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Clumps of genetically engineered bacteria grow in a petri dish. Photo by David Sharpe. 44

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THE UNFETTERED MIND

Stephen Hawking encounters the dark edges of the universe.

by John Boslough

Photographs by Homer Sykes
Woodfin Camp

The Department of Applied Mathematics and Theoretical Physics, where Stephen Hawking works, is on a narrow back street in the medieval market town of Cambridge. The dark brick Victorian building resembles an abandoned factory. Hawking greets visitors with an impish grin, blue eyes twinkling behind heavy glasses; he looks more like a university student than a distinguished member of the faculty. His brown hair is early Beatles, and he is dressed in scientist's garb: baggy trousers, garish tie mismatched with broad-striped shirt, plaid coat, scruffy academic soft soles.

Hawking holds the Lucasian professorship of mathematics at England's Cambridge University, the university's most prestigious scientific post. His office is filled with physics texts, papers on cosmology, a blackboard with scribbled equations, a computer terminal, a tidy paper-laden desk, and pictures of three handsome children. From this orderly room, some scientists believe, may emerge the single theory that will unite the two branches of physics that have been at odds with one another for half a century: quantum mechanics, which describes the behavior of matter at the atomic level, and general relativity, which explains the workings of the universe as a whole.

"My goal is simple," Hawking says. "It is complete understanding of the universe, why it is as it is and why it exists at all." A presumptuous statement. But Hawking, 39, has the credentials to make it. He has established himself as one of the premier scientific theorists of the century with three major breakthroughs to his credit, each of which has changed the course of physics.

Hawking's arena is the physics of black holes, those theoretical regions of space so dense and so distorted by Einsteinian gravitational effects that nothing, not even light, can escape from them. At least that is what everyone thought until Hawking, in a bold theoretical gambit in 1974, showed that tiny black holes could emit radiation and eventually explode. It was a startling proposition. It convinced Hawking and others that the long-sought, single unifying theory—the so-called Holy Grail of physics—that would explain all the interactions of matter and all the forces that control them lay within the black hole.

Ideas such as this one have drawn an outstanding group of theoretical physicists to Cambridge from both sides of the Atlantic. Most days at lunch and again at tea time they assemble. Some scrawl nota-

Hawking's feats of memory are said to be akin to Mozart's composing an entire symphony in his head.

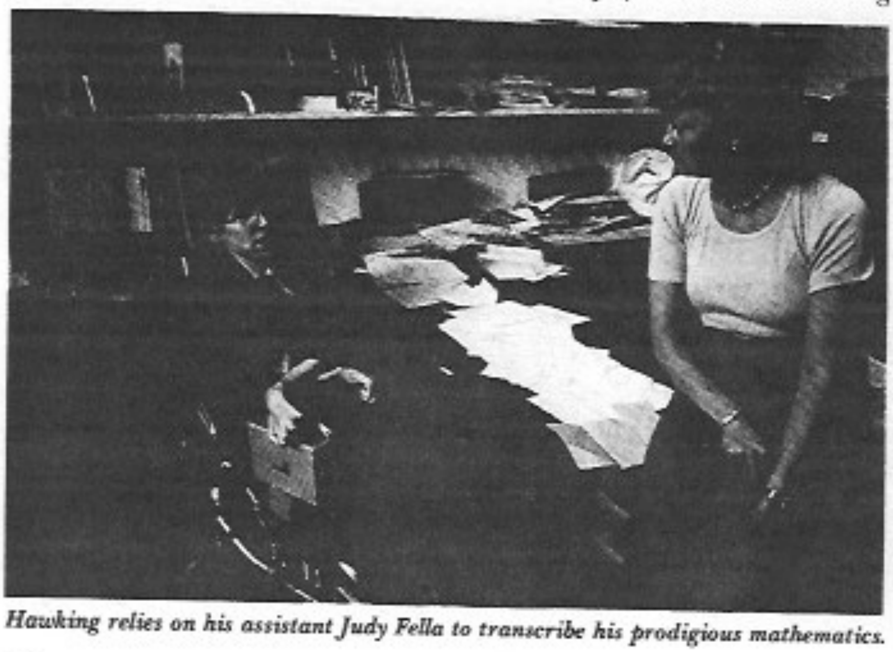
tions while others debate. The talk is fast, often punctuated with put-downs and one-liners, and Hawking, no slouch himself with rapid repartee, lights up at a good line.

This is all the more remarkable because since 1962 Hawking has suffered from Lou Gehrig's disease, a progressive and degenerative illness that lays waste the nerves and muscles. He speaks in a labored croak that only a few intimates can understand. He has been confined to a wheelchair for a decade. He cannot write, and he talks to visitors through an interpreter, usually his assistant, Judy Fella. Hawking has an electronic page turner and a specially equipped telephone so he can talk to those who can understand him. Most of the time he sits huddled in his wheelchair and thinks.

How he thinks. Blessed with a prodigious memory, Hawking is able to work out and retain page after page of complex equations, twirling, spinning, and weaving them together and apart as an ordinary person might rearrange the words in a sentence. The University of Alberta's Werner Israel, a theoretical physicist and Hawking's coauthor on the book *General Relativity*, says his feats of memory are akin to Mozart composing an entire symphony in his head.

Theoretical physicists strive to uncover the master plan, if one exists, that unites the interactions of the elementary particles with the life and death of the stars and galaxies. Black holes—"the greatest crisis ever faced by physics," according to John Wheeler, the University of Texas physicist who coined the term—may point the way to that master plan. It is not surprising, therefore, that Stephen Hawking was drawn to these theoretical gashes in the fabric of space and time.

A black hole lives most of its life as an ordinary star, withstanding a tug-of-war between the powerful outward force of its heat and radiation and the strong inward thrust of gravity. But when the star's nuclear fuel is spent, it dies, collapsing under its own weight to a point where gravity is so strong that not even light can escape. It is there in the black hole, which defies all the laws of physics, that Hawking hopes to unify the twin pillars o 20th-century physics: Einstei theory of general relativity an Max Planck's quantum theory. S far the two theories have been incompatible as fire and water. N one, not even Einstein, has bee able to unify them.



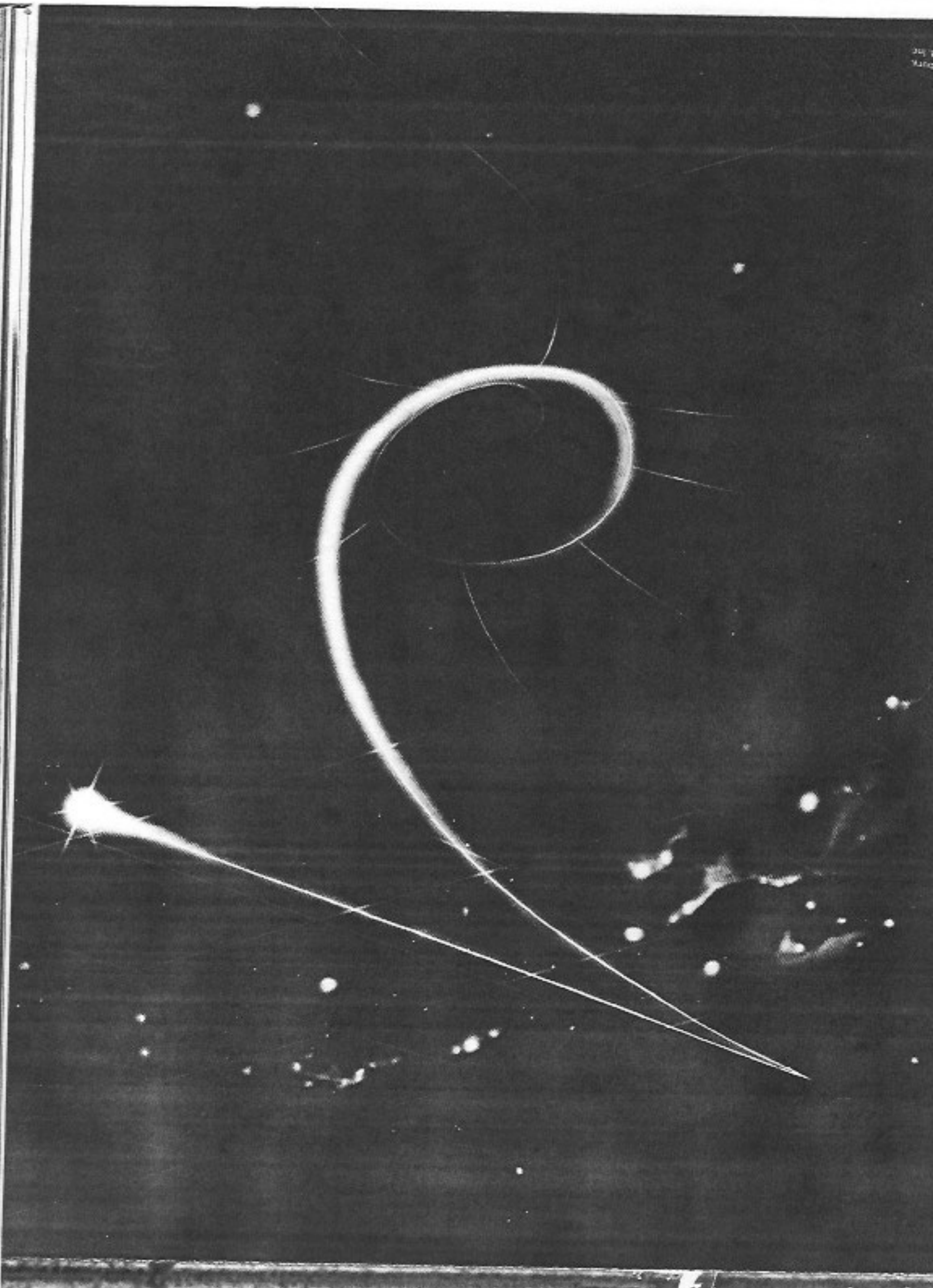
Hawking relies on his assistant Judy Fella to transcribe his prodigious mathematics.

Einstein's great achievement, th general theory of relativity, say that gravity, which affects the be havior of the universe, its plane stars, and galaxies, is a basic prop erty of "curved" space—a kind o tension in the interstellar void. Im agine a cannonball and a tennis ba lying on a trampoline. You woul expect the lighter tennis ball to ro toward the heavier cannonball- the heavier the cannonball, th steeper the curve of the trampolin and the faster the roll of the tenn ball. Relativity says that objects i space should behave in much th same way, and they do.

Quantum theory, on the othe hand, describes the behavior o atoms and their subnuclear parti cles. At the heart of quantum me chanics is the uncertainty princi ple, which states that certain pair of quantities, such as the positio and momentum of a particle, ca not be measured simultaneousl This means that the electron, fo example, is not only a particle, a classical physicists had envisione it, but a wave that would have to b smeared out around the nucleus o the atom.

Thus the paradox: General rel tivity says that large objects—rock footballs, planets, stars—behave i a predictable manner, while quan tum theory maintains that at th

"Empty" space contains many partic antiparticle pairs that are born simulta neously, move apart, then rejoin and an nihilate each other. But if this proce takes place near a black hole, one of th particles can become trapped in the hol intense gravitational field and disa pear, leaving the other particle to escap



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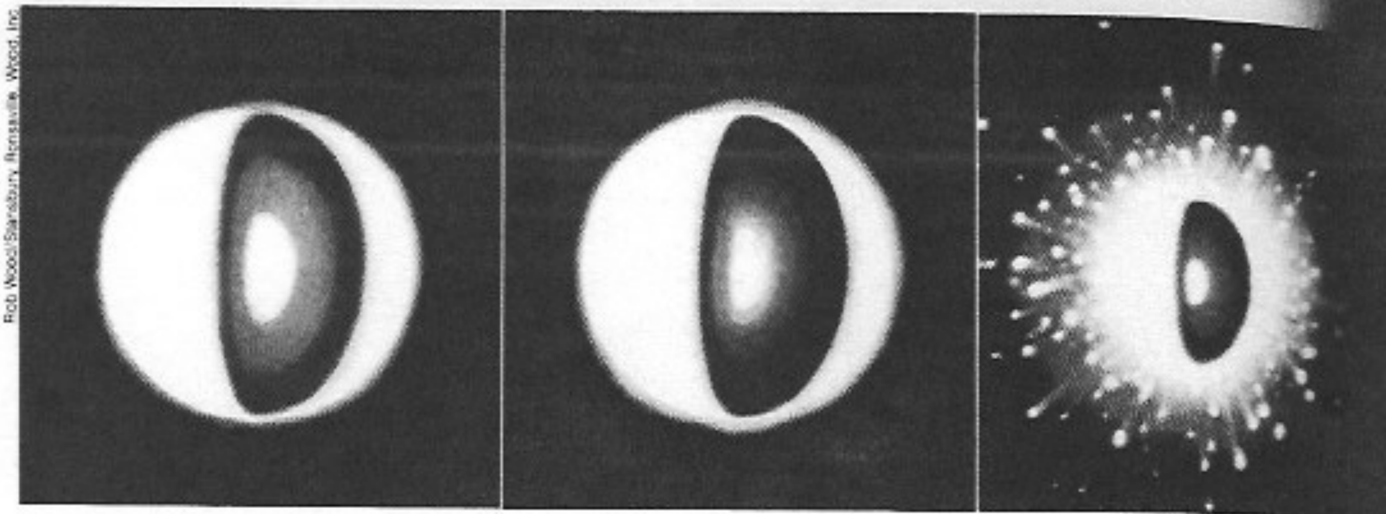


The evolution of a black hole begins when a star 10 times more massive than our sun fuses most of its hydrogen into helium; helium in turn fuses into carbon, 1. Late in the star's life, 2, successive fusions produce layers of silicon, oxygen, neon, carbon, helium, and hydrogen. As gravitational compression raises the temperature of the iron core, however, it becomes unstable and collapses, creating a shock wave that blows off the outer shell in a tremendous explosion called a supernova, 3. The remnants of the star are flung into space, 4, while the core collapses to form the center of a black hole.

atomic level, matter behaves randomly. Clearly there cannot be separate rules for different parts of the universe. Einstein spent the last 30 years of his life trying to resolve the problem. "God does not play dice with the universe," he said, rebelling against the randomness of quantum mechanics.

Unifying quantum theory and general relativity would remove the last barrier to understanding why the universe is the way it is, and that is the goal toward which Stephen Hawking is working.

The Royal Society of London, the most eminent scientific body in England, helps set the tone of science worldwide. Its membership rolls list 22 Nobel laureates. In 1974 Stephen Hawking was inducted, at 32 one of the youngest members. It is customary for newly elected fellows to walk to the podium to shake the president's hand and sign the roll of honor. At Hawking's investiture, Sir Alan Hodgkin, Nobel-winning biologist and society president, brought the membership book into the audience. There was a long silence as the newest fellow labored to place his name on the list. Thunderous applause broke out when he finished.

Hawking was born in Oxford in 1942, the eldest of four children of an intellectual university family. His father was a research biologist in tropical diseases. At the age of 11, Stephen had already decided to become a scientist. "I was very good at taking things apart," he says. "But I wasn't very good with my hands, and often things didn't go back together very well."

He decided not to follow his father into biology. "Too vague, too undefined," he says. Things could have been different, he concedes, had the more exacting field of molecular biology existed in the 1950s. Like many brilliant individuals—Einstein comes to mind—Hawking had difficulties with grammar school routine, so much so that his family worried he might not pass the entrance exams for Oxford.

Despite their fears, Hawking was accepted at University College, Oxford. He admits he didn't work hard there. He rarely took notes and occasionally skipped tutorials. Later, though, as a graduate student at Cambridge, Hawking began to show signs of becoming an excellent theoretical physicist. His friend Roger Penrose, then a research associate at King's College, London, and now professor of mathematics at Oxford, recalls, "He used to ask the most awkward questions, questions that were very difficult to answer. He would aim right at the weakest part of your argument," says Penrose. "But it was not easy then to tell how original he was going to become."

It was also at Cambridge that two events occurred that were to change the course of Hawking's life. The first happened during his freshman year. After returning from a trip to the Middle East, Hawking began stumbling and slurring his speech. His condition was diagnosed as amyotrophic lateral sclerosis, Lou Gehrig's disease, named after the Yankee first baseman. The disease destroys the voluntary nerves and muscles, and in Hawking's case, it progressed rapidly in the early stages. "I was very depressed at the time," Hawking says. "I thought I had only a very few years to live."

At about the same time he met Jane Wilde, an attractive, auburn-haired student of languages. Jane liked Stephen and encouraged the courtship. The couple was married in 1965. "The turning point was my marriage," he says. "It made me determined to live, and it was about that time that I began making professional progress."

At Cambridge Hawking collaborated with Penrose in what Hawking calls his "first big piece of research." Using a new mathematical system they had devised, they developed a number of theories about singularities, those cosmic specks of infinite density and zero volume in the middle of black holes. They were able to show with intricate mathematics that the universe as a whole was a singularity when the Big Bang occurred 16 to 17 billion years ago. "In other

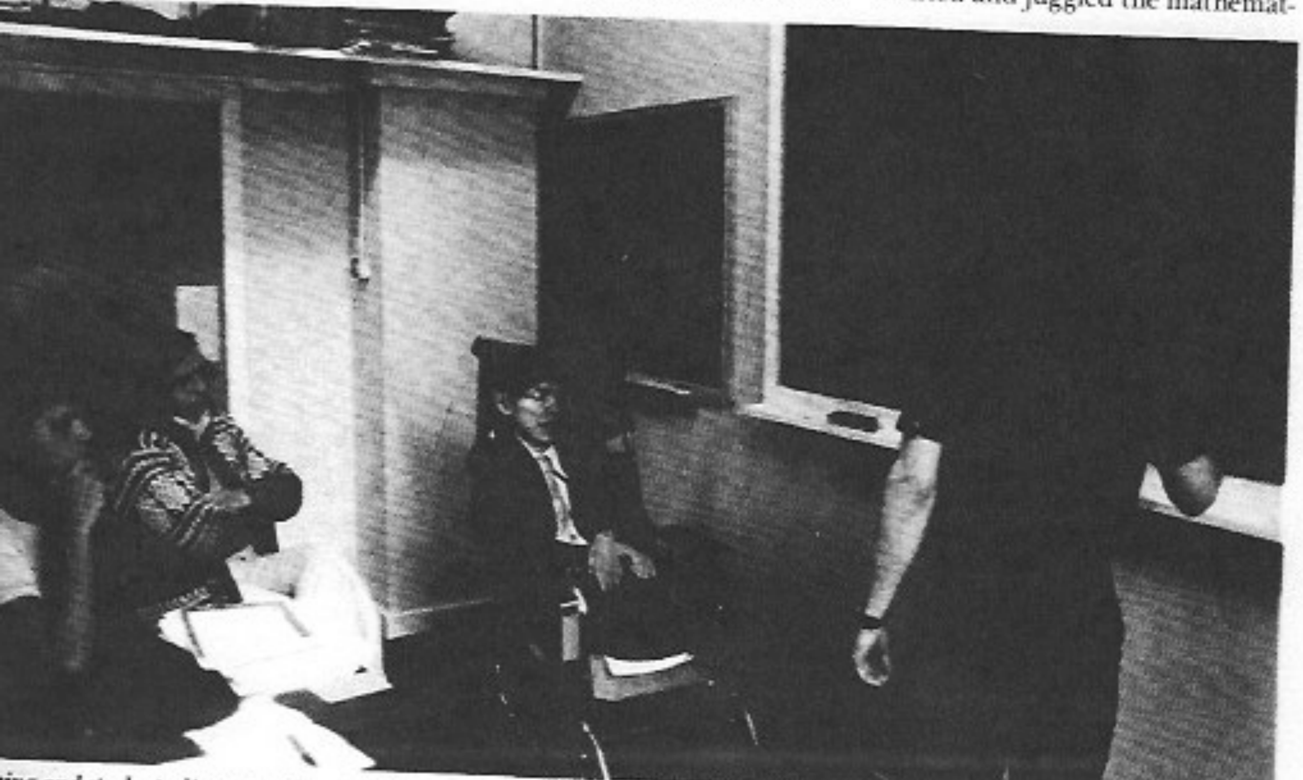
ords, time has a beginning," says awking with delight.

By the early 1970s, Hawking was nfined to a wheelchair. But his nd was soaring. He postulated at a black hole need not be born ly during the death throes of a r. Hawking reasoned, again athematically, that millions of miscule black holes the size of the otons in the nucleus of an atom uld be squeezed into existence by cataclysmic force of the Big ng. He calculated that these ni-holes were created within the t 10^{-20} seconds after the Big ng. That's a decimal point followed by 19 zeros and a one, which expresses a vanishingly small fragment of time. Hawking's mini–black holes explained so many previously unexplained phenomena —supplying the so-called missing mass, for instance, needed to close the universe—that the idea quickly won wide acceptance.

Today Hawking's illness has stabilized, and he leads a busy family and social life. Jane and Stephen have three children. Robert, 12, likes to program calculators and play chess and seems destined to follow his father in a science career. Lucy, nine, is learning to play the piano and cello. Timothy just turned two. Their parents frequently go to the theater and to concerts. Hawking has campaigned for better public facilities for the disabled—wheelchairs at Covent Garden, for example, and lowered curbs on the route he takes in his electric-powered wheelchair from the first floor of his Victorian house to his specially equipped office. Jane recently completed her thesis in medieval poetry. "One of my greatest regrets is that, not being a mathematician, I can understand Stephen's work only in picture terms," she says. "He has to keep everything down to Earth to explain it to me. It's good discipline for him."

In his book *The Structure of Scientific Revolutions*, Thomas Kuhn, the eminent Harvard historian of science, argues that a real breakthrough is rarely accepted right away. The inventor is likely to be ignored or ostracized as were Copernicus and Galileo. It happened to Stephen Hawking.

In 1973 he began to spend a lot of time thinking about the behavior of matter that happened to be in the periphery of black holes. As he twirled and juggled the mathemat-



king and students discuss mathematical concepts at Cambridge's department of Applied Mathematics and Theoretical Physics.

As he twirled the mathematical hieroglyphics in his head, Hawking formed a preposterous hypothesis.

ical hieroglyphics in his head, Hawking formed a hypothesis so preposterous he was convinced he had made a serious mistake. "The discovery was actually embarrassing, even to myself," says Hawking.

What Hawking proposed was that black holes, in defiance of every known principle, emit a steady stream of particles. Hawking spent weeks trying to make black hole emission go away, at one point even locking himself in a bathroom to work out the problem. "But it wouldn't vanish, and I finally accepted it."

What had convinced him that black holes, a creation of general relativity, could emit particles under the right conditions was the application of quantum theory to the problem. He reasoned that the uncertainty principle, the backbone of quantum mechanics, declares that space is active and cluttered. Pairs of elementary particles like electrons and their antimatter opposites, positrons, spontaneously come into being and exist for a fraction of a second before uniting and cancelling each other out. Hawking argued that the energy for this instantaneous creation and annihilation could come from a gravitational field nearby.

If such an event were carried out

Is the end in sight for theoretical physics?

It is possible that in the next 20 years or so, we may discover a complete unified theory that describes not only the physical laws but also the initial conditions of the universe. One has to be rather cautious about making such a prediction because we have thought that we were on the brink of finding such a theory at least twice before in this century. The theory would have to unify the four kinds of interaction known to physics. In order of strength they are the strong nuclear force, which works only at the atomic level; electromagnetism; the weak nuclear force, which controls radioactive decay; and finally, the weakest by far, gravity, which interacts with everything.

Abdus Salam, Stephen Weinberg, and Sheldon Glashow won the Nobel Prize for Physics in 1977 for unifying two of the four fundamental forces—electromagnetism and the weak force. This led to the search for a similar theory that would unify the strong interaction with the other two. We are making some progress on that front, but so far we have had no luck including gravity in the scheme. What we lack is a proper quantum theory of gravity. Although progress is very slow, we already know some of the features the theory should have.

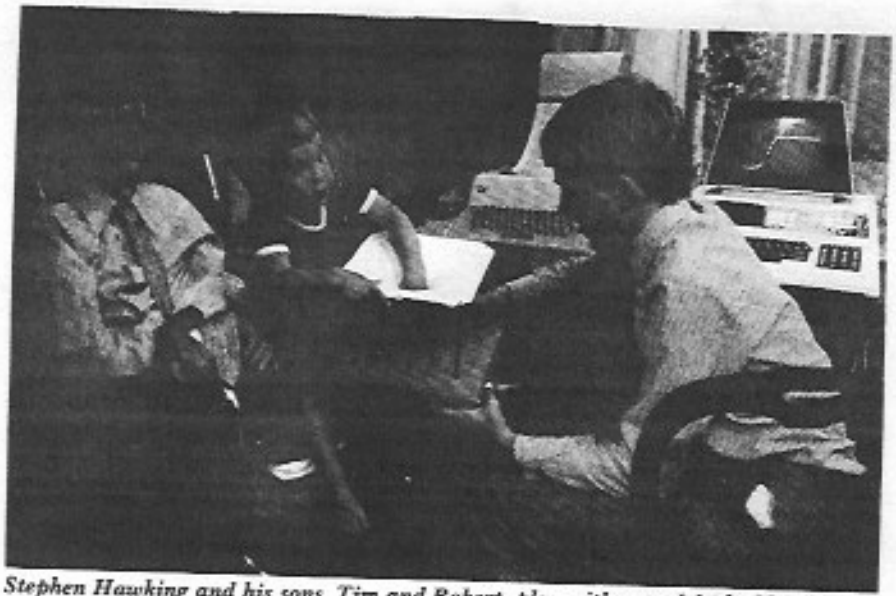
One of these is connected with the fact that gravity affects the causal structure of space-time, that is, gravity determines which events can be causally related to each other. An example of this in the classical theory of general relativity is provided by a black hole, which is a region of space-time in which the gravitational field is so strong that any light or other signal is dragged back into the region and cannot escape to the outside world. The intense gravitational field near the black hole causes the creation of pairs of particles and antiparticles, one of which falls into the black hole and the other of which escapes to infinity. The particle that escapes appears to have been emitted by the black hole. An observer at a distance from the black hole can measure only the outgoing particles, and he cannot correlate them with those that fell into the hole because he cannot observe them. This means that the outgoing particles have an extra degree of randomness or unpredictability over and above that which is usually associated with the uncertainty principle.

In normal situations the uncertainty principle implies that one can predict *either* the position *or* the velocity of a particle or a combination of position and velocity. Thus, roughly speaking, one's ability to make definite predictions is halved. However, in the case of particles emitted from a black hole, the fact that one cannot observe what is going on inside the black hole means that one can definitely predict *neither* the positions *nor* the velocities of the emitted particles. All one can give are probabilities that particles will be emitted in certain modes.

It seems, therefore, that even if we find a unified theory, we may be able to make only statistical predictions. We would also have to abandon the view that there is a unique universe that we observe. Instead we would have to adopt a picture in which there was an ensemble of all possible universes with some probability distribution. This might explain why the universe started off in the Big Bang when all matter and all forces were equal because thermal equilibrium would correspond to the largest number of microscopic configurations and hence the greatest probability. To paraphrase Voltaire's philospher, Pangloss, "We live in the most probable of all possible worlds."

at the edge of the black hole—at the event horizon, as it is called—one of the particles might wander down into the black hole never to be seen again. But the other particle theoretically could escape. To an observer, it would appear as if the particle had been ejected by the black hole.

Still aghast at his own findings, Hawking demonstrated that black holes evaporate over a long period of time because these "virtual" particles that Hawking envisions need energy to escape.



Stephen Hawking and his sons, Tim and Robert, play with a model of a black hole.

This was Hawking's first step toward merging general relativity with quantum theory. But evaporating and exploding black holes were so out of sync with conventional wisdom that Hawking, usually sure of his intellectual creations, doubted his own results. He sat on his findings for weeks, going over and over the calculations in his head. Finally his former Oxford tutor, Dennis Sciama, persuaded him to announce them.

In February 1974 Hawking presented a paper called "Black Hole Explosions?" The question mark underlined his doubts. The paper stunned and confused his colleagues, and the conference moderator, John Taylor, called it rubbish. But physicists today view the paper differently: It's one of the "most beautiful in the history of physics," says Sciama.

Hawking radiation, as black hole emission is called, demonstrates that the holes are not cut off from the rest of the universe as scientists used to think but are part of the continuum of space and time. In a quiet rejoinder to Einstein, Hawking says: "God not only plays dice [with the universe], but also sometimes throws them where they cannot be seen."

To first encounter Stephen Hawking is shocking. His condition seems far worse than one expected. But after a short time with this gentle, witty man, one forgets the illness. Judy Fella says he is amazing. "Stephen's really stubborn, nothing stops him. I take more days off than he does. He comes in when he's sick with the flu or with a cold. He travels a lot, and if he's got the worst jet lag, he's in the office the next day."

It is a spring afternoon in Cambridge. Judy is fussing on the phone with the supplier of wheelchair batteries who has failed to deliver a new batch. Sunshine streams through the window. Hawking is musing about the future of theoretical physics. "I think we'll come to the unifying theory within the next two decades, probably in small steps. . . . But you know," he says, "once we find it, it will rather take the fun out of theoretical physics."

Hawking reflects about scientists who have changed the course of history. "I've rather a soft spot for Galileo," he says. "He was the first man to start using his eyes, both physically and figuratively, to good effect. And he knew how to draw the right deductions from what he saw." Scientists today need those same qualities, Hawking thinks. "You've got to be prepared to step outside the currently accepted ideas, out of the mainstream." But, he adds with a grin, "You've got to know which way to step." S

John Boslough's forthcoming book on the lives of contemporary scientists will be published in the fall of 1982.

At the moment the only candidate to unify all four forces is supergravity, which relates particles with vastly different characteristics through a theory called supersymmetry.

We are likely to have some crucial calculations in the next few years, and if the theory survives testing, it will probably be some years more before we develop computational methods that will enable us to make predictions and before we can account for the initial conditions of the universe as well as local physical laws. These will be the outstanding problems for theoretical physicists during the next 20 years or so.

But, to end on a slightly alarmist note, they may not have much more time than that. At present, computers are useful aids in research, but they have to be directed by human minds. However, if one extrapolates their recent rapid rate of development, it would seem quite possible that they will take over altogether in theoretical physics. So maybe the end is in sight for theoretical physicists if not for theoretical physics.

Adapted from a lecture given by Stephen W. Hawking on his inauguration as Lucasian Professor of Mathematics at the University of Cambridge, April 29, 1980.