STEPHEN HAWKING'S UNIVERSE

John Boslough

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For my parents

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PROLOGUE

On a spring morning in 1974, a young man dressed in a suit was carried up the steps of a white-colonnaded mansion overlooking London's St. James's Park. Placed in a wheelchair inside the building, No. 6 Carlton House Terrace, he was wheeled into a large meeting room to receive one of the highest honors in Great Britain: induction into the Royal Society, one of the world's most eminent scientific bodies.

At thirty-two, Stephen William Hawking was one of the youngest inductees in society history, an honor bestowed for his work in theoretical physics. Tradition dating from the seventeenth century called for newly elected fellows to walk to the podium to shake the president's hand and sign the roll of honor. But at this investiture, Sir Alan Hodgkin, Nobel-winning biologist and president of the society, brought the roll book down from the stage to Hawking's wheelchair at the front of the room. As the new member labored over his signature, there was protracted silence. When he finished with a broad smile, thunderous applause broke out.

I met Hawking for the first time seven years later in a corridor outside the meeting hall where the investiture had taken place. We were introduced by Roger Penrose, a mathematician and theoretical physicist at Oxford University. Penrose, an old friend and collaborator of Hawking, had himself been inducted into the society just two years before, partly for work they had done together.

Since 1962 Hawking has suffered from a wasting disease called motor neuron disease. It has slowly taken most of his nervous and muscular functions. He cannot walk and can barely talk. I had been warned by Penrose and others that I would find his condition worse than I expected.

In fact, I was stunned. Before me, slumped in his wheelchair, was one of the world's foremost scientists, a man not much older than myself. I estimated his weight at no more than 110 pounds. Because he was so thin, it was impossible to judge his height, although he appeared about average—perhaps five feet nine. His face was youthful, but his body had the frailty and muscle structure of a bedridden old man.

When Penrose had concluded the introductions, Hawking began speaking in such a low voice that I had to bend down to hear. He seemed to be struggling to speak, his voice a labored moan punctuated with gasps. I looked to Penrose for guidance. He quickly translated Hawking's remark: "I'll see you in my office at eleven o'clock next Tuesday

Afterward I asked Penrose if Hawking had been having a particularly bad day. On the contrary, Penrose said. He thought Hawking looked particularly good.

I have seen Hawking many times in Cambridge and the United States. Each time I wondered how he does it. He has not walked for over twelve years, and his voice is so feeble only a few intimates can understand him, yet he has made some of the most significant strides in theoretical physics in his generation, changing the way we look at the universe.

As I came to know Hawking, the truth became apparent. His accomplishment is not due simply to his will to live or to the fact that he is a survivor, though he is certainly a tough and stubborn man. He succeeds because of his intellect, and as the ravages of his disease have, over two decades, taken his physical powers from him, he has come to live a life of the mind.

Hawking's mind is his most powerful tool. It is also his work, his plaything, his recreation, his joy—his life. His wheelchair gives him a special vantage point for the major preoccupation of that mind: the universe we inhabit, how it came into being, how it operates, and how it will end. A totally cerebral man, he demonstrates the power of the human intellect to fathom the universe when the restless mind is set free.

1

QUARKS AND QUASARS

"It is the most persistent and greatest adventure in human history, this search to understand the universe, how it works and where it came from. It is difficult to imagine that a handful of residents of a small planet circling an insignificant star in a small galaxy have as their aim a complete understanding of the entire universe, a small speck of creation truly believing it is capable of comprehending the whole."

Murray Gell-Mann, who made this statement, is one of a group of theoretical physicists engaged on this adventure. They are searching for a single interaction at the heart of the universe, one that will explain all of the phenomena that surround us.

The task of finding this single interaction is so monumental it eluded even Einstein, who spent the last thirty years of his life in an unsuccessful search for unity. We are a little closer today, nearly thirty years after Einstein's death, but still the universe seems to operate by several sets of rules that act in layers, independently of each other.

The most apparent of these basic rules of nature, gravity, controls the biggest objects in the universe—the stars, the planets, you and me. The other three that scientists have uncovered operate at the subatomic level: the strong nuclear force, trillions of times more powerful than gravitation, holds the nucleus of an atom together; electromagnetism keeps electrons in place around the nucleus, making ordinary matter seem solid; the weak nuclear force causes radioactive decay in certain atoms, like uranium.

Groping in a morass of mathematics, Einstein was unable to reconcile these different sets of natural laws. He believed in his heart that beyond them lay a final simplicity in which they could all be explained as a single law. This belief was based purely on an aesthetic appeal, a notion of an irreducible set of equations that could explain everything.

Not all physicists believe that such unification is possible. Wolfgang Pauli, an Austrian theorist, once joked, "What god hath put asunder, no man shall ever join." But a unified theory is not something science actually requires for its continued progress. Physicists need a unified theory only in the sense that Sir Edmund Hillary needed to climb Mount Everest.

If this law is found, it could prove almost meaningless, or it could lead to a new golden age of science. Scientists don't know just as they had no idea that Einstein's unification of mass and energy would lead to the age of the atom. Or that quantum mechanics, the mathematical system used by physicists to explain the movement of subatomic particles, would be used to make the first laser. Yet a unification theory remains an almost religious vision to some scientists, a Zen-like view of reality in which all the forces and all the matter in nature come from a single source.

Taking a look at the world around us today, a reconciliation of such diverse forces appears far from possible. The reason is that we live in a low-energy, cold universe, one in which forces and matter seem stable and disconnected. But the universe was not always as we observe it today. The cosmos has cooled down dramatically since the moment of its origin. As it cooled, the infant universe left a trail of clues that physicists have followed back to the beginning. There, at the instant of the Big Bang or shortly thereafter, most physicists believe, lies the key to the universe. In that instant, the four forces may have existed in the intense energy of the primordial cataclysm for a fraction of a second as a single interaction. This interaction is thought to be so basic that all subsequent forces have descended from it.

Theoretical physicists using the latest mathematical reconstructions have developed a good idea of what happened within less than a billion trillionth of a second after the Big Bang. A remarkable achievement, but still it doesn't go far enough back in time for them to see, in their equations, the moment when all the forces and laws of nature were unified.

In later stages each of the four forces has had a time of dominance in the history of the universe, like periods of ascendancy of political parties in democratic governments. In the universe we inhabit, gravitation, the weakest but most pervasive, is the major force. Its pull acts over vast distances—on galaxies, stars, and quasars, the most distant and least understood objects in the universe. Gravitation has been the major factor during almost all of the universe's fourteen- or fifteen-billion-year lifetime. Before that, in the first few seconds after the Big Bang, the weak nuclear force prevailed, and before that electromagnetism.

It is likely that the strong nuclear force was almost completely dominant during the first few billionths of a second after the Big Bang, an instant when matter and energy were one, and stars and galaxies had not yet developed. In the billionths of a second earlier in the history of the cosmos, energy was so intense that none of the four forces could be distinguished from each other. At least, most theorists have convinced themselves of that scenario.

"It is the job of the theoretical physicist, using all the mathematical tools at his disposal, to find out what happened before things cooled down enough that the four forces divided and obscured the underlying interaction," Sheldon Glashow, a Harvard theorist, told me on a rainy day in August 1982 at the Aspen Physics Center. "A lot of people, including myself, are working on that very problem. But nobody has yet shown that all the interactions were in fact one and the same in the very early universe."

Glashow has led the way in the search for the underlying interaction. During the 1960s he tried—without success—to group certain short-lived subatomic particles in ways that would lead to this unifying force. His approach kept producing unexplained and unworkable mathematical infinities.

Steven Weinberg, then at the Massachusetts Institute of Technology, and Abdus Salam, at the Imperial College in London, were more successful. Working independently, they produced in 1967 a set of equations that seemed to prove that the weak nuclear force and electromagnetism were, if certain obscuring factors were ignored, one and the same.

The beauty of the Weinberg-Salam model was that it predicted that certain events would occur under special conditions in particle accelerators, the atom smashers that physicists use to strip away the many layers of atoms. Weinberg, Salam, and Glashow shared the Nobel Prize in 1979 for this work.

During the 1970s other physicists developed different groups of calculations that purported to show that not only were the weak force and electromagnetism the same, but also that the strong force holding the nuclei of atoms together was a member of the same family. These types of calculations are called grand unified theories, or GUTs.

Some scientists are not so sure the GUTs approach is exactly on target. Murray Gell-Mann says, "They are neither grand, nor unified. It might even be said that they are not even theories—just glorified models." Still, he admits that the approach may be one of the most promising in the pursuit of the underlying interaction.

Gell-Mann himself originated the concept of quarks, the sub-subatomic particles that most theorists believe are the fundamental constituents of the protons and neutrons that make up the nuclei of every atom in the universe. Before Gell-Mann conceived and named them (indirectly from a line in James Joyce's *Finnegans Wake*, "Three quarks for Muster Mark"), particle physics was in a state of disarray, having failed miserably to cope with the dozens of new particles found in accelerators in the 1950s and early 1960s. As a result of Gell-Mann's quark synthesis, particle physicists once again viewed the atom's core as a more or less orderly little universe of its own.

Gell-Mann admits he would like to see a unification of the four forces, but he's not sure it will happen in his lifetime. "Nobody's even yet shown that the three forces at work inside the atom have the same root. Some people may be close. I don't know. But it hasn't been shown to me yet."

And what about gravity, the force we are all most familiar with? Where does it fit into grand unification? Although particle physicists may be coming close to a unified theory of the universe with the three forces that push and pull within the atom, gravitation is still the odd force out. And this despite the fact that the vast world of cosmology and the tiny universe within the atom are finally converging as particle physicists looking inward with their giant accelerators and cosmologists looking outward with their telescopes begin to realize they are looking at the same thing.

There are several groups of scientists working on unifying all four forces, trying to add gravity to the other three. Gell-Mann told me, "Most of them don't know what they're doing. They're just using various mathematical tricks." He conceded somewhat cautiously that there was one group of theorists who had a chance of making some progress toward finding this great secret of the universe.

The group is headed by Stephen Hawking at Cambridge University in England. "Hawking is the only one on the relativity side who understands particle physics," said Gell-Mann. "He's a remarkable man, an absolutely astonishing fellow."

2

AGAINST THE ODDS

Stephen Hawking was the eldest of four children of a bookish, tightly knit family. His father was a research biologist in tropical diseases for the National Institute for Medical Research. Born January 8, 1942, in Oxford, he grew up in London and in the city of St. Albans, about twenty miles to the north. From the age of eleven he attended St. Albans School, a private school his parents hoped would prepare him for entrance into Oxford University.

By the time he was eight or nine, he knew that he wanted to be a scientist. He had already shown a knack for taking clocks and radios apart to find out how they worked, and science seemed to him to be where the truth about the things surrounding him would be found. As a teenager, though, he found much of science too imprecise: "The biological sciences were too descriptive, too hazy for me," Hawking recalls. "Of course, it has become more exact today because of molecular biology." By the time he was fourteen, he had made up his mind to become a mathematician or physicist. Fearing his son would never find work, Hawking's father tried unsuccessfully to talk him out of it.

At about the same time, Hawking's mind took a skeptical turn. When he was fifteen, he tried the same dice-throwing experiments being conducted in the extrasensory program at Duke University in the 1950s. After following the Duke experiments closely for a while, he became convinced that ESP was a fraud. "Whenever the experiments got results, the experimental techniques were faulty," he says now. "Whenever the experimental techniques were sound, the results were no good."

To this day he thinks parapsychology is a waste of time. "People taking it seriously are at the stage where I was when I was a teenager," he says, laughing.

Despite these occasional bouts with precocity, he was not outstanding in secondary school. His parents worried he might fail his entrance exam for Oxford, and his father, an alumnus of University College, tried to pull strings to ensure his acceptance. But the father had underestimated the son. Stephen received a nearly perfect score on the physics section of the entrance exams and performed so well during the interview that there was no question about admission; he entered Oxford in 1959.

At Oxford, Hawking was a popular student, known for his wit, and at one time the coxswain for one of the college's eight-man rowing shells. Most of the people who remember him from those days recall a spirited undergraduate with long hair and an interest in classical music and science fiction. He took an independent and freewheeling approach to studies although his tutor, Dr. Robert Berman, recalls that he and other dons were aware that Hawking had a first-rate mind, "completely different from his contemporaries."

He was so good at physics that he had to put little work into it. "Undergraduate physics was simply not a challenge for him," says Berman. "He could do any problem put before him without even trying." One day in class after reading a solution he had worked out, he balled the paper up and disdainfully threw it across the room into a wastebasket.

Hawking could prove forgetful at appropriately crucial —or convenient—moments. During his last year at Oxford, he applied for a job with Britain's Ministry of Works. He then forgot to appear for the examination. Had he passed, he might well have ended up taking care of monuments.

When it came time to graduate, Hawking needed first-class honors to receive a scholarship for a graduate physics program at Cambridge University, Oxford's ancient rival eighty miles to the northeast. At a crucial oral exam he responded thus to an examiner about his plans: "If I get a first, I shall go to Cambridge. If I receive a second, I will remain at Oxford. So I expect that you will give me a first." Those who know him agree it's pure Hawking.

Dr. Berman reported later of Hawking's meeting with the examiners: "At least they were intelligent enough to realize they were talking to someone more intelligent than they." Hawking received his first and entered the graduate program at Cambridge the following year.

By then Hawking had settled on a career in theoretical physics, specializing in cosmology. He had considered other areas in physics, but only briefly. Once, while taking a special summer course at the Royal Greenwich observatory, he helped Sir Richard Woolley, then Great Britain's Royal Astronomer, measure the constituents of a double star. When he looked through the observatory's telescope, he was profoundly disappointed to see just a pair of fuzzy spots of light going in and out of focus.

Since then he has only looked through a telescope once or twice and has remained unimpressed with observational astronomy. Theory was always more exciting for Hawking, and cosmology the most exciting of all, since it involves the question, Where does the universe come from?

By the time he was in graduate school he had begun showing signs of becoming a top theoretical physicist. Roger Penrose, then a research associate at King's College, London, recalls first coming across Hawking in those days. "He used to ask the most awkward questions, questions that were very difficult to answer," Penrose remembers. "He would always take aim right at the weakest part of your argument. But it was not easy then to tell how original he was going to become."

Signs of serious illness initially appeared at the beginning of his first year in graduate school—a lack of dexterity and slight paralysis that made it difficult for Hawking to tie his shoes and, occasionally, to talk. After some initial difficulty, doctors diagnosed the disease as amyotrophic lateral sclerosis, or motor neuron disease, a rare and potentially crippling disease. It is sometimes called Lou Gehrig's disease, after the Yankee first baseman who died from it. The same disease claimed the life of David Niven in 1983.

Motor neuron disease is marked by the gradual disintegration of nerve cells in the spinal cord and brain that regulate voluntary muscular activity. The first symptoms are weakness and twitching of the hands along with, perhaps, slurred speech or difficulty in swallowing. As the neurons stop functioning, the muscles under their control atrophy; a victim becomes increasingly disabled although the mind remains lucid. Death usually occurs from either pneumonia or suffocation, when the respiratory muscles finally fail.

Doctors hoped that Hawking's illness would stabilize, but his condition continued to deteriorate. He was given just a couple of years to live. "I was understandably quite depressed at the prognosis," Hawking recalls. The prospect of an early death propelled him into a stupefying depression for two years, a period in which he spent little time on his research and a great deal of time in his room listening to classical music—mostly Wagner—and reading science fiction. He also began "drinking a fair amount."

His tutor, a theorist named Dennis Sciama who headed the general relativity group at Cambridge, was both aware of his student's potential and concerned about his illness. "He always had a feeling for what we were discussing. With other bright students, it might take a couple of years. With Stephen it was just a month. He was always saying, 'But . . .' to almost any statement you would make." Sciama allowed Hawking to indulge his depression. If he wanted to drink himself into a stupor to forget his troubles, fine; if he didn't want to work on his thesis, too bad. But Sciama turned down an appeal from Hawking's father to help his son finish his dissertation early.

As the months passed, Hawking's condition finally began to stabilize. He realized that death was not imminent. His spirits lifted, and with the encouragement of friends, family, and tutor, his natural buoyancy reappeared. He also began to realize that he was working in a purely cerebral area—one with virtually no emphasis on human physical prowess. The disease had not affected his mind; it would not affect his work. The depression vanished, Sciama urged him on, and he started to work on his dissertation again.

At about this time, one of the most important events in Hawking's life occurred: He attended a party and met Jane Wilde, a student of languages in London. In 1965, after a two-year courtship carried on between London and Cambridge, they were married. "He already had the beginnings of the condition when I first knew him, so I've never known a fit, able-bodied Stephen," she says. "I simply decided what I was going to do, and I did it."

Hawking's marriage was the turning point. "It made me determined to live, to go on. Jane really gave me the will to live."

Everybody who knows her describes Jane Wilde Hawking as a remarkable woman. During the first year of their marriage, she commuted between London and Cambridge so she could finish up her own graduate studies, and in the meanwhile typed her husband's dissertation. For nearly two decades she has taken care of Hawking's physical needs and has made certain that the Hawking family leads a relatively normal life, in spite of both Hawking's disability and the fame that has recently come his way. Their first child, Robert, was born in 1967. A daughter, Lucy, arrived three years later, and Timothy was born in 1979.

Although Jane and other people around Stephen are protective to a degree, they all tend to ignore his condition. "Stephen doesn't make any concessions to his illness, and I don't make any concessions to him," Jane once said. The major problem in their life is not her husband's physical condition; it is that she cannot follow all the details of his work in theoretical physics.

During the three years after he received his doctorate, Hawking worked as a research associate at Cambridge and began collaborating with Penrose on what was to be his first major piece of research, the mathematical proof of the beginning of time. His physical condition was deteriorating again, and by the early 1970s Hawking was permanently confined to a wheelchair. But by then his mind was soaring. His induction into the Royal Society in

1974 was a stunning triumph for a man who, a decade earlier, thought he would not live to his twenty-fifth birthday.

Those were happy years, both professionally and personally, for Jane and Stephen Hawking. Since then his condition has more or less stabilized, although some of his colleagues believe that it has become more difficult to understand him in the past year or two. And some of his friends, particularly those who do not see him regularly, fear that his overall condition has begun worsening again over the past few years.

The dirty brick structure housing the Department of Applied Mathematics and Theoretical Physics, where Hawking works, looks like an abandoned nineteenth-century factory lost among the Gothic façades and spires of Cambridge. Its main door faces onto an alleyway off Silver Street. Toward the rear of the building, in another alley, is a twenty-five-foot ramp Hawking uses to enter the building through a swinging door. He commutes each day by motorized wheelchair from his home on the ground floor of a Victorian house in West Road about a half mile away.

The office facing into a gray and uninviting lounge is scientific gothic. It contains racks of physics texts, a computer terminal, pictures of three handsome children, and a special page turner Hawking fought the bureaucracy to obtain. There is also a specially fitted telephone that now sits idle. Lists of scientific papers are suspended by transparent tape on the walls so he can view them easily.

It is almost impossible to understand Hawking upon first meeting him. After a few hours of listening closely to his thin monotone—translated by Judy Fella, the young woman who was then his secretary—I found I could understand about half of what he was saying. Some words were incomprehensible even to Fella, who had worked with him for years, and Hawking was forced to spell them out. I told him, to his amusement, that part of the problem for an American in understanding him was his British accent.

As he works, his body occasionally droops down into his wheelchair, his head sometimes collapsing onto his chest. He has almost no head or facial control, and a smile sometimes turns into a grimace. Nonetheless, when I first appeared in his office, Hawking greeted me with an impish grin, his blue eyes twinkling behind heavy glasses.

His brown hair, flecked with gray, is early Beatles, and he normally dresses in standard scientist garb: baggy trousers, garish tie often mismatched with a broad-striped shirt, plaid or tweed sport coat, academic soft soles or boots with bottoms noticeably unused.

Hawking thinks things through carefully before speaking so that he will not have to repeat himself. He does not waste words. Sometimes after he stops working for a few minutes—for a bit of secretarial business or tea—he resumes talking in midsentence exactly where he left off. He so completely ignores his physical limitations that, after a while, I found myself doing the same.

One day, as I spoke with him, I had become so fully oblivious to his condition that I carelessly began talking about a problem I was having with my elbow as the result of a squash match in London the day before. Hawking made no comment. He simply steered his wheelchair out of the room and waited in the hall for me to return to the subject at hand, theoretical physics.

Most days at work Hawking just thinks. He spends much of his time developing new approaches to problems in theoretical physics. One of his colleagues, Ian Moss, told me one morning, "Stephen comes up with all the ideas. The rest of us only test them out to see if they work."

Hawking is blessed with a prodigious memory. He is able to work out and retain page after page of complex equations, weaving the mathematical hieroglyphs together as an ordinary person might arrange the words in a sentence. The University of Alberta's Werner Israel, a theoretical physicist and Hawking's co-author on the book *General Relativity*, has said that his feats of memory are akin to Mozart's composing an entire symphony in his head.

His colleagues are constantly stunned by what Hawking has remembered. A secretary who worked for him while he was visiting the California Institute of Technology said he once recalled twenty-four hours later a tiny mistake he had made while dictating—from memory—forty pages of equations.

One of Hawking's students told me that, while driving him to London for a physics conference once, Hawking remembered the page number of a minute mistake he had read in a book years before. Other physicists have said that the complex equations that pour forth finished from his mind are both elegant and inspired—the ultimate accolades for a theoretical physicist.

Hawking's work has drawn an outstanding group of theoretical physicists to Cambridge from both sides of the Atlantic. Most days at lunch and again at teatime they assemble to share their wit and wisdom with Hawking. The setting is nineteenth-century institutional. But the discussion is twenty-first-century science fiction, jumping from red shifts and quantum effects to black holes and singularities at the beginning of time, light-years beyond the surroundings.

The talk is fast, punctuated with put-downs and one-liners. "Hey, Stephen's showing his age," one graduate student says when Hawking makes a minor mathematical error. Hawking lights up at such lines, and the sessions can be the high point of the day. One of his students once told me that teatime with Stephen can be more enlightening than a semester with somebody else.

It is remarkable that Hawking has been able to achieve what he has. Doctors, in fact, believe it is a miracle he is alive. An American doctor familiar with Hawking's disease told me that each day he lives he sets a new medical record.

Hawking's colleagues shake their heads at such dramatic pronouncements. "Stephen's just Stephen," a former graduate student of his, Malcolm Perry, now a physicist at Princeton University, said. "He doesn't take it very seriously, so we don't either."

Gerald Wasserburg, a geologist and physicist at the California Institute of Technology, who has met Hawking at a number of conferences, says of him, "He is one of the most striking examples in the history of science of the power of the human intellect."

However, Hawking is not without his critics in the tightly knit physics community. One top theoretician at Princeton told me once, "He's working on the same things everybody else is. He just receives a lot of attention because of his condition." Other physicists have accused him of being overly dramatic and argumentative at science conferences.

Despite these bouts with temperamental and jealous colleagues, Hawking's work has been widely honored. In 1978 he received the Albert Einstein Award, considered by some the highest honor in theoretical physics.

In 1982 alone he received honorary degrees from Notre Dame, the University of Chicago, Princeton, and New

York University. Queen Elizabeth has named him a Commander of the British Empire. The media have frequently labeled Hawking this half century's answer to Einstein. Hawking himself disputes such notions with one of his standard remarks: "You shouldn't believe everything you read."

3

GALILEO'S EYES

Stephen Hawking suggested to me that Galileo Galilei, the seventeenth-century astronomer, may have been the best scientist of the twentieth century. "He was the first scientist to actually start using his eyes, both figuratively and physically. And in that sense, he was responsible for the age of science we now enjoy," said Hawking.

"And he used his eyes to good effect. He knew what he had seen, and he acted on it. He knew how to draw the right deductions. Once he knew he was right, he stuck with it." Hawking believes today's scientists, some 340 years after Galileo's death, could use a little more of the same attitude.

"Like Galileo, scientists today have to be prepared to step outside the mainstream, out beyond the currently accepted ideas. That is the way you make progress." He laughed almost silently for a few seconds. "Of course, you have to know which way to step."

Several letters each week come to Hawking from people far out of the mainstream. He is rather amused by them. One he showed me was a savage scrawl of equations on a single sheet sent by a man from Michigan. "He thinks he may have found the secret to the universe," Hawking said. "But this man is no Galileo."

Galileo was Hawking's—as well as Einstein's and Newton's—direct intellectual forebear in the sense that he was the first to define gravitation, nature's most pervasive yet, paradoxically, its weakest force. Since Galileo, it has been a matter of correcting, redefining, and adjusting the original explanation. Newton repaired and refined Galileo; Einstein honed and broadened Newton's basic laws to include the entire universe. Now Hawking and other cosmologists are trying to do the same to Einstein's general relativity, the modern explanation of gravitation and the force that most concerns cosmologists.

In 1905, when he published three papers in Volume 17 of the German scientific journal *Annalen der Physik*, Einstein's ideas were revolutionary; it was then far from apparent that these papers would change the course of science history. The first paper dealt with statistical mechanics, and the second, which he thought the most important, with the photoelectric effect.

The third paper was the bombshell. Destined to change forever the way we look at time and space, it outlined the special theory of relativity, as it later came to be called and took on the old dictum that space consisted of a matter-permeating ether and that time worked like the flow of a river. These were ideas that had dominated science for hundreds of years.

Einstein showed that time and space must be defined in terms usable to scientists—not to poets or philosophers. They had to be quantities that ordinary men using ordinary tools could measure—not scientifically useless abstractions. There was nothing more to either space or time. It was a straightforward, twentieth-century solution to a nineteenth-century problem.

Boldly dismissing the best thinking of the previous two hundreds years, Einstein stated two postulates: One was that no matter the motion of its source, light always travels at a constant speed. This was not news. Every measurement ever taken up to then had borne this out, and it was well established that light traveled about 186,000 miles per second (186,282 miles per second is the precise figure used today). Yet none of the great experimentalists of the day was willing to believe the implications of the evidence that lay right in front of them.

Nobody saw what Einstein saw, that the velocity of light is always the same, that it never changes no matter its source or direction. This held true, Einstein wrote in the third paper, no matter where the light came from. In other words, the speed of light was constant through empty space even if its source was moving very fast—like a galaxy or star.

This was a heretical notion and seemed to violate common sense. It meant that light projected from a star moving toward us would have the same velocity as light from a star moving away from us. It was, and still is, an unsettling thought. It is logical to assume that a bullet fired from a gun aboard a moving train will have a greater speed—the velocity of the bullet in addition to the velocity of the train—than a bullet fired from a gun at rest.

The same, Einstein said, did not hold true for light: its speed is always constant, and as a result light's velocity is different from the speed of anything else. A bullet or moon or planet always has a speed that is relative to something else. The speed of light is relative to nothing; it is an absolute constant, always the same.

The other postulate was that an experimenter is able to detect only relative motion. In other words, to a person standing on a station platform as a train speeds by it is the train that is in motion, not the platform. Yet another person on the train could just as well imagine that he and the train are standing still while the person on the platform, and everything else, is flying past him.

These two postulates—one stating that all motion is relative, and the other excepting the speed of light, which is an absolute constant, seem contradictory. Yet in the world of special relativity they do not conflict, and the postulates served to abolish Newton's basic assumption that time is absolute and that, like a river, it always flows from past to present.

To demonstrate the constancy of the speed of light and the relativity of all other motion, Einstein used thought experiments like the following: If a person standing on a station platform sees two lightning bolts, one far to the east and the other far to the west, strike the tracks simultaneously, logically he would conclude that they occurred at the same time. Yet to a person sitting on a train moving at high speed from east to west just in front of the platform, it would look as if the bolt in the west had struck first.

The reason, according to Einstein, was that the observer on the train was moving toward the bolt in the west, and because light speed is constant, its light reached him slightly sooner than from the one in the east. The person on the platform thus saw two simultaneous flashes, while the observer on the train saw first one and then another. They would have reported different phenomena that, in fact, were the same. Moreover, had the bolts struck at slightly different times, the one in the east first, it would have been the person on the train who reported two simultaneous flashes.

Which of the observers was wrong? Both were right, depending on their frame of reference—the train or the platform. By similar reasoning, Einstein showed that time and space were linked and equally fickle, depending

on the motion of the observer. Using reasonably simple mathematics, he showed, for instance, that to the person on the station platform, the windows of the train flying by would actually be shortened. As the train speeded up, approaching light speed, the windows' length would shrink to nothing. To the person on the train, the windows would remain the same.

Nothing remained the same in Einstein's bold new relativistic world—except, of course, the speed of light. Some bizarre conclusions emerged from such thinking. For instance, if the person on the platform could see the watch of the person on the speeding train, the timepiece would move more slowly, even at the slow speeds of normal, earthbound trains. Of course, the slowing down of the watch would be impossible to measure, it would be so slight. But at higher speeds, near the speed of light, the changes would be monumental.

Einstein demonstrated mathematically that to a person on earth watching a spaceship move away at a speed of 160,000 miles per second, about 86 percent the velocity of light, a clock aboard the ship would seem to be moving at only half speed. It also would look as if the ship's mass had doubled while its dimensions had shrunk to half their previous size. To an astronaut aboard the spacecraft, the changes seem to be occurring not aboard his spaceship but on earth, where time would also appear as it if were slowing down.

In declaring that time is measured differently for objects or people moving relative to one another, Einstein abolished absolute time forever (the concept of "forever" was another idea that no longer had meaning in the relativistic universe). Einstein later showed that an astronaut aboard the ship traveling close to the speed of light would age more slowly than his twin brother left behind on earth.

In his fourth and final paper in 1905, Einstein made perhaps the boldest stroke of all. He had already abolished previous notions of space and time; now he did the same for mass and energy. Before Einstein, mass and energy were viewed as separate and distinct. Intuition tells us, as it had physicists before Einstein, that a ball and the energy to throw it are not the same thing. Einstein found, from the postulates to special relativity, that this distinction was not valid.

Using mathematics from special relativity and some ideas from his paper on the photoelectric effect, Einstein came to the conclusion that if an object emits energy in the form of light, its mass will be reduced by the amount of energy divided by the velocity of light squared—that is, $m = \frac{E}{c^2}$. From there it was just a simple algebraic step to the most famous equation in history, $E = mc^2$, which was published in 1907.

Einstein showed that mass and energy are not merely equivalent, but interchangeable. The implications were enormous. It meant that even a small portion of matter under the right conditions could be converted into an awesome amount of energy, equivalent to the explosive power of thousands of tons of TNT.

That special relativity works, that mass and energy are indeed interchangeable, has been demonstrated thousands of times in particle accelerators, the immense atom smashers physicists use today to explore the nucleus of the atom. At Fermi National Accelerator Laboratory the masses of protons accelerated through a tube four miles around have been found to increase many thousands of times as the velocity becomes a significant fraction of the speed of light.

In working out his special theory of relativity and the postulates, Einstein had dealt only with new laws involving the measurement of space and time between observers moving at uniform velocity, that is, not accelerating or slowing down or traveling along a curve such as a planetary orbit. Einstein knew he had to solve the more complicated questions of accelerated motion.

One of the biggest problems of nonuniform motion involved gravitation, manifested in accelerated velocity as the earth pulls an object toward the ground. The remarkable thing about gravity, noticed by Newton and Galileo, was that it seemed to act the same on all bodies regardless of their weight. In his famous—although probably apocryphal—experiments from the Tower of Pisa, Galileo supposedly had shown that objects of different mass struck the ground at the same instant when dropped simultaneously. If there was any difference, such as when a cannonball hit the ground sooner than a feather, it was due to air resistance.

Galileo and Newton had seen gravitation as a unique force in nature: a force peculiar to the earth or other heavenly bodies. Einstein saw it as a broader phenomenon.

Suppose, he said, a scientist rides in an elevator in a spaceship far from the influence of the earth's gravity. Imagine that the elevator inside the spacecraft is accelerating upward at the rate of 32 feet per second each second. That is the exact rate an object—like a cannon ball dropped from a tower—is pulled toward the earth by gravity. But in the spaceship's elevator, away from gravity's influence, the scientist's feet still press against the floor as his body resists its upward acceleration and if he drops a stone, it falls to the floor just as on earth.

The scientist cannot tell whether the downward pull is caused by gravitation or because of the inertia of his body resisting the upward acceleration of the elevator. This means that there is no difference between acceleration caused by gravitation or acceleration from other sources, Einstein said. It was called the principle of equivalence: A gravitational field has a "relative existence."

Had Galileo jumped from the Tower of Pisa and then dropped a stone on his way down, both he and the stone would have been in free fall. The stone would have appeared to Galileo to be in a state of rest, and with the effects of gravity momentarily suspended, Galileo could have, for a few seconds, considered himself in a state of rest as well.

Then what *is* gravity? Einstein used ideas from special relativity and added new ones to describe it in a unique way—an explanation that showed gravity wasn't really a force in the usual sense. Einstein added to special relativity a different kind of geometry, since he had found the old kind—Euclidean geometry—too limited for his new way of looking at the universe.

An old friend, Marcel Grossman, whose notes had helped Einstein pass an important exam when they were classmates in a Swiss high school years before, told him where to look. It was a type of non-Euclidean geometry that had been developed by a German mathematician named Bernhard Riemann. It gave Einstein the mathematical tool he lacked: the geometry of curved space.

But what have curved space and accelerating elevators to do with gravitation? Imagine again, said Einstein, that the elevator on the spaceship holding the scientist was accelerated so immensely that its speed began approaching that of light. If that were the case, a beam of light entering through a hole in one wall would appear to the scientist inside to bend a little bit down in an arc and strike the opposite wall at a lower point.

The reason is that, by Einstein's earlier formulation, light and mass are equivalent under certain conditions. Since light has energy, it therefore has a mass, and everything with mass is attracted by gravity. And what is gravity, but a form of acceleration. Thus, in the accelerating elevator, the light and the scientist are equally affected, and both are drawn toward the elevator's floor. By the same reasoning, Einstein said, if a beam of light passes near a heavy object such as a planet, gravitation will actually bend the light path in toward the planet.

Einstein brought these concepts together in ten mathematical formulations or field equations, which he published as his theory of general relativity in 1916. It was even more revolutionary than special relativity, since it had virtually no theoretical antecedents at the time.

The most remarkable thing about general relativity was that Einstein did away with the concept of gravitation as a force. In fact, he said, there was no such thing as the force of gravity. It was instead the geometry of the universe—the curved geometry supplied by Riemann—that was responsible for the force we think of as gravity. Einstein called his curved space a space-time continuum.

It was a bit like a trampoline. If you placed a cannonball on it, a large indentation was the result. An orange would make a smaller dent in the trampoline, and have an inclination to roll toward the deeper hole. Stars and planets have the same effect on space that balls have on a trampoline; heavenly bodies actually put a dent in the space around them, altering the geometry of space itself. Larger objects in this dented, curved space tend, like a cannonball on a trampoline, to pull less massive objects toward them.

General relativity moved far beyond the conventional thinking of the day. It was a new physics altogether, an entirely different way of looking at the universe, and there were a number of disbelievers.

Two natural phenomena existed which Einstein was certain would prove that his ideas about curved space were right. The first involved the orbit of Mercury, which for more than a century had refused to move in the elliptical orbit described by Newton's physics: its orbit had 43 seconds of arc too many when the planet was nearest the sun. Nobody had been able explain this difference, small but measurable with the technology of the nineteenth century. When Einstein's field equations were applied to Mercury's orbit, they predicted a difference of precisely 43 seconds of arc.

The other test of the theory was more difficult. Einstein's equations showed that light from a distant star would be bent slightly by the gravitational field around the sun—just like the light beam in the scientist's elevator in the spaceship. The deflection would be exactly 1.75 seconds of arc, the equations predicted. The only time to test the idea was when the sun was in total eclipse, since the light from any star in line with the sun would be obscured by sunlight.

As it happened, a total eclipse was to occur in the Southern Hemisphere on May 29, 1919, about three years after the publication of general relativity. An expedition was launched by the Royal Society to Principe, an island off the west coast of Africa. And during the eclipse, British physicist Arthur Eddington found deflections in starlight that nearly matched Einstein's calculations. When informed of this confirmation in Berlin, Einstein responded that he had never doubted what the results would be. Asked what he would have thought had the measurements not confirmed general relativity, he replied, "Then I would have felt sorry for the dear Lord."

With the observations seeming to prove general relativity—the first of many confirmations that the universe behaved almost exactly the way general relativity dictated it should—modern theoretical cosmology was born.

A reworking of man's conceptual view of the universe nearly always follows a period when the old view has begun to fail. New facts are discovered, which do not fit the old scheme of things, and the old conceptual view begins to crumble. Science was ripe for a conceptual overthrow when Einstein appeared on the scene. There were enough chinks in the Newtonian edifice to require a vastly different look at things. Whether there are now enough chinks in the monolith of twentieth-century physics to lead to a new conceptual view is not certain.

Hawking, born into a universe wholly and acceptably described by general relativity, is among the second generation of scientists who grew up with its dogma. Progress in the twentieth century has been so rapid that Einstein has already become less than sacred. Has Einstein's vision of the universe begun to crumble so much that we might be on the threshold of a new age of science? Hawking doesn't quite answer the question, "One cannot say until it happens. One of the beauties of something undiscovered is that it is undiscovered."

4

THE EINSTEIN CONNECTION

On several occasions Einstein said or wrote, "God does not play dice with the universe." This was a declaration of his abiding exasperation with quantum mechanics, the mathematical system developed in the 1920s and 1930s to explain the behavior of subatomic particles. Decades later Stephen Hawking replied, "God not only plays dice, but sometimes he throws them where they cannot be seen." It was not as pithy as Einstein's remark, but it made Hawking's point: Time and knowledge have at last overtaken Einstein.*

In his office Hawking has a small collection of photographs and posters of Einstein. Old ones are replaced with new arrivals from time to time. Yet all Hawking would say to me of Einstein was, "Well, he was a very fine physicist."

Following experimental confirmation of general relativity, Einstein received much worldwide acclaim. He was received by kings; newspapers and magazines beat a

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*The remark about the dice being where they cannot be seen refers to the possibility that they may be inside a black hole.

path to his door for interviews; and popular books on general relativity sought to explain its secrets. There was also resistance to relativity. Some people refused to believe that a lone man using only mathematical hieroglyphics could redefine the entire universe.

Despite the acclaim and controversy, Einstein forged ahead with his work. It would have been impossible to duplicate a feat as revolutionary as general relativity, but he wanted to broaden it. Its equations describe the geometry of space-time, and he was certain they would work for the geometry of all space-time—that is, for the universe from its beginning to its end. He published a paper a year later, in 1917, that, more than anything else, established modern cosmology—the study of the origin, history, and shape of the universe.

It was a remarkable piece. In it he set down the principle of the laser forty years before the first one was made, a stunning achievement in itself. But more important, he described how the equations of general relativity could describe the behavior of large pieces of matter in the universe over long periods of time. He ran into trouble right away.

The problem was that the best and simplest interpretations of his equations pointed to an unstable universe, possibly even one that was expanding. Among others, the Dutch astronomer Willem de Sitter had already solved the equations indicating that the universe was nonstatic, either expanding or collapsing, but not standing still. Einstein balked. He wanted his equations to show the heavens as portrayed by most astronomers: stable and unchanging, isotropic—the same in all directions—and homogeneous—the same everywhere.

Einstein found a rather odd way out. In order to make general relativity fit this model of the universe, he altered his equations, adding a figure he called the cosmological constant, referring to it as a "slight modification."

One immediate problem with the cosmological constant was that general relativity was a theory so complete in itself that it did not need universal constants. So the "delta terms," as they were called, were really unnecessary. Einstein himself was keenly aware of this, and the last sentence of the 1917 paper declared, "That [delta] term is necessary only for the purpose of making possible a quasi-static distribution of matter as required by the fact of the small velocities of the stars."

In 1922 a Russian mathematician, Alexander Friedman, solved Einstein's equations both with and without the cosmological constant. Like Einstein's, his solution with the cosmological constant produced a static universe that remained the same forever. Friedman's more daring second solution left out the delta terms and led to the first model of an expanding universe, actually two different models. It has yet to be determined which is correct; each posits a different view of the universe's eventual fate.

The two Friedman models of an expanding universe are, in fact, the basis of cosmology today. The first is one in which the density of matter is less than a certain critical amount, meaning that the universe is infinite and will expand forever. In the second—the one approved by most modern cosmologists—the density is greater than the critical level. The expansion of the universe will, as a result, one day cease. It is finite, but also unbounded; in it, if you start off in a straight line, you eventually come back to where you started.

It's a bizarre concept that we have come to accept as naturally as the notion that eggs fry in a hot skillet. Hawking thinks that such a universe, curved back on itself, is like a gigantic black hole that also curves around itself. At least, he says, the mathematical descriptions are similar.