing inflation, or "chaotic inflation," because he envisions a never-ending process of continual inflation of parallel universes. "Inflation pretty much forces the idea of multiple universes upon us," declares Alan Guth, who first proposed the inflation theory.

This theory also means that our universe may, at some time, bud a baby universe of its own. Perhaps our own universe may have gotten its start by budding off from a more ancient, earlier universe.

As the Astronomer Royal of Great Britain, Sir Martin Rees, has said, "What's conventionally called 'the universe' could be just one member of an ensemble. Countless other ways may exist in which the laws are different. The universe in which we've emerged belongs to the unusual subset that permits complexity and consciousness to develop."

All this research activity on the subject of the multiverse has given rise to speculation about what these other universes may look like, whether they harbor life, and even whether it's possible to eventually make contact with them. Calculations have been made by



Theoretical evidence is mounting to support the existence of the multiverse, in which entire universes continually sprout or "bud" off other universes. If true, it would unify two of the great religious mythologies, Genesis and Nirvana. Genesis would take place continually within the fabric of timeless Nirvana.

scientists at Cal Tech, MIT, Princeton, and other centers of learning to determine whether entering a parallel universe is consistent with the laws of physics.

M-THEORY AND THE ELEVENTH DIMENSION

The very idea of parallel universes was once viewed with suspicion by scientists as being the province of mystics, charlatans, and cranks. Any scientist daring to work on parallel universes was subject to ridicule and was jeopardizing his or her career, since even today there is no experimental evidence proving their existence.

But recently, the tide has turned dramatically, with the finest minds on the planet working furiously on the subject. The reason for this sudden change is the arrival of a new theory, string theory, and its latest version, M-theory, which promise not only to unravel the nature of the multiverse but also to allow us to "read the Mind of God," as Einstein once eloquently put it. If proved correct, it would represent the crowning achievement of the last two thousand years of research in physics, ever since the Greeks first began the search for a single coherent and comprehensive theory of the universe.

The number of papers published in string theory and M-theory is staggering, amounting to tens of thousands. Hundreds of international conferences have been held on the subject. Every single major university in the world either has a group working on string theory or is desperately trying to learn it. Although the theory is not testable with our feeble present-day instruments, it has sparked enormous interest among physicists, mathematicians, and even experimentalists who hope to test the periphery of the theory in the future with powerful gravity wave detectors in outer space and huge atom smashers.

Ultimately, this theory may answer the question that has dogged cosmologists ever since the big bang theory was first proposed: what happened before the big bang?

This requires us to bring to bear the full force of our physical knowledge, of every physical discovery accumulated over the centuries. In other words, we need a "theory of everything," a theory of every physical force that drives the universe. Einstein spent the last thirty years of his life chasing after this theory, but he ultimately failed.

At present, the leading (and only) theory that can explain the diversity of forces we see guiding the universe is string theory or, in its latest incarnation, M-theory. (M stands for "membrane" but can also mean "mystery," "magic," even "mother." Although string theory and M-theory are essentially identical, M-theory is a more mysterious and more sophisticated framework which unifies various string theories.)

Ever since the Greeks, philosophers have speculated that the ultimate building blocks of matter might be made of tiny particles called atoms. Today, with our powerful atom smashers and particle accelerators, we can break apart the atom itself into electrons and nuclei, which in turn can be broken into even smaller subatomic particles. But instead of finding an elegant and simple framework, it was distressing to find that there were hundreds of subatomic particles streaming from our accelerators, with strange names like neutrinos, quarks, mesons, leptons, hadrons, gluons, W-bosons, and so forth. It is hard to believe that nature, at its most fundamental level, could create a confusing jungle of bizarre subatomic particles.

String theory and M-theory are based on the simple and elegant idea that the bewildering variety of subatomic particles making up the universe are similar to the notes that one can play on a violin string, or on a membrane such as a drum head. (These are no ordinary strings and membranes; they exist in ten- and eleven-dimensional hyperspace.)

Traditionally, physicists viewed electrons as being point particles, which were infinitesimally small. This meant physicists had to introduce a different point particle for each of the hundreds of subatomic particles they found, which was very confusing. But according to string theory, if we had a supermicroscope that could peer into the heart of an electron, we would see that it was not a point particle at all but a tiny vibrating string. It only appeared to be a point particle because our instruments were too crude.

This tiny string, in turn, vibrates at different frequencies and resonances. If we were to pluck this vibrating string, it would change mode and become another subatomic particle, such as a quark. Pluck it again, and it turns into a neutrino. In this way, we can explain the blizzard of subatomic particles as nothing but different musical notes of the string. We can now replace the hundreds of subatomic particles seen in the laboratory with a single object, the string.

In this new vocabulary, the laws of physics, carefully constructed after thousands of years of experimentation, are nothing but the laws of harmony one can write down for strings and membranes. The laws of chemistry are the melodies that one can play on these strings. The universe is a symphony of strings. And the "Mind of God," which Einstein wrote eloquently about, is cosmic music resonating throughout hyperspace. (Which raises another question: If the universe is a symphony of strings, then is there a composer? I address this question in chapter 12.)

MUSICAL ANALOGY	STRING COUNTERPART
Musical notation	Mathematics
Violin strings	Superstrings
Notes	Subatomic particles
Laws of harmony	Physics
Melodies	Chemistry
Universe	Symphony of strings
"Mind of God"	Music resonating through hyperspace
Composer	?

THE END OF THE UNIVERSE

The WMAP not only gives the most accurate glimpse of the early universe, it also gives the most detailed picture of how our universe will die. Just as the mysterious antigravity force pushed the galaxies apart at the beginning of time, this same antigravity force is now pushing the universe to its final fate. Previously, astronomers thought that the expansion of the universe was gradually winding down. Now, we realize that the universe is actually accelerating, with the galaxies hurtling away from us at increasing speed. The same dark energy that makes up 73 percent of the matter and energy in the universe is accelerating the expansion of the universe, pushing the galaxies apart at ever increasing speeds. "The universe is behaving like a driver who slows down approaching a red stoplight and then hits the accelerator when the light turns green," says Adam Riess of the Space Telescope Institute.

Unless something happens to reverse this expansion, within 150 billion years our Milky Way galaxy will become quite lonely, with 99.99999 percent of all the nearby galaxies speeding past the edge of the visible universe. The familiar galaxies in the night sky will be rushing so fast away from us that their light will never reach us. The galaxies themselves will not disappear, but they will be too far for our telescopes to observe them anymore. Although the visible universe contains approximately 100 billion galaxies, in 150 billion years only a few thousand galaxies in the local supercluster of galaxies will be visible. Even further in time, only our local group, consisting of about thirty-six galaxies, will comprise the entire visible universe, with billions of galaxies drifting past the edge of the horizon. (This is because the gravity within the local group is sufficient to overcome this expansion. Ironically, as the distant galaxies slip away from view, any astronomer living in this dark era may fail to detect an expansion in the universe at all, since the local group of galaxies itself does not expand internally. In the far future, astronomers analyzing the night sky for the first time might not realize that there is any expansion and conclude that the universe is static and consists of only thirty-six galaxies.)

If this antigravity force continues, the universe will ultimately die in a big freeze. All intelligent life in the universe will eventually freeze in an agonizing death, as the temperature of deep space plunges toward absolute zero, where the molecules themselves can

CHAPTER TWO

The Paradoxical Universe

Had I been present at the creation, I would have given some useful hints for the better ordering of the universe.

—Alphonse the Wise

Damn the solar system. Bad light; planets too distant; pestered with comets; feeble contrivance; could make a better [universe] myself.

—Lord Jeffrey

IN THE PLAY *As You Like It*, Shakespeare wrote the immortal words

All the world's a stage,
And all the men and women merely players.
They have their exits and their entrances.

During the Middle Ages, the world was indeed a stage, but it was a small, static one, consisting of a tiny, flat Earth around which the heavenly bodies moved mysteriously in their perfect celestial orbs. Comets were seen as omens foretelling the death of kings. When the great comet of 1066 sailed over England, it terrified the Saxon soldiers of King Harold, who quickly lost to the advancing, victorious troops of William the Conqueror, setting the stage for the formation of modern England.

That same comet sailed over England once again in 1682, again instilling awe and fear throughout Europe. Everyone, it seemed, from peasants to kings, was mesmerized by this unexpected celestial visitor which swept across the heavens. Where did the comet come from? Where was it going, and what did it mean?

One wealthy gentleman, Edmund Halley, an amateur astronomer, was so intrigued by the comet that he sought out the opinions of one of the greatest scientists of the day, Isaac Newton. When he asked Newton what force might possibly control the motion of the comet, Newton calmly replied that the comet was moving in an ellipse as a consequence of an inverse square force law (that is, the force on the comet diminished with the square of its distance from the sun). In fact, said Newton, he had been tracking the comet with a telescope that he had invented (the reflecting telescope used today by astronomers around the world) and its path was following his law of gravitation that he had developed twenty years earlier.

Halley was shocked beyond belief. "How do you know?" demanded Halley. "Why, I have calculated it," replied Newton. Never in his wildest dreams did Halley expect to hear that the secret of the celestial bodies, which had mystified humanity since the first humans gazed at the heavens, could be explained by a new law of gravity.

Staggered by the significance of this monumental breakthrough, Halley generously offered to pay for the publication of this new theory. In 1687, with Halley's encouragement and funding, Newton published his epic work *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)*. It has been hailed as one of the most important works ever published. In a single stroke, scientists who were ignorant of the larger laws of the solar system were suddenly able to predict, with pinpoint precision, the motion of heavenly bodies.

So great was the impact of *Principia* in the salons and courts of Europe that the poet Alexander Pope wrote:

Nature and nature's laws lay hid in the night,
God said, Let Newton Be! *and all was light.*

(Halley realized that if the comet's orbit was an ellipse, one might be able to calculate when it might sail over London again. Searching old records, he found that the comets of 1531, 1607, and 1682 were indeed the same comet. The comet that was so pivotal to the creation of modern England in 1066 was seen by people throughout recorded history, including Julius Caesar. Halley predicted that the comet would return in 1758, long after Newton and Halley had passed away. When the comet did indeed return on Christmas Day that year, on schedule, it was christened Halley's comet.)

Newton had discovered the universal law of gravity twenty years earlier, when the black plague shut down Cambridge University and he was forced to retreat to his country estate at Woolsthorpe. He fondly recalled that while walking around his estate, he saw an apple fall. Then he asked himself a question that would eventually change the course of human history: if an apple falls, does the moon also fall? In a brilliant stroke of genius, Newton realized that apples, the moon, and the planets all obeyed the same law of gravitation, that they were all falling under an inverse square law. When Newton found that the mathematics of the seventeenth century were too primitive to solve this force law, he invented a new branch of mathematics, the calculus, to determine the motion of falling apples and moons.

In *Principia*, Newton had also written down the laws of mechanics, the laws of motion that determine the trajectories of all terrestrial and celestial bodies. These laws laid the basis for designing machines, harnessing steam power, and creating locomotives, which in turn helped pave the way for the Industrial Revolution and modern civilization. Today, every skyscraper, every bridge, and every rocket is constructed using Newton's laws of motion.

Newton not only gave us the eternal laws of motion; he also overturned our worldview, giving us a radically new picture of the universe in which the mysterious laws governing celestial bodies were identical to the laws governing Earth. The stage of life was no longer surrounded by terrifying celestial omens; the same laws that applied to the actors also applied to the set.

BENTLEY'S PARADOX

Because *Principia* was such an ambitious work, it raised the first disturbing paradoxes about the construction of the universe. If the world is a stage, then how big is it? Is it infinite or finite? This is an age-old question; even the Roman philosopher Lucretius was fascinated by it. "The Universe is not bounded in any direction," he wrote. "If it were, it would necessarily have a limit somewhere. But clearly a thing cannot have a limit unless there is something outside to limit it . . . In all dimensions alike, on this side or that, upward or downward throughout the universe, there is no end."

But Newton's theory also revealed the paradoxes inherent in any theory of a finite or infinite universe. The simplest questions lead to a morass of contradictions. Even as Newton was basking in the fame brought to him by the publication of *Principia*, he discovered that his theory of gravity was necessarily riddled with paradoxes. In 1692, a clergyman, Rev. Richard Bentley, wrote a disarmingly simple but distressing letter to Newton. Since gravity was always attractive and never repulsive, wrote Bentley, this meant that any collection of stars would naturally collapse into themselves. If the universe was finite, then the night sky, instead of being eternal and static, should be a scene of incredible carnage, as stars plowed into each other and coalesced into a fiery superstar. But Bentley also pointed out that if the universe were infinite, then the force on any object, tugging it to the left or right, would also be infinite, and therefore the stars should be ripped to shreds in fiery cataclysms.

At first, it seemed as if Bentley had Newton checkmated. Either the universe was finite (and it collapsed into a fireball), or it was infinite (in which case all the stars would be blown apart). Either possibility was a disaster for the young theory being proposed by

Newton. This problem, for the first time in history, revealed the subtle but inherent paradoxes that riddle any theory of gravity when applied to the entire universe.

After careful thought, Newton wrote back that he found a loophole in the argument. He preferred an infinite universe, but one that was totally uniform. Thus, if a star is tugged to the right by an infinite number of stars, this is canceled exactly by an equal tug of another infinite sequence of stars in the other direction. All forces are balanced in each direction, creating a static universe. Thus, if gravity is always attractive, the only solution to Bentley's paradox is to have a uniform, infinite universe.

Newton had indeed found a loophole in Bentley's argument. But Newton was clever enough to realize the weakness of his own response. He admitted in a letter that his solution, although technically correct, was inherently unstable. Newton's uniform but infinite universe was like a house of cards: seemingly stable, but liable to collapse at the slightest disturbance. One could calculate that if even a single star is jiggled by a tiny amount, it would set off a chain reaction, and star clusters would immediately begin to collapse. Newton's feeble response was to appeal to "a divine power" that prevented his house of cards from collapsing. "A continual miracle is needed to prevent the Sun and the fixt stars from rushing together through gravity," he wrote.

To Newton, the universe was like a gigantic clock wound up at the beginning of time by God which has been ticking away ever since, according to his three laws of motion, without Divine interference. But at times, even God himself had to intervene and tweak the universe a bit, to keep it from collapsing. (In other words, occasionally God has to intervene to prevent the sets on the stage of life from collapsing on top of the actors.)

OLBERS' PARADOX

In addition to Bentley's paradox, there was an even deeper paradox inherent in any infinite universe. Olbers' paradox begins by asking best an amateur scientist, have perceived the right explanation 140 years ago when in our colleges the wrong explanation . . . is still being taught?"

In 1901, Scottish physicist Lord Kelvin also discovered the correct answer. He realized that when you look at the night sky, you are looking at it as it was in the past, not as it is now, because the speed of light, although enormous by earth standards (186,282 miles per second), is still finite, and it takes time for light to reach Earth from the distant stars. Kelvin calculated that for the night sky to be white, the universe would have to extend hundreds of trillions of light-years. But because the universe is not trillions of years old, the sky is necessarily black. (There is also a second, contributing reason why the night sky is black, and that is the finite lifespan of the stars, which is measured in billions of years.)

Recently, it has become possible to experimentally verify the correctness of Poe's solution, using satellites like the Hubble space telescope. These powerful telescopes, in turn, allow us to answer a question even children ask: Where is the farthest star? And what lies beyond the farthest star? To answer these questions, astronomers programmed the Hubble space telescope to perform a historic task: to take a snapshot of the farthest point in the universe. To capture extremely faint emissions from the deepest corners of space, the telescope had to perform an unprecedented task: to aim at precisely the same point in the sky near the constellation Orion for a total of several hundred hours, which required the telescope to be aligned perfectly for four hundred orbits of Earth. The project was so difficult that it had to be spread out over four months.

In 2004, a stunning photograph was released which made front-page headlines around the world. It showed a collection of ten thousand infant galaxies as they condensed out of the chaos of the big bang itself. "We might have seen the end of the beginning," declared Anton Koekemoer of the Space Telescope Science Institute. The photograph showed a jumble of faint galaxies over 13 billion light-years from Earth—that is, it took over 13 billion years for their light to reach Earth. Since the universe itself is only 13.7 billion years old, this means these galaxies were formed roughly half a billion years after creation, when the first stars and galaxies were condensing out of the "soup" of gases left over from the big bang. "Hubble takes us to within a stone's throw of the big bang itself," said astronomer Massimo Stivavelli of the Institute.

But this raises the question: What lies beyond the farthest galaxies? When peering at this remarkable photograph, what is quite apparent is that there is only blackness between these galaxies. This blackness is what causes the night sky to be black. It is the ultimate cutoff for light from the distant stars. However, this blackness in turn is actually the background microwave radiation. So the final answer to the question of why the night sky is black is that the night sky is not really black at all. (If our eyes could somehow see microwave radiation, and not just visible light, we would see radiation from the big bang itself flooding the night sky. In some sense, radiation from the big bang comes out every night. If we had eyes able to see microwaves, we could see that beyond the farthest star lies creation itself.)

EINSTEIN THE REBEL

Newton's laws were so successful that it took over two hundred years for science to take the next fateful step, with the work of Albert Einstein. Einstein started his career as a most unlikely candidate for such a revolutionary. After he graduated with a bachelor's degree from the Polytechnic Institute in Zurich, Switzerland, in 1900, he found himself hopelessly unemployable. His career was sabotaged by his professors, who disliked this impudent, cocky student who often cut classes. His pleading, depressing letters show the depths to which he descended. He considered himself to be a failure and a painful financial burden on his parents. In one poignant letter, he confessed that he even considered ending his life: "The misfortune of my poor parents, who for so many years have not had a happy moment, weighs most heavily on me . . . I am nothing but a burden to my relatives . . . It would surely be better if I did not live at all," he wrote dejectedly.

In desperation, he thought of switching careers and joining an insurance company. He even took a job tutoring children but got into an argument with his employer and was fired. When his girlfriend, Mileva Maric, unexpectedly became pregnant, he realized sadly that their child would be born illegitimate because he did not have the resources to marry her. (No one knows what eventually happened to his illegitimate daughter, Lieseral.) And the deep, personal shock he felt when his father suddenly died left an emotional scar from which he never fully recovered. His father died thinking his son was a failure.

Although 1901–02 was perhaps the worst period in Einstein's life, what saved his career from oblivion was the recommendation of a classmate, Marcel Grossman, who was able to pull some strings and secure a job for him as a lowly clerk at the Swiss Patent Office in Bern.

PARADOXES OF RELATIVITY

On the surface, the Patent Office was an unlikely place from which to launch the greatest revolution in physics since Newton. But it had its advantages. After quickly disposing of the patent applications piling up on his desk, Einstein would sit back and return to a dream he had when he was a child. In his youth, Einstein had read a book, Aaron Bernstein's *People's Book on Natural Science*, "a work which I read with breathless attention," he recalled. Bernstein asked the reader to imagine riding alongside electricity as it raced down a telegraph wire. When he was sixteen, Einstein asked himself a similar question: what would a light beam look like if you could catch up to it? Einstein would recall, "Such a principle resulted from a paradox upon which I had already hit at the age of sixteen: If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations." As a child, Einstein thought that if you could race alongside a light beam, it should appear frozen, like a motionless wave. However, no one had ever seen frozen light, so something was terribly wrong.

At the turn of the century, there were two great pillars of physics upon which everything rested: Newton's theory of mechanics and gravity, and Maxwell's theory of light. In the 1860s, Scottish physicist James Clerk Maxwell had shown that light consists of vibrating electric and magnetic fields constantly changing into each other. What Einstein discovered, much to his shock, was that these two pillars were in contradiction to each other, and that one of them had to fall.

Within Maxwell's equations, he found the solution to the puzzle that had haunted him for ten years. Einstein found something that Maxwell himself had missed: Maxwell's equations showed that light traveled at a constant velocity, no matter how fast you tried to catch up to it. The speed of light *c* was the same in all inertial frames (that is, frames traveling at constant velocity). Whether you were standing still, riding on a train, or sitting on a speeding comet, you would see a light beam racing ahead of you at the same speed. No matter how fast you moved, you could never outrace light.

This immediately led to a thicket of paradoxes. Imagine, for the moment, an astronaut trying to catch up to a speeding light beam. The astronaut blasts off in his rocket ship until he is racing neck-and-neck with the light beam. A bystander on Earth witnessing this hypothetical chase would claim that the astronaut and the light beam were moving side by side to each other. However, the astronaut would say something completely different, that the light beam sped away from him, just as if his rocket ship were at rest.

The question confronting Einstein was: how can two people have such different interpretations of the same event? In Newton's theory, one could always catch up to a light beam; in Einstein's world, this was impossible. There was, he suddenly realized, a fundamental flaw in the very foundation of physics. In the spring of 1905, Einstein recalled, "a storm broke out in my mind." In one stroke, he finally found the solution: *time beats at different rates, depending on how fast you move.* In fact, the faster you move, the slower time progresses.

Time is not an absolute, as Newton once thought. According to Newton, time beat uniformly throughout the universe, so that the passage of one second on Earth was identical to one second on Jupiter or Mars. Clocks beat in absolute synchronization throughout the universe. To Einstein, however, different clocks beat at different rates throughout the universe.

If time could change depending on your velocity, Einstein realized, then other quantities, such as length, matter, and energy, should also change. He found that the faster you moved, the more distances contracted (which is sometimes called the Lorentz-FitzGerald contraction). Similarly, the faster you moved, the heavier you became. (In fact, as you approached the speed of light, time would slow down to a stop, distances would contract to nothing, and your mass would become infinite, which are all absurd. This is the reason why you cannot break the light barrier, which is the ultimate speed limit in the universe.)

This strange distortion of space-time led one poet to write:

There was a young fellow named Fisk
Whose fencing was exceedingly brisk.
So fast was his action,
The FitzGerald contraction
Reduced his rapier to a disk.

In the same way that Newton's breakthrough unified Earthbound physics with heavenly physics, Einstein unified space with time. But he also showed that matter and energy are unified and hence can change into each other. If an object becomes heavier the faster it moves, then it means that the energy of motion is being transformed into matter. The reverse is also true—matter can be converted into energy. Einstein computed how much energy would be converted into matter, and he came up with the formula $E = mc^2$, that is, even a tiny amount of matter m is multiplied by a huge number (the square of the speed of light) when it turns into energy E. Thus, the secret energy source of the stars themselves was revealed to be the conversion of matter into energy via this equation, which bending of the fabric of space-time itself, then the disappearance of the Sun can be compared to suddenly lifting the bowling ball from the bed. As the bed bounces back to its original shape, waves are sent down the bed sheet traveling at a definite speed. Thus, by reducing gravity to the bending of space and time, Einstein was able to reconcile gravity and relativity.

Imagine an ant trying to walk across a crumpled sheet of paper. He will walk like a drunken sailor, swaying to the left and right, as he tries to walk across the wrinkled terrain. The ant would protest that he is not drunk, but that a mysterious force is tugging on him, yanking him to the left and to the right. To the ant, empty space is full of mysterious forces that prevent him from walking in a straight path. Looking at the ant from a close distance, however, we see that there is no force at all pulling him. He is being pushed by the folds in the crumpled sheet of paper. The forces acting on the ant are an illusion caused by the bending of space itself. The "pull" of the force is actually the "push" created when he walks over a fold in the paper. In other words, gravity does not pull; space pushes.

By 1915, Einstein was finally able to complete what he called the general theory of relativity, which has since become the architecture upon which all of cosmology is based. In this startling new picture, gravity was not an independent force filling the universe but the apparent effect of the bending of the fabric of space-time. His theory was so powerful that he could summarize it in an equation about an inch long. In this brilliant new theory, the amount of bending of space and time was determined by the amount of matter and energy it contained. Think of throwing a rock into a pond, which creates a series of ripples emanating from the impact. The larger the rock, the more the warping of the surface of the pond. Similarly, the larger the star, the more the bending of space-time surrounding the star.

THE BIRTH OF COSMOLOGY

Einstein tried to use this picture to describe the universe as a whole. Unknown to him, he would have to face Bentley's paradox, formulated centuries earlier. In the 1920s, most astronomers believed that the universe was uniform and static. So Einstein started by assuming that the universe was filled uniformly with dust and stars. In one model, the universe could be compared to a large balloon or bubble. We live on the skin of the bubble. The stars and galaxies that we see surrounding us can be compared to dots painted on the surface of the balloon.

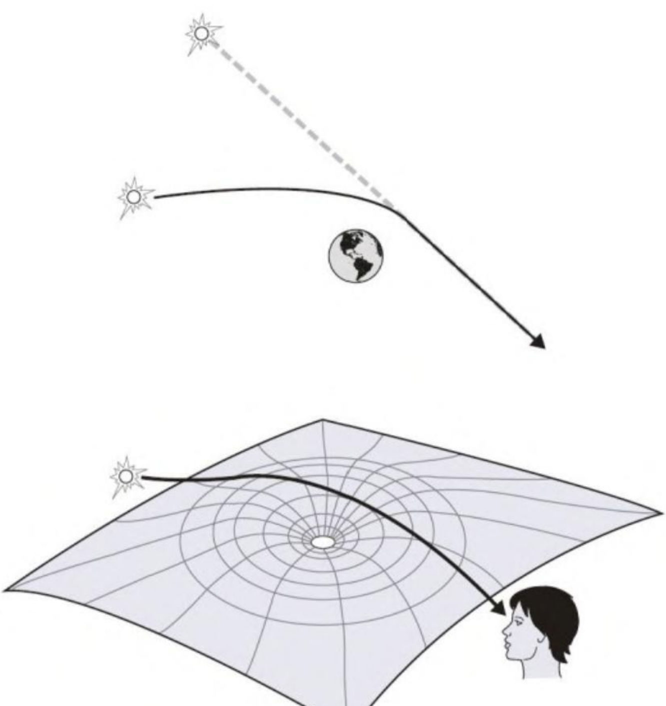
To his surprise, whenever he tried to solve his equations, he found that the universe became dynamic. Einstein faced the same problem identified by Bentley over two hundred years earlier. Since gravity is always attractive, never repulsive, a finite collection of stars should collapse into a fiery cataclysm. This, however, contradicted the prevailing wisdom of the early twentieth century, which stated that the universe was static and uniform.

As revolutionary as Einstein was, he could not believe that the universe could be in motion. Like Newton and legions of others, Einstein believed in a static universe. So in 1917, Einstein was forced to introduce a new term into his equations, a "fudge factor" that produced a new force into his theory, an "antigravity" force that pushed the stars apart. Einstein called this the "cosmological constant," an ugly duckling that seemed like an afterthought to Einstein's theory. Einstein then arbitrarily chose this antigravity to cancel precisely the attraction of gravity, creating a static universe. In other words, the universe became static by fiat: the inward contraction of the universe due to gravity was canceled by the outward force of dark energy. (For seventy years, this antigravity force was considered to be something of an orphan, until the discoveries of the last few years.)

In 1917, the Dutch physicist Willem de Sitter produced another solution to Einstein's theory, one in which the universe was infinite but was completely devoid of any matter; in fact, it consisted only of energy contained in the vacuum, the cosmological constant. This pure antigravity force was sufficient to drive a rapid, exponential expansion of the universe. Even without matter, this dark energy could create an expanding universe.

Physicists were now faced with a dilemma. Einstein's universe had matter, but no motion. De Sitter's universe had motion, but no matter. In Einstein's universe, the cosmological constant was necessary to neutralize the attraction of gravity and create a static universe. In de Sitter's universe, the cosmological constant alone was sufficient to create an expanding universe.

Finally, in 1919, when Europe was trying to dig its way out of the rubble and carnage of World War I, teams of astronomers were sent around the world to test Einstein's new theory. Einstein had earlier proposed that the curvature of space-time by the Sun would be suf-



In 1919, two groups confirmed Einstein's prediction that light from a distant star would bend when passing by the Sun. Thus, the position of the star would appear to move from its normal position in the presence of the Sun. This is because the Sun has warped the space-time surrounding it. Thus, gravity does not "pull." Rather, space "pushes."

ficient to bend starlight that is passing in its vicinity. Starlight should bend around the Sun in a precise, calculable way, similar to the way glass bends light. But since the brilliance of Sun's light masks any stars during the day, scientists would have to wait for an eclipse of the Sun to make the decisive experiment.

A group led by British astrophysicist Arthur Eddington sailed to the island of Principe in the Gulf of Guinea off the coast of West Africa to record the bending of starlight around the Sun during the next solar eclipse. Another team, led by Andrew Crommelin, set sail to Sobral in northern Brazil. The data they gathered indicated an average deviation of starlight to be 1.79 arc seconds, which confirmed Einstein's prediction of 1.74 arc seconds (to within experimental error). In other words, light did bend near the Sun. Eddington later claimed that verifying Einstein's theory was the greatest moment in his life.

On November 6, 1919, at a joint meeting of the Royal Society and the Royal Astronomical Society in London, Nobel laureate and Royal Society president J. J. Thompson said solemnly that this was "one of the greatest achievements in the history of human thought. It is not the discovery of an outlying island but of a whole continent of new scientific ideas. It is the greatest discovery in connection with gravitation since Newton enunciated his principles."

(According to legend, Eddington was later asked by a reporter, "There's a rumor that only three people in the entire world understand Einstein's theory. You must be one of them." Eddington stood in silence, so the reporter said, "Don't be modest, Eddington." Eddington shrugged, and said, "Not at all. I was wondering who the third might be.")

The next day, the London *Times* splashed the headline: "Revolution in Science—New Theory of the Universe—Newton's Ideas Overthrown." The headline marked the moment when Einstein became a world-renowned figure, a messenger from the stars.

So great was this announcement, and so radical was Einstein's departure from Newton, that it also caused a backlash, as distinguished physicists and astronomers denounced the theory. At Columbia University, Charles Lane Poor, a professor of celestial mechanics, led the criticism of relativity, saying, "I feel as if I had been wandering with Alice in Wonderland and had tea with the Mad Hatter."

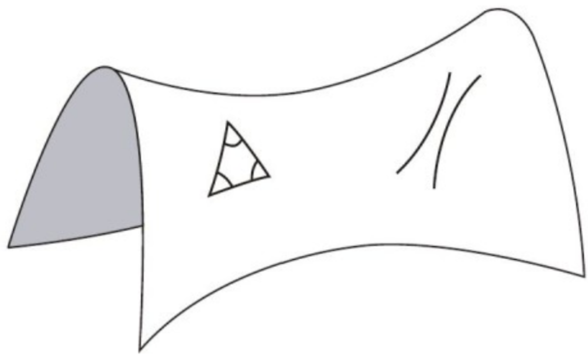
The reason that relativity violates our common sense is not that relativity is wrong, but that our common sense does not represent reality. *We* are the oddballs of the universe. We inhabit an unusual piece of real estate, where temperatures, densities, and velocities are quite mild. However, in the "real universe," temperatures can be blisteringly hot in the center of stars, or numbingly cold in outer space, and subatomic particles zipping through space regularly travel near light-speed. In other words, our common sense evolved in a highly unusual, obscure part of the universe, Earth; it is not surprising that our common sense fails to grasp the true universe. The problem lies not in relativity but in assuming that our common sense represents reality.

THE FUTURE OF THE UNIVERSE

Although Einstein's theory was successful in explaining astronomical phenomena such as the bending of starlight around the Sun and the slight wobbling of the orbit of the planet Mercury, its cosmological predictions were still confusing. Matters were greatly clarified by the Russian physicist Aleksandr Friedmann, who found the most general and realistic solutions of Einstein's equations. Even today, they are taught in every graduate course in general relativity. (He discovered them in 1922, but he died in 1925, and his work was largely forgotten until years later.)

Normally, Einstein's theory consists of a series of extraordinarily difficult equations which often require a computer to solve. However, Friedmann assumed that the universe was dynamic and then made two simplifying assumptions (called the cosmological principle): that the universe is isotropic (it looks the same no matter where we look from a given point), and that the universe is homogeneous (it is uniform no matter where you go in the universe).

Under these two simplifying assumptions, we find that these



If the Omega is less than 1 (and Lambda is 0), then the universe is open and its curvature is negative, as in a saddle. Parallel lines never meet, and the interior angles of triangles sum to less than 180 degrees.

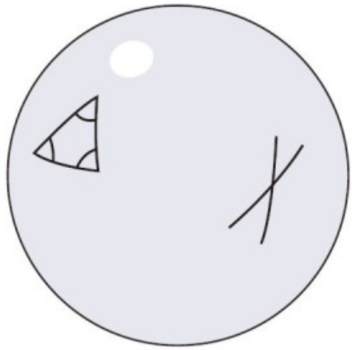
as the universe heads toward a fiery "big crunch." (Astronomer Ken Croswell labels this process "from Creation to Cremation.")

A third possibility is that Omega is perched precisely at 1; in other words, the density of the universe equals the critical density, in which case the universe hovers between the two extremes but will still expand forever. (This scenario, we will see, is favored by the inflationary picture.)

And last, there is the possibility that the universe, in the aftermath of a big crunch, can reemerge into a new big bang. This theory is referred to as the oscillating universe.

Friedmann showed that each of these scenarios, in turn, determines the curvature of space-time. If Omega is less than 1 and the universe expands forever, Friedmann showed that not only is time infinite, but space is infinite as well. The universe is said to be "open," that is, infinite in both space and time. When Friedmann computed the curvature of this universe, he found it to be negative. (This is like the surface of a saddle or a trumpet. If a bug lived on the surface of this surface, it would find that parallel lines never meet, and the interior angles of a triangle sum up to less than 180 degrees.)

If Omega is larger than 1, then the universe will eventually con-



If Omega is greater than 1, then the universe is closed and its curvature is positive, like in a sphere. Parallel lines always meet, and the angles of a triangle sum to greater than 180 degrees.

tract into a big crunch. Time and space are finite. Friedmann found that the curvature of this universe is positive (like a sphere). Finally, if Omega equals 1, then space is flat and both time and space are unbounded.

Not only did Friedmann provide the first comprehensive approach to Einstein's cosmological equations, he also gave the most realistic conjecture about Doomsday, the ultimate fate of the universe—whether it will perish in a big freeze, fry in a big crunch, or oscillate forever. The answer depends upon the crucial parameters: the density of the universe and the energy of the vacuum.

But Friedmann's picture left a gaping hole. If the universe is expanding, then it means that it might have had a beginning. Einstein's theory said nothing about the instant of this beginning. What was missing was the moment of creation, the big bang. And three scientists would eventually give us a most compelling picture of the big bang.