CONTENTS

PROLOGUE

NOTHING IS CERTAIN. This hopeful message went to an Albuquerque sanatorium from the secret world at Los Alamos. *We lead a charmed life.*

Afterward demons afflicted the bomb makers. J. Robert Oppenheimer made speeches about his shadowed soul, and other physicists began to feel his uneasiness at having handed humanity the power of self-destruction. Richard Feynman, younger and not so responsible, suffered a more private grief. He felt he possessed knowledge that set him alone and apart. It gnawed at him that ordinary people were living their ordinary lives oblivious to the nuclear doom that science had prepared for them. Why build roads and bridges meant to last a century? If only they knew what he knew, they surely would not bother. The war was over, a new era of science was beginning, and he was not at ease. For a while he could hardly work—by day a boyish and excitable professor at Cornell University, by night wild in love, veering from freshman mixers (where women sidled away from this rubber-legged dancer claiming to be a scientist who had made the atomic bomb) to bars and brothels. Meanwhile new colleagues, young physicists and mathematicians of his own age, were seeing him for the first time and forming their quick impressions. “Half genius and half buffoon,” Freeman Dyson, himself a rising prodigy, wrote his parents back in England. Feynman struck him as uproariously American—unbuttoned and burning with physical energy. It took him a while to realize how obsessively his new friend was tunneling into the very bedrock of modern science.

In the spring of 1948, still in the shadow of the bomb they had made, twenty-seven physicists assembled at a resort hotel in the Pocono Mountains of northern Pennsylvania to confront a crisis in their understanding of the atom. With Oppenheimer's help (he was now more than ever their spiritual leader) they had scraped together the thousand-odd dollars needed to cover their rooms and train fare, along with a small outlay for liquor. In the annals of science it was the last time but one that such men would meet in such circumstances, without ceremony or publicity. They were indulging a fantasy, that their work could remain a small, personal, academic enterprise, invisible to most of the public, as it had been a decade before, when a modest building in Copenhagen served as the hub of their science. They were not yet conscious of how effectively they had persuaded the public and the military to make physics a mission of high technology and expense. This meeting was closed to all but the few invited participants, the elite of physics. No transcript was kept. Next year most of these men would meet once more, hauling their two blackboards and eighty-two cocktail and brandy glasses in Oppenheimer's station wagon, but by then the modern era of physics had begun in earnest, science conducted on a scale the world had not seen, and never again would its chiefs come together privately, just to work.

The bomb had shown the aptness of physics. The scientists had found enough sinew behind their penciled abstractions to change history. Yet in the cooler days after the war's end, they realized how fragile their theory was. They thought that quantum mechanics gave a crude, perhaps temporary, but at least workable way to make calculations about light and matter. When pressed, however, the theory gave wrong results. And not merely wrong—they were senseless. Who could love a theory that worked so neatly at first approximation and then, when a scientist tried to make the results more exact, broke down so grotesquely? The Europeans who had invented quantum physics had tried everything they could imagine to shore up the theory, without success.

How were these men to know anything? The mass of the electron? Up for grabs: a quick glance gave a reasonable number, a hard look gave infinity—nonsense. The very idea of mass was unsettled: mass was not exactly stuff, but not exactly energy, either. Feynman toyed with an extreme view. On the last page of his tiny olive-green dime-store address book, mostly for phone numbers of women (annotated *dancer beauty* or *call when her nose is not red),* he scrawled a near haiku.

Principles
You can’t say A is made of B
or vice versa.
All mass is interaction.

Even when quantum physics worked, in the sense of predicting nature’s behavior, it left scientists with an uncomfortable blank space where their picture of reality was supposed to be. Some of them, though never Feynman, put their faith in Werner Heisenberg’s wistful dictum, “The equation knows best.” They had little choice. These scientists did not even know how to visualize the atom they had just split so successfully. They had created and then discarded one sort of picture, a picture of tiny particles orbiting a central nucleus as planets orbit the sun. Now they had nothing to replace it. They could write numbers and symbols on their pads, but their mental picture of the substance beneath the symbols had been reduced to a fuzzy unknown.

As the Pocono meeting began, Oppenheimer had reached the peak of his public glory, having risen as hero of the atomic bomb project and not yet having fallen as the antihero of the 1950s security trials. He was the meeting's nominal chairman, but more accomplished physicists were scattered about the room: Niels Bohr, the father of the quantum theory, on hand from his institute in Denmark; Enrico Fermi, creator of the nuclear chain reaction, from his laboratory in Chicago; Paul A. M. Dirac, the British theorist whose famous equation for the electron had helped set the stage for the present crisis. It went without saying that they were Nobel laureates; apart from Oppenheimer almost everyone in the room either had won or would win this honor. A few Europeans were absent, as was Albert Einstein, settling into his statesmanlike retirement, but with these exceptions the Pocono conclave represented the whole priesthood of modern physics.

Night fell and Feynman spoke. Chairs shifted. The priesthood had trouble following this brash young man. They had spent most of the day listening to an extraordinary virtuoso presentation by Feynman's exact contemporary, Julian Schwinger of Harvard University. This had been difficult to follow (when published, Schwinger's work would violate the *Physical Review*'s guidelines limiting the sprawl of equations across the width of the page) but convincing nonetheless. Feynman was offering fewer and less meticulous equations. These men knew him from Los Alamos, for better and for worse. Oppenheimer himself had privately noted that Feynman was the most brilliant young physicist at the atomic bomb project. Why he had acquired such a reputation none of them could say precisely. A few knew of his contribution to the key equation for the efficiency of a nuclear explosion (still classified forty years later, although the spy Klaus Fuchs had transmitted it promptly to his incredulous masters in the Soviet Union) or his theory of predetonation, measuring the probability that a lump of uranium might explode too soon. If they could not describe his actual scientific work, nevertheless they had absorbed an intense image of an original mind. They remembered him organizing the world's first large-scale computing system, a hybrid of new electro-mechanical business calculators and teams of women with color-coded cards; or delivering a hypnotic lecture on, of all things, elementary arithmetic; or frenetically twisting a control knob in a game whose object was to crash together a pair of electric trains; or sitting defiantly upright, for once motionless, in an army weapons carrier lighted by the purple-white glare of the century's paradigmatic explosion.

Facing his elders in the Pocono Manor sitting room, Feynman realized that he was drifting deeper and deeper into confusion. Uncharacteristically, he was nervous. He had not been able to sleep. He, too, had heard Schwinger's elegant lecture and feared that his own presentation seemed unfinished by comparison. He was trying to put across a new program for making the more exact calculations that physics now required—more than a program, a vision, a dancing, shaking picture of particles, symbols, arrows, and fields. The ideas were unfamiliar, and his slightly reckless style irritated some of the Europeans. His vowels were a raucous urban growl. His consonants slurred in a way that struck them as lower-class. He shifted his weight back and forth and twirled a piece of chalk rapidly between his fingers, around and around and end over end. He was a few weeks shy of his thirtieth birthday, too old now to pass for a boy wonder. He was trying to skip some details that would seem controversial—but too late. Edward Teller, the contentious Hungarian physicist, on his way to heading the postwar project to build the Super, the hydrogen bomb, interrupted with a question about basic quantum physics: “What about the exclusion principle?”

Feynman had hoped to avoid this. The exclusion principle meant that only one electron could inhabit a particular quantum state; Teller thought he had caught him pulling two rabbits from a single hat. Indeed, in Feynman’s scheme particles did seem to violate this cherished principle by coming into existence for a ghostly instant. “It doesn’t make any difference—” he started to reply.

“How do you know?

“I know, I worked from a—”

“How could it be!” Teller said.

Feynman was drawing unfamiliar diagrams on the blackboard. He showed a particle of antimatter going backward in time. This mystified Dirac, the man who had first predicted the existence of antimatter. Dirac now asked a question about causality: “Is it unitary?” Unitary! What on earth did he mean?

“I’ll explain it to you,” Feynman said, “and then you can see how it works, then you can tell me if it’s unitary.” He went on, and from time to time he thought he could still hear Dirac muttering, “Is it unitary?”

Feynman—mystifyingly brilliant at calculating, strangely ignorant of the literature, passionate about physics, reckless about proof—had for once overestimated his ability to charm and persuade these great physicists. Yet in truth he had now found what had eluded all of his elders, a way to carry physics forward into a new era. He had created a private new science that brought past and future together in a starkly majestic tapestry. His new friend Dyson at Cornell had glimpsed it—“this wonderful vision of the world as a woven texture of world lines in space and time, with everything moving freely," as Dyson described it. "It was a unifying principle that would either explain everything or explain nothing." Twentieth-century physics had reached an edge. Older men were looking for a way beyond an obstacle to their calculations. Feynman's listeners were eager for the new ideas of young physicists, but they were wedded to a certain view of the atomic world—or rather, a series of different views, each freighted with private confusion. Some were thinking mostly about waves—mathematical waves carrying the past into the present. Often, of course, the waves behaved as particles, like the particles whose trajectories Feynman sketched and erased on the blackboard. Some merely took refuge in the mathematics, chains of difficult calculations using symbols as stepping stones on a march through fog. Their systems of equations represented a submicroscopic world defying the logic of everyday objects like baseballs and water waves, ordinary objects with, "thank God," as W. H. Auden put it (in a poem Feynman detested):

> sufficient mass
> To be altogether there,
> Not an indeterminate gruel
> Which is partly somewhere else.

The objects of quantum mechanics were always partly somewhere else. The chicken-wire diagrams that Feynman had etched on the blackboard seemed, by contrast, quite definite. Those trajectories looked classical in their precision. Niels Bohr stood up. He knew this young physicist from Los Alamos—Feynman had argued freely and vehemently with Bohr. Bohr had sought Feynman's private counsel there, valuing his frankness, but now he was disturbed by the evident implications of those crisp lines. Feynman's particles seemed to be following paths neatly fixed in space and time. This they could not do. The uncertainty principle said so.

"Already we know that the classical idea of the trajectory in a path is not a legitimate idea in quantum mechanics," he said, or so Feynman thought—Bohr's soft voice and notoriously vague Danish tones kept his listeners straining to understand. He stepped forward and for many minutes, with Feynman standing unhappily to the side, delivered a humiliating lecture on the uncertainty principle. Afterward Feynman kept his despair to himself. At Pocono a generation of physics was melting into the next, and the passing of generations was neither as clean nor as inevitable as it later seemed.

Architect of quantum theories, brash young group leader on the atomic bomb project, inventor of the ubiquitous Feynman diagram, ebullient bongo player and storyteller, Richard Phillips Feynman was the most brilliant, iconoclastic, and influential physicist of modern times. He took the half-made conceptions of waves and particles in the 1940s and shaped them into tools that ordinary physicists could use and understand. He had a lightning ability to see into the heart of the problems nature posed. Within the community of physicists, an organized, tradition-bound culture that needs heroes as much as it sometimes mistrusts them, his name took on a special luster. It was permitted in connection with Feynman to use the word *genius*. He took center stage and remained there for forty years, dominating the science of the postwar era—forty years that turned the study of matter and energy down an unexpectedly dark and spectral road. The work that made its faltering appearance at Pocono tied together in an experimentally perfect package all the varied phenomena at work in light, radio, magnetism, and electricity. It won Feynman a Nobel Prize. At least three of his later achievements might also have done so: a theory of superfluidity, the strange, frictionless behavior of liquid helium; a theory of weak interactions, the force at work in radioactive decay; and a theory of partons, hypothetical hard particles inside the atom's nucleus, that helped produce the modern understanding of quarks. His vision of particle interaction kept returning to the forefront of physics as younger scientists explored esoteric new domains. He continued to find new puzzles. He could not, or would not, distinguish between the prestigious problems of elementary particle physics and the apparently humbler everyday questions that seemed to belong to an earlier era. No other physicist since Einstein so ecumenically accepted the challenge of all nature's riddles. Feynman studied friction on highly polished surfaces, hoping—and mostly failing—to understand how friction worked. He tried to make a theory of how wind makes ocean waves grow; as he said later, "We put our foot in a swamp and we pulled it up muddy." He explored the connection between the forces of atoms and the elastic properties of the crystals they form. He assembled experimental data and theoretical ideas on the folding of strips of paper into peculiar shapes called flexagons. He made influential progress—but not enough to satisfy himself—on the quantum theory of gravitation that had eluded Einstein. He struggled for years, in vain, to penetrate the problem of turbulence in gases and liquids.

Feynman developed a stature among physicists that transcended any raw sum of his actual contributions to the field. Even in his twenties, when his published work amounted to no more than a doctoral thesis (profoundly original but little understood) and a few secret papers in the Los Alamos archives, his legend was growing. He was a master calculator: in a group of scientists he could create a dramatic impression by slashing his way through a difficult problem. Thus scientists—believing themselves to be unforgiving meritocrats—found quick opportunities to compare themselves unfavorably to Feynman. His mystique might have belonged to a gladiator or a champion arm-wrestler. His personality, unencumbered by dignity or decorum, seemed to announce: Here is an unconventional mind. The English writer C. P. Snow, observing the community of physicists, thought Feynman lacked the "*gravitas*" of his seniors. "A little bizarre ... He would grin at himself if guilty of stately behaviour. He is a showman and enjoys it ... rather as though Groucho Marx was suddenly standing in for a great scientist." It made Snow think of Einstein, now so shaded and dignified that few remembered the "merry boy" he had been in his creative time. Perhaps Feynman, too, would grow into a stately personage. Perhaps not. Snow predicted, "It will be interesting for young men to meet Feynman in his later years."

One team of physicists, assembled for the Manhattan Project, met him for the first time in Chicago, where he solved a problem that had baffled them for a month. It was "a shallow way to judge a superb mind," one of them admitted later, but they had to be impressed, by the unprofessorial manner as much as the feat itself: "Feynman was patently not struck in the prewar mold of most young academics. He had the flowing, expressive postures of a dancer, the quick speech we thought of as Broadway, the pat phrases of the hustler and the conversational energy of a finger snapper." Physicists quickly got to know his bounding theatrical style, his way of bobbing sidelong from one foot to the other when he lectured. They knew that he could never sit still for long and that when he did sit he would slouch comically before leaping up with a sharp question. To Europeans like Bohr his voice was as American as any they had heard, a sort of musical sandpaper; to the Americans it was raw, unregenerate New York. No matter. “We got the indelible impression of a star,” another young physicist noted. “He may have emitted light as well as words.... Isn’t *areté* the Greek word for that shining quality? He had it.”

Originality was his obsession. He had to create from first principles—a dangerous virtue that sometimes led to waste and failure. He had the cast of mind that often produces cranks and misfits: a willingness, even eagerness, to consider silly ideas and plunge down wrong alleys. This strength could have been a crippling weakness had it not been redeemed, time and again, by a powerful intelligence. “Dick could get away with a lot because he was so goddamn smart,” a theorist said. “He really *could* climb Mont Blanc barefoot.” Isaac Newton spoke of having stood on the shoulders of giants. Feynman tried to stand on his own, through various acts of contortion, or so it seemed to the mathematician Mark Kac, who was watching Feynman at Cornell:

> There are two kinds of geniuses, the “ordinary” and the “magicians.” An ordinary genius is a fellow that you and I would be just as good as, if we were only many times better. There is no mystery as to how his mind works. Once we understand what they have done, we feel certain that we, too, could have done it. It is different with the magicians. They are, to use mathematical jargon, in the orthogonal complement of where we are and the working of their minds is for all

> intents and purposes incomprehensible. Even after we understand what they have done, the process by which they have done it is completely dark. They seldom, if ever, have students because they cannot be emulated and it must be terribly frustrating for a brilliant young mind to cope with the mysterious ways in which the magician's mind works. Richard Feynman is a magician of the highest caliber.

Feynman resented the polished myths of most scientific history, submerging the false steps and halting uncertainties under a surface of orderly intellectual progress, but he created a myth of his own. When he had ascended to the top of the physicists' mental pantheon of heroes, stories of his genius and his adventures became a sort of art form within the community. Feynman stories were clever and comic. They gradually created a legend from which their subject (and chief purveyor) seldom emerged. Many of them were transcribed and published in the eighties in two books with idiosyncratic titles, *Surely You're Joking, Mr. Feynman!* and *What Do You Care What Other People Think?* To the surprise of their publisher these became popular best-sellers. After his death in 1988 his sometime friend, collaborator, office neighbor, foil, competitor, and antagonist, the acerbic Murray Gell-Mann, angered his family at a memorial service by asserting, "He surrounded himself with a cloud of myth, and he spent a great deal of time and energy generating anecdotes about himself." These were stories, Gell-Mann added, "in which he had to come out, if possible, looking smarter than anyone else." In these stories Feynman was a gadfly, a rake, a clown, and a naïf. At the atomic bomb project he was the thorn in the side of the military censors.

On the commission investigating the 1986 space-shuttle explosion he was the outsider who pushed aside red tape to uncover the true cause. He was the enemy of pomp, convention, quackery, and hypocrisy. He was the boy who saw the emperor with no clothes. So he was in life. Yet Gell-Mann spoke the truth, too. Amid the legend were misconceptions about Feynman's accomplishments, his working style, and his deepest beliefs. His own view of himself worked less to illuminate than to hide the nature of his genius.

The reputation, apart from the person, became an edifice standing monumentally amid the rest of the scenery of modern science. Feynman diagrams, Feynman integrals, and Feynman rules joined Feynman stories in the language that physicists share. They would say of a promising young colleague, "He's no Feynman, but ..." When he entered a room where physicists had gathered—the student cafeteria at the California Institute of Technology, or the auditorium at any scientific meeting—with him would come a shift in the noise level, a disturbance of the field, that seemed to radiate from where he was carrying his tray or taking his front-row seat. Even his senior colleagues tried to look without looking. Younger physicists were drawn to Feynman's rough glamour. They practiced imitating his handwriting and his manner of throwing equations onto the blackboard. One group held a half-serious debate on the question, Is Feynman human? They envied the inspiration that came (so it seemed to them) in flashes. They admired him for other qualities as well: a faith in nature's simple truths, a skepticism about official wisdom, and an impatience with mediocrity.

He was widely considered a great educator. In fact few physicists of even the middle ranks left behind so small a cadre of students, or so assiduously shirked ordinary teaching duties.

Although science remained one of the few domains of true apprenticeship, with students learning their craft at the master's side, few learned this way from Feynman. He did not have the patience to guide a student through a research problem, and he raised high barriers against students who sought him as a thesis adviser. Nevertheless when Feynman did teach he left a deep imprint on the subject. Although he never actually wrote a book, books bearing his name began to appear in the sixties—*Theory of Fundamental Processes* and *Quantum Electrodynamics*, lightly edited versions of lectures transcribed by students and colleagues. They became influential. For years he offered a mysterious noncredit course called Physics X, for undergraduates only, in a small basement room. Some physicists years later remembered this unpredictable free-form seminar as the most intense intellectual experience of their education. Above all in 1961 he took on the task of reorganizing and teaching the introductory physics course at Caltech. For two years the freshmen and sophomores, along with a team of graduate-student teaching assistants, struggled to follow a tour de force, the universe according to Feynman. The result was published and became famous as "the red books"—*The Feynman Lectures on Physics*. They reconceived the subject from the bottom up. Colleges that adopted the red books dropped them a few years later: the texts proved too difficult for their intended readers. Instead, professors and working physicists found Feynman's three volumes reshaping their own conception of their subject. They were more than just authoritative. A physicist, citing one of many celebrated passages, would dryly pay homage to "Book II, Chapter 41, Verse 6."

Authoritative, too, were Feynman's views of quantum mechanics, of the scientific method, of the relations between science and religion, of the role of beauty and uncertainty in the creation of knowledge. His comments on such subjects were mostly expressed offhand in technical contexts, but also in two slim models of science writing, again distilled from lectures: *The Character of Physical Law* and *QED: The Strange Theory of Light and Matter*. Feynman was widely quoted by scientists and science writers (although he seldom submitted to interviews). He despised philosophy as soft and unverifiable. Philosophers "are always on the outside making stupid remarks," he said, and the word he pronounced *philozawfigal* was a mocking epithet, but his influence was philosophical anyway, particularly for younger physicists. They remembered, for example, his Gertrude Stein–like utterance on the continuing nervousness about quantum mechanics—or, more precisely, the "world view that quantum mechanics represents":

> It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.

or, similarly, what may have been the literature's most quoted mixed metaphor:

> Do not keep saying to yourself, if you can possibly avoid it, "But how can it be like that?" because you will get "down the drain," into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.

In private, with pencil on scratch paper, he labored over aphorisms that he later delivered in spontaneous-seeming lectures:

> Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry.

Why is the world the way it is? Why is science the way it is? How do we discover new rules for the flowering complexity around us? Are we reaching toward nature's simple heart, or are we merely peeling away layers of an infinitely deep onion? Although he sometimes retreated to a stance of pure practicality, Feynman gave answers to these questions, philosophical and unscientific though he knew they were. Few noticed, but his answer to the starkest of science's metaphysical questions—Is there a meaning, a simplicity, a comprehensibility at the core of things?—underwent a profound change in his lifetime.

Feynman's reinvention of quantum mechanics did not so much explain how the world was, or why it was that way, as tell how to confront the world. It was not knowledge of or knowledge about. It was knowledge how to. How to compute the emission of light from an excited atom. How to judge experimental data, how to make predictions, how to construct new tool kits for the new families of particles that were about to proliferate through physics with embarrassing fecundity.

There were other kinds of scientific knowledge, but pragmatic knowledge was Feynman's specialty. For him knowledge did not describe; it acted and accomplished. Unlike many of his colleagues, educated scientists in a cultivated European tradition, Feynman did not look at paintings, did not listen to music, did not read books, even scientific books. He refused to let other scientists explain anything to him in detail, often to their immense frustration. He learned anyway. He pursued knowledge without prejudice. During a sabbatical he learned enough biology to make a small but genuine contribution to geneticists' understanding of mutations in DNA. He once offered (and then awarded) a one-thousand-dollar prize for the first working electric motor less than one sixty-fourth of an inch long, and his musing on the possibilities of tiny machinery made him, a generation later, the intellectual father of a legion of self-described nanotechnologists. In his youth he experimented for months on end with trying to observe his unraveling stream of consciousness at the point of falling asleep. In his middle age he experimented with inducing out-of-body hallucinations in a sensory-deprivation tank, with and without marijuana. His lifetime saw a stratification of the branch of knowledge called physics. Those specializing in the understanding of elementary particles came to control much of the field's financing and much of its public rhetoric. With the claim that particle physics was the most fundamental science, they scorned even subdisciplines like solid-state physics—"squalid-state" was Gell-Mann's contemptuous phrase. Feynman embraced neither the inflating language of Grand Unified Theories nor the disdain for other sciences.

Democratically, as if he favored no skill above any other, he taught himself how to play drums, to give massages, to tell stories, to pick up women in bars, considering all these to be crafts with learnable rules. With the gleeful prodding of his Los Alamos mentor Hans Bethe ("Don't you know how to take squares of numbers near 50?") he taught himself the tricks of mental arithmetic, having long since mastered the more arcane arts of mental differentiation and integration. He taught himself how to make electroplated metal stick to plastic objects like radio knobs, how to keep track of time in his head, and how to make columns of ants march to his bidding. He had no difficulty learning to make an impromptu xylophone by filling water glasses; nor had he any shyness about playing them, all evening, at a dinner party for an astonished Niels Bohr. At the same time, when he was engrossed in the physicists' ultimate how-to endeavor, the making of an atomic bomb, he digressed to learn how to defeat the iron clamp of an old-fashioned soda machine, how to pick Yale locks, and then how to open safes—a mental, not physical, skill, though his colleagues mistakenly supposed he could feel the vibrations of falling tumblers in his fingertips (as well they might, after watching him practice his twirling motion day after day on their office strongboxes). Meanwhile, dreamily wondering how to harness atomic power for rockets, he worked out a nuclear reactor thrust motor, not quite practical but still plausible enough to be seized by the government, patented, and immediately buried under an official secrecy order. With no less diligence, much later, having settled into a domestic existence complete with garden and porch, he taught himself how to train dogs to do counterintuitive tricks—for example, to pick up a nearby sock not by the direct route but by the long way round, circling through the garden, in the porch door and back out again. (He did the training in stages, breaking the problem down until after a while it was perfectly obvious to the dog that one did not go directly to the sock.) Then he taught himself how to find people bloodhound-style, sensing the track of their body warmth and scent. He taught himself how to mimic foreign languages, mostly a matter of confidence, he found, combined with a relaxed willingness to let lips and tongue make silly sounds. (Why then, his friends wondered, could he never learn to soften his Far Rockaway accent?) He made islands of practical knowledge in the oceans of personal ignorance that remained: knowing nothing about drawing, he taught himself to make perfect freehand circles on the blackboard; knowing nothing about music, he bet his girlfriend that he could teach himself to play one piece, "The Flight of the Bumblebee," and for once failed dismally; much later he learned to draw after all, after a fashion, specializing in sweetly romanticized female nudes and letting his friends know that a concomitant learned skill thrilled him even more—how to persuade a young woman to disrobe. In his entire life he could never quite teach himself to feel a difference between right and left, but his mother finally pointed out a mole on the back of his left hand, and even as an adult he checked the mole when he wanted to be sure. He taught himself how to hold a crowd with his not-jazz, not-ethnic improvisational drumming; and how to sustain a two-handed polyrhythm of not just the usual three against two and four against three but—astonishing to classically trained musicians—seven against six and thirteen against twelve. He taught himself how to write Chinese, a skill acquired specifically to annoy his sister and limited therefore to the characters for "elder brother also speaks." In the era when high-energy particle accelerators came to dominate theoretical physics, he taught himself how to read the most modern of hieroglyphics, the lacy starburst photographs of particle collisions in cloud chambers and bubble chambers—how to read them not for new particles but for the subtler traces of experimental bias and self-deception. He taught himself how to discourage autograph seekers and refuse lecture invitations; how to hide from colleagues with administrative requests; how to force everything from his field of vision except for his research problem of the moment; how to hold off the special terrors of aging that shadow scientists; then how to live with cancer, and how to surrender to it.

After he died several colleagues tried to write his epitaph. One was Schwinger, in a certain time not just his colleague but his preeminent rival, who chose these words: “An honest man, the outstanding intuitionist of our age, and a prime example of what may lie in store for anyone who dares to follow the beat of a different drum.” The science he helped create was like nothing that had come before. It rose as his culture’s most powerful achievement, even as it sometimes sent physicists down the narrowing branches of an increasingly obscure tunnel. When Feynman was gone, he had left behind—perhaps his chief legacy—a lesson in what it meant to know something in this most uncertain of centuries.

FAR ROCKAWAY

EVENTUALLY THE ART went out of radio tinkering. Children forgot the pleasures of opening the cabinets and eviscerating their parents' old Kadettes and Clubs. Solid electronic blocks replaced the radio set's messy innards—so where once you could learn by tugging at soldered wires and staring into the orange glow of the vacuum tubes, eventually nothing remained but featureless ready-made chips, the old circuits compressed a thousandfold or more. The transistor, a microscopic quirk in a sliver of silicon, supplanted the reliably breakable tube, and so the world lost a well-used path into science.

In the 1920s, a generation before the coming of solid-state electronics, one could look at the circuits and see how the electron stream flowed. Radios had valves, as though electricity were a fluid to be diverted by plumbing. With the click of the knob came a significant hiss and hum, just at the edge of audibility. Later it was said that physicists could be divided into two groups, those who had played with chemistry sets and those who had played with radios. Chemistry sets had their appeal, but a boy like Richard Feynman, loving diagrams and maps, could see that the radio was its own map, a diagram of itself. Its parts expressed their function, once he learned to break the code of wires, resistors, crystals, and capacitors. He assembled a crystal set, attached oversized earphones from a rummage sale, and listened under the bedcovers until he fell asleep. Sometimes his parents would tiptoe in and take the earphones off their sleeping boy. When atmospheric conditions were right, his radio could pull in signals from far away

—Schenectady in upstate New York or even station WACO from Waco, Texas. The mechanism responded to the touch. To change channels he slid a contact across a wire coil. Still, the radio was not like a watch, with gears and wheels. It was already one step removed from the mechanical world. Its essential magic was invisible after all. The crystal, motionless, captured waves of electromagnetic radiation from the ether.

Yet there was no ether—no substance bearing these waves. If scientists wished to imagine radio waves propagating with the unmistakable undulating rhythm of waves in a pond, they nonetheless had to face the fact that these waves were not *in* anything. Not in the era of relativity: Einstein was showing that if an ether existed it would have to be motionless with respect to any and all observers—though they themselves moved in different directions. This was impossible. "It seems that the aether has betaken itself to the land of the shades in a final effort to elude the inquisitive search of the physicist!" the mathematician Hermann Weyl wrote in 1918, the year Feynman was born. Through what medium, then, were radio waves sweeping in their brief journey from the aerials of downtown New York to Feynman's second-story bedroom in a small frame house on the city's outskirts? Whatever it was, the radio wave was only one of the many sorts of oscillations disturbing every region of space. Waves of light, physically identical to radio waves but many times shorter, crisscrossing hectically; infrared waves, perceptible as heat on the skin; the ominously named X rays; the ultra-high-frequency gamma rays, with wavelengths smaller than atoms—all these were just different guises of one phenomenon, electromagnetic radiation. Already space was an electromagnetic babel, and human-built transmitters were making it busier still. Fragmented voices, accidental clicks, slide-whistle drones: strange noises passed through one another, more waves in a well-corrugated waviness. These waves coexisted not in the ether but in a rather more abstract medium, the precise nature of which was posing difficulties for physicists. They could not imagine what it was—a problem that was only mildly allayed by the fact that they had a name for it, the electromagnetic field, or just the field. The field was merely a continuous surface or volume across which some quantity varied. It had no substance, yet it shook; it vibrated. Physicists were discovering that the vibrations sometimes behaved like particles, but this just complicated the issue. If they were particles, they were nonetheless particles with an undeniably wavelike quality that enabled boys like Feynman to tune in to certain desirable wavelengths, the ones carrying "The Shadow" and "Uncle Don" and advertisements for Eno Effervescent Salts. The scientific difficulties were obscure, known only to a handful of scientists more likely to speak German than English. The essence of the mystery, however, was clear to amateurs who read about Einstein in the newspapers and pondered the simple magic of a radio set.

No wonder so many future physicists started as radio tinkerers, and no wonder, before *physicist* became a commonplace word, so many of them grew up thinking they might become electrical engineers, professionals known to earn a good wage. Richard, called Ritty by his friends, seemed to be heading single-mindedly in that direction. He accumulated tube sets and an old storage battery from around the neighborhood. He assembled transformers, switches, and coils. A coil salvaged from a Ford automobile made showy sparks that burned brown-black holes in newspaper. When he found a leftover rheostat, he pushed 110-volt electricity through it until it overloaded and burned. He held the stinking, smoking thing outside his second-floor window, as the ashes drifted down to the grassy rear yard. This was standard emergency procedure. When a pungent odor drifted in downstairs during his mother's bridge game, it meant that Ritty was dangling his metal wastebasket out the window, waiting for the flames to die out after an abortive experiment with shoe polish—he meant to melt it and use the liquid as black paint for his "lab," a wooden crate roughly the size of a refrigerator, standing in his bedroom upstairs in the rear of the house. Screwed into the crate were various electrical switches and lights that Ritty had wired, in series and in parallel. His sister, Joan, nine years younger, served eagerly as a four-cents-a-week lab assistant. Her duties included putting a finger into a spark gap and enduring a mild shock for the entertainment of Ritty's friends.

It had already occurred to psychologists that children are innate scientists, probing, puttering, experimenting with the possible and impossible in a confused local universe. Children and scientists share an outlook on life. *If I do this, what will happen?* is both the motto of the child at play and the defining refrain of the physical scientist. Every child is observer, analyst, and taxonomist, building a mental life through a sequence of intellectual revolutions, constructing theories and promptly shedding them when they no longer fit. The unfamiliar and the strange—these are the domain of all children and scientists.

None of which could fully account for the presence of laboratory, rheostat, and lab assistant—tokens of a certain vivid cultural stereotype. Richard Feynman was relentless in filling his bedroom with the trappings and systems of organized science.

Neither Country nor City

Charmed lives were led by the children of Far Rockaway, a village that amounted to a few hundred acres of frame houses and brick apartment blocks on a spit of beach floating off Long Island's south shore. The neighborhood had been agglomerated into the political entity of New York City as one of the more than sixty towns and neighborhoods that merged as the borough of Queens in 1898. The city was investing generously in these neighborhoods, spending tens of millions of dollars on the laying of water mains, sewers, and roadways and the construction of grand public buildings. Still, in the first part of the twentieth century, before the IND subway line reached out across the marshes of Jamaica Bay, the city seemed a faraway place. Commuters took the Long Island Rail Road. Beyond Far Rockaway's eastern border lay the small towns of Nassau County, Long Island. To the northwest, across marshy tongues of ocean called Mott Basin and Hassock Channel, lay a flat expanse that later became Idlewild Airport and then Kennedy International Airport. On foot or on their bicycles, Far Rockaway's children had free run of a self-contained world: ivy-covered houses, fields, and vacant lots. No one has yet isolated the circumstances that help a child grow whole and independent, but they were present. At some point in a town's evolution, houses and fences grow dense enough to form a connected barrier. When that critical point is reached, movement is mostly restricted to public streets. In Far Rockaway boys and girls still percolated through the neighborhood and established their own paths through backyards and empty lots behind the houses and streets. They were autonomous and enterprising in play, roaming far from their parents' immediate oversight, riding their bicycles without accounting for their whereabouts. They could wander through fields on the way to the shore, and then they could rent boats and row them up and down the protected inlets. Richard walked to the library and, sitting on the stone steps, watched people go by in all directions. Distant as New York seemed, he felt bound enough to the great city to look down on the outsiders living a few blocks away, in Cedarhurst, Long Island. But he also knew that his neighborhood was a place apart.

"When I was a child I thought we lived at the end of the world," wrote another New Yorker, the critic Alfred Kazin; he grew up in Brownsville, a Brooklyn neighborhood a little poorer and almost as remote, another district of Jewish immigrants and children of immigrants occupying that unusual boundary between the urban and the rural. "There were always raw patches of unused city land all around us filled with 'monument works' where they cut and stored tombstones, as there were still on our street farmhouses and the remains of old cobbled driveways," he wrote —"most of it dead land, neither country nor city.... That was the way to the ocean we always took summer evenings—through silent streets of old broken houses whose smoky red Victorian fronts looked as if the paint had clotted like blood and had then been mixed with soot—past infinite weedy lots...."

For Ritty Feynman the beach was best of all—the long southern strand stretching almost unbroken to the far east end of Long Island, framed by its boardwalk and summer hotels, cottages and thousands of private lockers. Far Rockaway was a summer resort with beach clubs for people from the city: the Ostend Baths, Roche's (for a long time Richard thought this was named after the insect), the Arnold. There were wooden pavilions and changing rooms for rent by the season, with shiny locks and keys. For the local children, though, the beach served its purpose the year round. They splashed in the light surf, attenuated by a long breakwater pale beneath the waves. At the height of the summer's crowds the pink and green of bathing suits dotted the sand like gumdrops. It was his favorite place. He usually rode his bicycle the four thousand feet from his house (a distance that expanded in his later memory to two miles). He went with friends or alone. The sky was larger there than anywhere else in the city's confines; the ocean tempted his imagination as it does any child's. All those waves, all that space, the boats crawling like apparitions along the horizon toward New York Harbor, Europe and Africa lying far beyond, at the end of a long uninterrupted vector curving downward below the sky. It sometimes seemed that the things near the sea were the only things that were any good.

The dome of the sky stretched upward. The arcs of the sun and moon crossed directly ahead, rising and falling with the season. He could splash his heels in the surf and recognize a line that formed the tripartite boundary between earth, sea, and air. At night he would take his flashlight. For teenagers the beach was a site for social mixing between boys and girls; he did his best, though he sometimes felt gawky. He often swam. When he was forty-three, setting out nearly everything he knew about physics in the historic two-year undergraduate course that became *The Feynman Lectures on Physics*, he stood before a hall of freshmen and tried to place them mentally at the beach. "If we stand on the shore and look at the sea," he said, "we see the water, the waves breaking, the foam, the sloshing motion of the water, the sound, the air, the winds and the clouds, the sun and the blue sky, and light; there is sand and there are rocks of various hardness and permanence, color and texture. There are animals and seaweed, hunger and disease, and the observer on the beach; there may even be happiness and thought." Nature was elemental there, though for Feynman *elemental* did not mean simple or austere. The questions he considered within the physicist's purview—the fundamental questions—arose on the beach. "Is the sand other than the rocks? That is, is the sand perhaps nothing but a great number of very tiny stones? Is the moon a great rock? If we understood rocks, would we also understand the sand and the moon? Is the wind a sloshing of the air analogous to the sloshing motion of the water in the sea?"

The great European migration to America was ending. For the Jews of Russia, Eastern Europe, and Germany, for the Irish and the Italians, the first-hand and first-generation memories would now recede. The outer neighborhoods of New York flourished in the generations before World War II and then began to wane. In Far Rockaway not much changed visibly in the sixty-nine years of Feynman's lifetime. When Feynman returned on a visit with his children a few years before his death, everything seemed shrunken and forlorn, the fields and vacant lots were gone, but it was the same beach with its boardwalk, the same high school, the same house he had wired for radio broadcasts—the house now divided, to accommodate a tenant, and not nearly so spacious as in memory. He did not ring the bell. The village's main street, Central Avenue, seemed shabby and narrow. The population had become largely Orthodox Jewish, and Feynman was vaguely disturbed to see so many yarmulkes, or, as he actually said, "those little hats that they wear"—meaning: *I don't care what things are called.* And casually repudiating the culture that hung as thick in the air of his childhood as the smoke of the city or the salt of the ocean.

The Judaism of Far Rockaway took in a liberal range of styles of belief, almost broad enough to encompass atheists like Richard's father, Melville. It was a mostly Reform Judaism, letting go the absolutist and fundamental traditions for the sake of a gentle, ethical humanism, well suited for fresh Americans pinning their hopes on children who might make their way into the mainstream of the New World. Some households barely honored the Sabbath. In some, like Feynman's, Yiddish would have been a foreign language. The Feynmans belonged to the neighborhood temple. Richard went to Sunday school for a while and belonged to a Shaaray Tefila youth group that organized after-school activities. Religion remained part of the village's ethical core. Families like the Feynmans, in neighborhoods all around greater New York City, produced in the first half of the twentieth century an outpouring of men and women who became successful in many fields, but especially science. These hundred-odd square miles of the planet's surface were disproportionately fertile in the spawning of Nobel laureates. Many families, as Jews, were embedded in a culture that prized learning and discourse; immigrants and the children of immigrants worked to fulfill themselves through their own children, who had to be sharply conscious of their parents' hopes and sacrifices. They shared a sense that science, as a profession, rewarded merit. In fact, the best colleges and universities continued to raise barriers against Jewish applicants, and their science faculties remained determinedly Protestant, until after World War II. Science nevertheless offered the appearance of a level landscape, where the rules seemed mathematical and clear, free from the hidden variables of taste and class.

As a town Far Rockaway had a center that even Cedarhurst lacked. When Richard's mother, Lucille, walking down to Central Avenue, headed for stores like Nebenzahl's and Stark's, she appreciated the centralization. She knew her children's teachers personally, helped get the school lunchroom painted, and joined her neighbors in collecting the set of red glassware given out as a promotion by a local movie theater. This village looked inward as carefully as the shtetl that remained in some memories. There was a consistency of belief and behavior. To be honest, to be principled, to study, to save money against hard times—the rules were not so much taught as assumed. Everyone worked hard. There was no sense of poverty—certainly not in Feynman's family, though later he realized that two families had shared one house because neither could get by alone. Nor in his friend Leonard Mautner's, even after the father had died and an older brother was holding the family together by selling eggs and butter from house to house. "That was the way the world was," Feynman said long afterward. "But now I realize that everybody was struggling like mad. Everybody was struggling and it didn't seem like a struggle." For children, life in such neighborhoods brought a rare childhood combination of freedom and moral rigor. It seemed to Feynman that morality was made easy. He was allowed to surrender to a natural inclination to be honest. It was the downhill course.

A Birth and a Death

Melville Feynman (he pronounced his surname like the more standard variants: Fineman or Feinman) came from Minsk, Byelorussia. He immigrated with his parents, Louis and Anne, in 1895, at the age of five, and grew up in Patchogue, Long Island. He had a fascination with science but, like other immigrating Jews of his era, no possible means to fulfill it. He studied a fringe version of medicine called homeopathy; then he embarked on a series of businesses, selling uniforms for police officers and mail carriers, selling an automobile polish called Whiz (for a while the Feynmans had a garage full of it), trying to open a chain of cleaners, and finally returning to the uniform business with a company called Wender & Goldstein. He struggled for much of his business life.

His wife had grown up in better circumstances. Lucille was the daughter of a successful milliner who had emigrated as a child from Poland to an English orphanage, where he acquired the name Henry Phillips. From there Lucille's father came to the United States, where he got his first job selling needles and thread from a pack on his back. He met Johanna Helinsky, a daughter of German-Polish immigrants, when she repaired his watch in a store on the Lower East Side of New York. Henry and Johanna not only married but also went into business together. They had an idea that rationalized the trimming of the elaborate hats that women wore before World War I, and their millinery business thrived. They moved to a town house well uptown on the East Side, on 92d Street near Park Avenue, and there Lucille, the youngest of their five children, was born in 1895.

Like many well-off, assimilating Jews, Lucille Phillips attended the Ethical Culture School (an institution whose broad humanist ethos soon left its mark on J. Robert Oppenheimer, nine years her junior). She prepared to teach kindergarten. Instead, soon after graduating, still a teenager, she met Melville. The introduction to her future husband came through her best friend. Melville was the friend's date; Lucille was invited to accompany a friend of Melville's. They went for a drive, with Lucille joining Melville's friend sitting in the back seat. On the return trip, it was Lucille and Melville who sat together.

A few days later he said, "Don't get married to anybody else."

This was not quite a proposal, and her father would not allow her to marry Melville until three years later, when she turned twenty-one. They moved into an inexpensive apartment in upper Manhattan in 1917, and Richard was born in a Manhattan hospital the next year.

A later family legend held that Melville announced in advance that, if the baby was a boy, he would be a scientist. Lucille supposedly replied, Don't count your chickens before they hatch. But Richard's father undertook to help his prophecy along. Before the baby was out of his high chair, he brought home some blue and white floor tiles and laid them out in patterns, blue-white-blue-white or blue-white-white-blue-white-white, trying to coax the baby to recognize visual rhythms, the shadow of mathematics. Richard had walked at an early age, but he was two before he talked. His mother worried for months. Then, as late talkers so often do, Richard became suddenly and unstoppably voluble. Melville bought the *Encyclopaedia Britannica*, and Richard devoured it. Melville took his son on trips to the American Museum of Natural History, with its animal tableaux in glass cases and its famous, towering, bone-and-wire dinosaurs. He described dinosaurs in a way that taught a lesson about expressing dimensions in human units: "twenty-five feet high and the head is six feet across" meant, he explained, that "if he stood in our front yard he would be high enough to put his head through the window but not quite because the head is a little bit too wide and it would break the window"—a vivid enough illustration for any small boy.

Melville's gift to the family was knowledge and seriousness. Humor and a love of storytelling came from Lucille. At any rate, that was how family lore tended to apportion their influence. Melville liked to laugh at the stories his wife and children told, at dinner and afterward, when the family regularly read aloud. He had a surprising giggle, and his son acquired an eerily exact facsimile. Comedy, for Lucille, was a high calling and a way of defying misfortune: the hard reality of her grandparents' lives in a Polish ghetto, and tragedy in her own family. Her mother suffered from epilepsy and her eldest sister from schizophrenia. Except for another sister, Pearl, her brothers and sisters died young.

Early death also came to her new household. In the winter Richard was five, she gave birth to a second son, named Henry Phillips Feynman, after her father, who had died a year before. Four weeks later the baby came down with a fever. A fingernail had been bleeding and never quite healed. Within days the baby was dead, probably from spinal meningitis. The grief, the quick turning of happiness into despair—and surely for Richard the fear as well—darkened their home for a long time. He had waited for a brother. Now he had a lesson in human precariousness, in the cruelty of nature's untamed accidents. Later he almost never spoke of the harsh death that dominated this year. He had no brother or sister again until finally, when he was nine, Joan was born. Henry's presence remained a shadow in the household. Richard knew—even Joan knew—that their mother always kept a birth certificate and a hat that had once belonged to a boy whose remains now lay in the vault of the family mausoleum five miles away, behind a stone plate inscribed, "HENRY PHILLIPS FEYNMAN JANUARY 24, 1924–FEBRUARY 25, 1924."

The Feynmans moved several times, leaving Manhattan for the small towns straddling the city border: first to Far Rockaway; then from Far Rockaway to Baldwin, Long Island; then to Cedarhurst, when Richard was about ten, and then back to Far Rockaway. Lucille's father owned a house there, and they moved in

—a two-story house of stucco the color of sand, on a small lot at 14 New Broadway. There were front and rear yards and a double driveway. They shared the house with Lucille's sister Pearl and her family—her husband, Ralph Lewine, a boy, Robert, just older than Richard, and a girl, Frances, just younger. A rail of white wood ringed the porch. The ground floor held two living rooms, one for show and one for general use, with gas logs in a fireplace for cold days. The bedrooms were small, but there were eight of them. Richard's, on the second floor, overlooked the back yard, with its forsythia and peach tree. Some evenings the adults would come home to find his cousin, Frances, shivering at the upstairs landing, unable to sleep because Richard, as chief baby-sitter, had told ghost stories drawing their mood from the old Gothic panels that lined the stairs.

The household had two other members during those pre-Depression years, a German immigrant couple, Ludwig and Marie, easing their passage into the United States by working as household servants for room and board. Marie cooked; Ludwig said wryly that he was gardener, chauffeur, and butler, serving meals in a formal white coat. They also arranged some serious and inventive play. With Ludwig's help the north window of the garage became the North Fenster Bank. Everyone took turns playing teller and customer. As Ludwig and Marie learned English they taught the children other routines: the protocols of gardening and formal table manners. If Feynman acquired such skills, he carefully shed them later.

To Joan, the youngest of all the children, it seemed like a well-run household where things happened when they were supposed to happen. Late one night, however, when she was three or four, her brother shook her awake in violation of the routine. He said he had permission to show her something rare and wonderful. They walked, holding hands, onto Far Rockaway's small golf course, away from the illuminated streets. "Look up," Richard said. There, far above them, the streaky wine-green curtains of the aurora borealis rippled against the sky. One of nature's surprises. Somewhere in the upper atmosphere solar particles, focused by the earth's magnetosphere, ripped open trails of luminous high-voltage ionization. It was a sight that the street lights of a growing city would soon cast out forever.

It's Worth It

The mathematics and the tinkering developed separately. At home the scientific inventory expanded to include chemicals from chemistry sets, lenses from a telescope, and photographic developing equipment. Ritty wired his laboratory into the electrical circuits of the entire house, so that he could plug his earphones in anywhere and make impromptu broadcasts through a portable loudspeaker. His father declared—something he had heard—that electrochemistry was an important new field, and Ritty tried in vain to figure out what electrochemistry was: he made piles of dry chemicals and set live wires in them. A jury-rigged motor rocked his baby sister's crib. When his parents came home late one night, they opened the door to a sudden clang-clang-clang and Ritty's shout: "It works!" They now had a burglar alarm. If his mother's bridge partners asked how she could tolerate the noise, or the chemical smoke, or the not-so-invisible ink on the good linen hand towels, she said calmly that it was worth it. There were no second thoughts in the middle-class Jewish families of New York about the value of ambition on the children's behalf.

The Feynmans raised their children according to a silent creed shared with many of their neighbors. Only rarely did they express its tenets, but they lived by them. They were sending their children into a world of hardships and dangers. A parent does all he or she can to bring a child up “so that he can better face the world and meet the intense competition of others for existence,” as Melville once put it. The child will have to find a niche in which he can live a useful and fruitful life. The parents’ motives are selfish—for nothing can magnify parents in the eyes of their neighbors as much as the child’s success. “When a child does something *good* and unusual,” Melville wrote, “it is the parents chest that swells up and who looks around and says to his neighbors (without actually speaking, of course) ‘See what I have wrought? Isn’t he wonderful? What have you got that can equal what I can show?’ And the neighbors help the ego of the parent along by acclaiming the wonders of the child and by admiring the parent for *his* success ...” A life in the business world, “the commercial world,” is arid and exhausting; turn rather to the professions, the world of learning and culture. Ultimately, for the sacrifices of his parents a child owes no debt—or rather the debt is paid to his own children in turn.

The adult Richard Feynman became an adept teller of stories about himself, and through these stories came a picture of his father as a man transmitting a set of lessons about science. The lessons were both naïve and wise. Melville Feynman placed a high value on curiosity and a low value on outward appearances. He wanted Richard to mistrust jargon and uniforms; as a salesman, he said, he saw the uniforms empty. The pope himself was just a man in a uniform. When Melville took his son on walks, he would turn over stones and tell him about the ants and the worms or the stars and the waves. He favored process over facts. His desire to explain such things often outstripped his knowledge of them; much later Feynman recognized that his father must have invented sometimes. The gift of these lessons, as Feynman expressed it in his two favorite stories about his father, was a way of thinking about scientific knowledge.

One was the story about birds. Fathers and sons often walked together on summer weekends in the Catskill Mountains of New York, and one day a boy said to Richard, “See that bird? What kind of bird is that?”

I said, “I haven’t the slightest idea what kind of bird it is.”

He says, “It’s a brown-throated thrush. Your father doesn’t teach you anything!”

But it was the opposite. He had already taught me: “See that bird?” he says. “It’s a Spencer’s warbler.” (I knew he didn’t know the real name.) “Well, in Italian, it’s a *Chutto Lapittida*. In Portuguese, it’s a *Bom da Peida*. In Chinese, it’s a *Chung-long-tah*, and in Japanese, it’s a *Katano Tekeda*. You can know the name of that bird in all the languages of the world, but when you’re finished, you’ll know absolutely nothing whatever about the bird. You’ll only know about humans in different places and what they call the bird. So let’s look at the bird and see what it’s *doing*—that’s what counts.”

The second story also carried a moral about the difference between the name and the thing named. Richard asks his father why, when he pulls his red wagon forward, a ball rolls to the back.

> “That,” he says, “nobody knows. The general principle is that things that are moving try to keep on moving,

> and things that are standing still tend to stand still, unless you push on them hard." And he says, "This tendency is called inertia, but nobody knows why it's true." Now that's a deep understanding.

Deeper than Melville could have known: few scientists or educators recognized that even a complete Newtonian understanding of force and inertia leaves the *why* unanswered. The universe does not have to be that way. It is hard enough to explain inertia to a child; to recognize that the ball actually moves forward slightly with respect to the ground while moving backward sharply with respect to the wagon; to see the role of friction in transferring the force; to see that *every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed upon it.* It is hard enough to convey all that without adding an almost scholastically subtle lesson about the nature of explanation. Newton's laws do explain why balls roll to the back of wagons, why baseballs travel in wind-bent parabolas, and even why crystals pick up radio waves, up to a point. Later Feynman became acutely conscious of the limits of such explanations. He agonized over the difficulty of truly explaining how a magnet picks up an iron bar or how the earth imparts the force called gravity to a projectile. The Feynman who developed an agnosticism about such concepts as inertia had a stranger physics in mind as well, the physics being born in Europe while father and son talked about wagons. Quantum mechanics imposed a new sort of doubt on science, and Feynman expressed that doubt often, in many different ways. *Do not ask how it can be like that. That, nobody knows.*

Even when he was young, absorbing such wisdom, Feynman sometimes glimpsed the limits of his father's understanding of science. As he was going to bed one night, he asked his father what algebra was.

"It's a way of doing problems that you can't do in arithmetic," his father said.

"Like what?"

"Like a house and a garage rents for $15,000. How much does the garage rent for?"

Richard could see the trouble with that. And when he started high school, he came home upset by the apparent triviality of Algebra 1. He went into his sister's room and asked, "Joanie, if 2^x is equal to 4 and x is an unknown number, can you tell me what x is?" Of course she could, and Richard wanted to know why he should have to learn anything so obvious in high school. The same year, he could see just as easily what x must be if 2^x was 32. The school quickly switched him into Algebra 2, taught by Miss Moore, a plump woman with an exquisite sense of discipline. Her class ran as a roundelay of problem solving, the students making a continual stream to and from the blackboard. Feynman was slightly ill at ease among the older students, but he already let friends know that he thought he was smarter. Still, his score on the school IQ test was a merely respectable 125.

At School

The New York City public schools of that era gained a reputation later for high quality, partly because of the nostalgic reminiscences of famous alumni. Feynman himself thought that his grammar school, Public School 39, had been stultifyingly barren: "an intellectual desert." At first he learned more at home, often from the encyclopedia. Having trained himself in rudimentary algebra, he once concocted a set of four equations with four unknowns and showed it off to his arithmetic teacher, along with his methodical solution. She was impressed but mystified; she had to take it to the principal to find out whether it was correct. The school had one course in general science, for boys only, taught by a blustering, heavyset man called Major Connolly—evidently his World War I rank. All Feynman remembered from the course was the length of a meter in inches, 39.37, and a futile argument with the teacher over whether rays of light from a single source come out radially, as seemed logical to Richard, or in parallel, as in the conventional textbook diagrams of lens behavior. Even in grade school he had no doubt that he was right about such things. It was just obvious, physically—not the sort of argument that could be settled by an appeal to authority. At home, meanwhile, he boiled water by running 110-volt house current through it and watched the lines of blue and yellow sparks that flow when the current breaks. His father sometimes described the beauty of the flow of energy through the everyday world, from sunlight to plants to muscles to the mechanical work stored in the spring of a windup toy. Assigned at school to write verse, Richard applied this idea to a fancifully bucolic scene with a farmer plowing his field to make food, grass, and hay:

... Energy plays an important part
And it’s used in all this work;
Energy, yes, energy with power so great,
A kind that cannot shirk.

If the farmer had not this energy,
He would be at a loss,

But it’s sad to think, this energy
Belongs to a little brown horse.

Then he wrote another poem, brooding self-consciously about his own obsession with science and with the idea of science. Amid some borrowed apocalyptic imagery he expressed a feeling that science meant skepticism about God—at least about the standardized God to whom he had been exposed at school. Over the Feynmans’ rational and humanistic household God had never held much sway. “Science is making us wonder,” he began—then on second thought he scratched out the word *wonder*.

Science is making us ~~wonder~~ wander,
Wander, far and wide;
And know, by this time,
Our face we ought to hide.

Some day, the mountain shall wither,
While the valleys get flooded with fire;
Or men shall be driven like horses,
And stamper, like beasts, in the mire.

And we say, “The earth was thrown from the sun,”
Or, “Evolution made us come to be
And we come from lowest of beasts,
Or one step back, the ape and monkey.”

Our minds are thinking of science,
And science is in our ears;
Our eyes are seeing science,
And science is in our fears.

Yes, we're wandering from the Lord our God,
Away from the Holy One;
But now we cannot help it,
For it is already done.

But poetry was (Richard thought) "sissy-like." This was no small problem. He suffered grievously from the standard curse of boy intellectuals, the fear of being thought, or of being, a sissy. He thought he was weak and physically awkward. In baseball he was inept. The sight of a ball rolling toward him across a street filled him with dread. Piano lessons dismayed him, too, not just because he played so poorly, but because he kept playing an exercise called "Dance of the Daisies." For a while this verged on obsession. Anxiety would strike when his mother sent him to the store for "peppermint patties."

As a natural corollary he was shy about girls. He worried about getting in fights with stronger boys. He tried to ingratiate himself with them by solving their school problems or showing how much he knew. He endured the canonical humiliations: for example, watching helplessly while some neighborhood children turned his first chemistry set into a brown, useless, sodden mass on the sidewalk in front of his house. He tried to be a good boy and then worried, as good boys do, about being too good—"goody-good." He could hardly retreat from intellect to athleticism, but he could hold off the taint of sissiness by staying with the more practical side of the mental world, or so he thought. The practical man—that was how he saw himself. At Far Rockaway High School he came upon a series of mathematics primers with that magical phrase in the title—*Arithmetic for the Practical Man*; *Algebra for the Practical Man*—and he devoured them. He did not want to let himself be too “delicate,” and poetry, literature, drawing, and music were too delicate. Carpentry and machining were activities for real men.

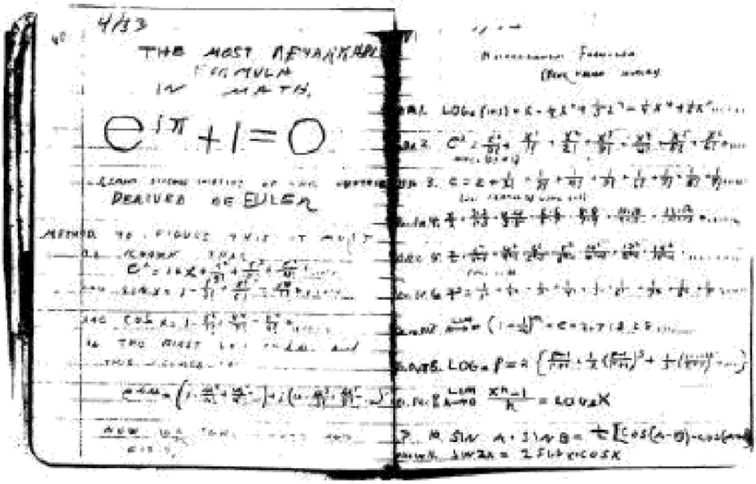
For students whose competitive instincts could not be satisfied on the baseball field, New York’s high schools had the Interscholastic Algebra League: in other words, math team. In physics club Feynman and his friends studied the wave motions of light and the odd vortex phenomenon of smoke rings, and they re-created the already classic experiment of the California physicist Robert Millikan, using suspended oil drops to measure the charge of a single electron. But nothing gave Ritty the thrill of math team. Squads of five students from each school met in a classroom, the two teams sitting in a line, and a teacher would present a series of problems. These were designed with special cleverness. By agreement they could require no calculus—nothing more than standard algebra—yet the routines of algebra as taught in class would never suffice within the specified time. There was always some trick, or shortcut, without which the problem would just take too long. Or else there was no built-in shortcut; a student had to invent one that the designer had not foreseen.

According to the fashion of educators, students were often taught that using the proper methods mattered more than getting the correct answer. Here only the answer mattered. Students could fill the scratch pads with gibberish as long as they reached a solution and drew a circle around it. The mind had to learn indirection and flexibility. Head-on attacks were second best. Feynman lived for these competitions. Other boys were president and vice president, but Ritty was team captain, and the team always won. The team’s number-two student, sitting directly behind Feynman, would calculate furiously with his pencil, often beating the clock, and meanwhile he had a sensation that Feynman, in his peripheral vision, was not writing—never wrote, until the answer came to him. You are rowing a boat upstream. The river flows at three miles per hour; your speed against the current is four and one-quarter. You lose your hat on the water. Forty-five minutes later you realize it is missing and execute the instantaneous, acceleration-free about-face that such puzzles depend on. How long does it take to row back to your floating hat?

A simpler problem than most. Given a few minutes, the algebra is routine. But a student whose head starts filling with 3s and $4^{1}/_{4}$s, adding them or subtracting them, has already lost. This is a problem about reference frames. The river's motion is irrelevant—as irrelevant as the earth's motion through the solar system or the solar system's motion through the galaxy. In fact all the velocities are just so much foliage. Ignore them, place your point of reference at the floating hat—think of yourself floating like the hat, the water motionless about you, the banks an irrelevant blur—now watch the boat, and you see at once, as Feynman did, that it will return in the same forty-five minutes it spent rowing away. For all the best competitors, the goal was a mental flash, achieved somewhere below consciousness. In these ideal instants one did not strain toward the answer so much as relax toward it. Often enough Feynman would get this unstudied insight while the problem was still being read out, and his opponents, before they could begin to compute, would see him ostentatiously write a single number and draw a circle around it. Then he would let out a loud sigh. In his senior year, when all the city's public and private schools competed in the annual championship at New York University, Feynman placed first.

For most people it was clear enough what mathematics was—a cool body of facts and rote algorithms, under the established headings of arithmetic, algebra, geometry, trigonometry, and calculus. A few, though, always managed to find an entry into a freer and more colorful world, later called “recreational” mathematics. It was a world where rowboats had to ferry foxes and rabbits across imaginary streams in nonlethal combinations; where certain tribespeople always lied and others always told the truth; where gold coins had to be sorted from false-gold in just three weighings on a balance scale; where painters had to squeeze twelve-foot ladders around inconveniently sized corners. Some problems never went away. When an eight-quart jug of wine needed to be divided evenly, the only measures available were five quarts and three. When a monkey climbed a rope, the end was always tied to a balancing weight on the other side of a pulley (a physics problem in disguise). Numbers were prime or square or perfect. Probability theory suffused games and paradoxes, where coins were flipped and cards dealt until the head spun. Infinities multiplied: the infinity of counting numbers turned out to be demonstrably smaller than the infinity of points on a line. A boy plumbed geometry exactly as Euclid had, with compass and straightedge, making triangles and pentagons, inscribing polyhedra in circles, folding paper into the five Platonic solids. In Feynman’s case, the boy dreamed of glory. He and his friend Leonard Mautner thought they had found a solution to the problem of trisecting an angle with the Euclidean tools—a classic impossibility. Actually they had misunderstood the problem: they could trisect one side of an equilateral triangle, producing three equal segments, and they mistakenly assumed that the lines joining those segments to the far corner mark off equal angles. Riding around the neighborhood on their bicycles, Ritty and Len excitedly imagined the newspaper headlines: “Two Children in High School First Learning Geometry Solve the Age-Old Problem of the Trisection of the Angle.”

This cornucopian world was a place for play, not work. Yet unlike its stolid high-school counterpart it actually connected here and there to real, adult mathematics. Illusory though the feeling was at first, Feynman had the sense of conducting research, solving unsolved problems, actively exploring a live frontier instead of passively receiving the wisdom of a dead era. In school every problem had an answer. In recreational mathematics one could quickly understand and investigate problems that were open. Mathematical game playing also brought a release from authority. Recognizing some illogic in the customary notation for trigonometric functions, Feynman invented a new notation of his own:  for sin  for cos (x),  for tan (x). He was free, but he was also extremely methodical. He memorized tables of logarithms and practiced mentally deriving values in between. He began to fill notebooks with formulas, continued fractions whose sums produced the constants π and *e.*



4/13

THE MOST REMARKABLE FORMULA IN MATH,

$e^{i\pi}+1=0$

DERIVED BY EULER

A page from Feynman's teenage notebok

A month before he turned fifteen he covered a page with an elated inch-high scrawl:

The Most Remarkable
Formula
In Math.
$ei\pi + 1 = 0$
(From Science History Of The Universe)

By the end of this year he had mastered trigonometry and calculus, both differential and integral. His teachers could see where he was heading. After three days of Mr. Augsbury's geometry class, Mr. Augsbury abdicated, putting his feet up on his desk and asking Richard to take charge. In algebra Richard had now taught himself conic sections and complex numbers, domains where the business of equation solving acquired a geometrical tinge, the solver having to associate symbols with curves in the plane or in space. He made sure the knowledge was practical. His notebooks contained not just the principles of these subjects but also extensive tables of trigonometric functions and integrals—not copied but calculated, often by original techniques that he devised for the purpose. For his calculus notebook he borrowed a title from the primers he had studied so avidly, *Calculus for the Practical Man*. When his classmates handed out yearbook sobriquets, Feynman was not in contention for the genuinely desirable Most Likely to Succeed and Most Intellectual. The consensus was Mad Genius.

All Things Are Made of Atoms

The first quantum idea—the notion that indivisible building blocks lay at the core of things—occurred to someone at least twenty-five hundred years ago, and with it physics began its slow birth, for otherwise not much can be understood about earth or water, fire or air. The idea must have seemed dubious at first. Nothing in the blunt appearance of dirt, marble, leaves, water, flesh, or bone suggests that it is so. But a few Greek philosophers in the fifth century B.C. found themselves hard pressed to produce any other satisfactory possibilities. Things change—crumble, fade, wither, or grow—yet they remain the same. The notion of immutability seemed to require some fundamental immutable parts. Their motion and recombination might give the appearance of change. On reflection, it seemed worthwhile to regard the basic constituents of matter as unchanging and indivisible: *atomos*—uncuttable. Whether they were also uniform was disputed. Plato thought of atoms as rigid blocks of pure geometry: cubes, octahedrons, tetrahedrons, and icosahedrons for the four pure elements, earth, air, fire, and water. Others imagined little hooks holding the atoms together (of what, though, could these hooks be made?).

Experiment was not the Greek way, but some observations supported the notion of atoms. Water evaporated; vapor condensed. Animals sent forth invisible messengers, their scents on the wind. A jar packed with ashes could still accept water; the volumes did not sum properly, suggesting interstices within matter. The mechanics were troubling and remained so. How did these grains move? How did they bind? "Cloudy, cloudy is the stuff of stones," wrote the poet Richard Wilbur, and even in the atomic era it was hard to see how the physicist's swarming clouds of particles could give rise to the hard-edged world of everyday sight and touch.

Someone who trusts science to explain the everyday must continually make connections between textbook knowledge and real knowledge, the knowledge we receive and the knowledge we truly own. We are told when we are young that the earth is round, that it circles the sun, that it spins on a tilted axis. We may accept the knowledge on faith, the frail teaching of a modern secular religion. Or we may solder these strands to a frame of understanding from which it may not so easily be disengaged. We watch the sun's arc fall in the sky as winter approaches. We guess the time from the shadow of a lamppost. We walk across a merry-go-round and strain against the sideways Coriolis force, and we try to connect the sensation to our received knowledge of the habits of earthly cyclones: northern hemisphere, low pressure, counterclockwise. We time the vanishing point of a tall-masted ship below the horizon. The sun, the winds, the waves all join in preventing our return to a flat-earth world, where we could watch the tides follow the moon without understanding.

All things are made of atoms—how much harder it is to reconcile this received fact with the daily experience of solid tables and chairs. Glancing at the smooth depressions worn in the stone steps of an office building, we seldom recognize the cumulative loss of invisibly small particles struck off by ten million footfalls. Nor do we connect the geometrical facets of a jewel to a mental picture of atoms stacked like cannonballs, favoring a particular crystalline orientation and so forcing regular angles visible to the naked eye. If we do think about the atoms in us and around us, the persistence of solid stone remains a mystery. Richard Feynman asked a high-school teacher (and never heard a satisfactory reply), "How do sharp things stay sharp all this time if the atoms are always jiggling?"

The adult Feynman asked: If all scientific knowledge were lost in a cataclysm, what single statement would preserve the most information for the next generations of creatures? How could we best pass on our understanding of the world? He proposed, "*All things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*," and he added, "In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied." Although millennia had passed since natural philosophers broached the atomic idea, Feynman's lifetime saw the first generations of scientists who truly and universally believed in it, not just as a mental convenience but as a hard physical reality. As late as 1922 Bohr, delivering his Nobel Prize address, felt compelled to remind his listeners that scientists "believe the existence of atoms to be proved beyond a doubt." Richard nevertheless read and reread in the Feynmans' *Encyclopaedia Britannica* that "pure chemistry, even to-day, has no very conclusive arguments for the settlement of this controversy." Stronger evidence was at hand from the newer science, physics: the phenomenon called radioactivity seemed to involve the actual disintegration of matter, so discretely as to produce audible pings or visible blips. Not until the eighties could people say that they had finally seen atoms. Even then the seeing was indirect, but it stirred the imagination to see shadowy globules arrayed in electron-microscope photographs or to see glowing points of orange light in the laser crossfire of "atom traps."

Not solids but gases began to persuade seventeenth- and eighteenth-century scientists of matter's fundamental granularity.

In the heady aftermath of Newton's revolution scientists made measurements, found constant quantities, and forged mathematical relationships that a philosophy without numbers had left hidden. Investigators made and unmade water, ammonia, carbonic acid, potash, and dozens of other compounds. When they carefully weighed the ingredients and end products, they discovered regularities. Volumes of hydrogen and oxygen vanished in a neat two-to-one ratio in the making of water. Robert Boyle found in England that, although one could vary both the pressure and the volume of air trapped at a given temperature in a piston, one could not vary their product. Pressure multiplied by volume was a constant. These measures were joined by an invisible rod—why? Heating a gas increased its volume or its pressure. Why?

Heat had seemed to flow from one place to another as an invisible fluid—"phlogiston" or "caloric." But a succession of natural philosophers hit on a less intuitive idea—that heat was motion. It was a brave thought, because no one could see the things in motion. A scientist had to imagine uncountable corpuscles banging invisibly this way and that in the soft pressure of wind against his face. The arithmetic bore out the guess. In Switzerland Daniel Bernoulli derived Boyle's law by supposing that pressure was precisely the force of repeated impacts of spherical corpuscles, and in the same way, assuming that heat was an intensification of the motion hither and thither, he derived a link between temperature and density. The corpuscularians advanced again when Antoine-Laurent Lavoisier, again with painstaking care, demonstrated that one could keep reliable account books of the molecules entering and exiting any chemical reaction, even when gases joined with solids, as in rusting iron.

"Matter is unchangeable, and consists of points that are perfectly simple, indivisible, of no extent"—that the atom could itself contain a crowded and measurable universe remained for a later century to guess—"& separated from one another." Ruggiero Boscovich, an eighteenth-century mathematician and director of optics for the French navy, developed a view of atoms with a strikingly prescient bearing, a view that Feynman's single-sentence credo echoed two centuries later. Boscovich's atoms stood not so much for substance as for forces. There was so much to explain: how matter compresses elastically or inelastically, like rubber or wax; how objects bounce or recoil; how solids hold together while liquids congeal or release vapors; "effervescences & fermentations of many different kinds, in which the particles go & return with as many different velocities, & now approach towards & now recede from one another."

The quest to understand the corpuscles translated itself into a need to understand the invisible attractions and repulsions that gave matter its visible qualities. *Attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*, Feynman would say simply. That mental picture was already available to a bright high-school student in 1933. Two centuries had brought more and more precise inquiry into the chemical behavior of substances. The elements had proliferated. Even a high-school laboratory could run an electric current through a beaker of water to separate it into its explosive constituents, hydrogen and oxygen. Chemistry as packaged in educational chemistry sets seemed to have reduced itself to a mechanical collection of rules and recipes. But the fundamental questions remained for those curious enough to ask, How do solids stay solid, with atoms always "jiggling"? What forces control the fluid motions of air and water, and what agitation of atoms engenders fire?

A Century of Progress

By then the search for forces had produced a decade of reinterpretation of the nature of the atom. The science known as chemical physics was giving way rapidly to the sciences that would soon be known as nuclear and high-energy physics. Those studying the chemical properties of different substances were trying to assimilate the first startling findings of quantum mechanics. The American Physical Society met that summer in Chicago. The chemist Linus Pauling spoke on the implications of quantum mechanics for complex organic molecules, primitive components of life. John C. Slater, a physicist from the Massachusetts Institute of Technology, struggled to make a connection between the quantum mechanical view of electrons and the energies that chemists could measure. And then the meeting spilled onto the fairgrounds of the spectacular 1933 Chicago World's Fair, "A Century of Progress." Niels Bohr himself spoke on the unsettling problem of measuring anything in the new physics. Before a crowd of visitors both sitting and standing, his ethereal Danish tones often smothered by crying babies and a balking microphone, he offered a principle that he called "complementarity," a recognition of an inescapable duality at the heart of things. He claimed revolutionary import for this notion. Not just atomic particles, but all reality, he said, fell under its sway. "We have been forced to recognize that we must modify not only all our concepts of classical physics but even the ideas we use in everyday life," he said. He had lately been meeting with Professor Einstein (their discussions were actually more discordant than Bohr now let on), and they had found no way out. “We have to renounce a description of phenomena based on the concept of cause and effect.”

Elsewhere amid the throngs at the fairground that summer, enduring the stifling heat, were Melville, Lucille, Richard, and Joan Feynman. For the occasion Joan had been taught to eat bacon with a knife and fork; then the Feynmans strapped suitcases to the back of a car and headed off crosscountry, a seemingly endless drive on the local roads of the era before interstate highways. On the way they stayed at farmhouses. The fair spread across four hundred acres on the shore of Lake Michigan, and the emblems of science were everywhere. Progress indeed: the fair celebrated a public sense of science that was reaching a crest. *Knowledge Is Power*—that earnest motto adorned a book of Richard’s called *The Boy Scientist*. Science was invention and betterment; it changed the way people lived. The eponymous business enterprises of Edison, Bell, and Ford were knotting the countryside with networks of wire and pavement—an altogether positive good, it seemed. How wonderful were these manifestations of the photon and the electron, lighting lights and bearing voices across hundreds of miles!

Even in the trough of the Depression the wonder of science fueled an optimistic faith in the future. Just over the horizon were fast airships, half-mile-high skyscrapers, and technological cures for diseases of the human body and the body politic. Who knew where the bright young students of today would be able to carry the world? One New York writer painted a picture of his city fifty years in the future: New York in 1982 would hold a magnificent fifty million people, he predicted, the East River and much of the Hudson River having been “filled in.” “Traffic arrangements will no doubt have provided for several tiers of elevated roadways and physicists gathering in Chicago, but, like most other American newspaper readers, they knew Einstein's name well. That summer he was traveling in Europe, uprooted, having left Germany for good, preparing to arrive in New York Harbor in October. For fourteen years America had been in the throes of a publicity craze over this "mathematician." The *New York Times*, the Feynmans' regular paper, had led a wave of exaltation with only one precedent, the near deification of Edison a generation earlier. No theoretical scientist, European or American, before or since, ignited such a fever of adulation. A part of the legend, the truest part, was the revolutionary import of relativity for the way citizens of the twentieth century should conceive their universe. Another part was Einstein's supposed claim that only twelve people worldwide could understand his work. "Lights All Askew in the Heavens," the *Times* reported in a 1919 classic of headline writing. "Einstein Theory Triumphs. Stars Not Where They Seem or Were Calculated to Be, but Nobody Need Worry. A Book for 12 Wise Men. No More in the World Could Comprehend It, Said Einstein." A series of editorials followed. One was titled "Assaulting the Absolute." Another declared jovially, "Apprehensions for the safety of confidence even in the multiplication table will arise."

The presumed obscurity of relativity contributed heavily to its popularity. Yet had Einstein's message really been incomprehensible it could hardly have spread so well. More than one hundred books arrived to explain the mystery. The newspapers mixed tones of reverence and self-deprecating amusement about the mystery of relativity's paradoxes; in actuality, they and their readers correctly understood the elements of this new physics. Space is curved—curved where gravity warps its invisible fabric. The ether is banished, along with the assumption of an absolute frame of reference for space and time. Light has a fixed velocity, measured at 186,000 miles per second, and its path bends in the sway of gravity. Not long after the general theory of relativity was transmitted by underwater cable to eager New York newspapers, schoolchildren who could barely compute the hypotenuse of a right triangle could nevertheless recite a formula of Einstein's, E equals MC squared, and some could even report its implication: that matter and energy are theoretically interchangeable; that within the atom lay unreleased a new source of power. They sensed, too, that the universe had shrunk. It was no longer merely *everything*—an unimaginable totality. Now it might be bounded, thanks to four-dimensional curvature, and somehow it began to seem artificial. As the English physicist J. J. Thomson said unhappily, "We have Einstein's space, de Sitter's space, expanding universes, contracting universes, vibrating universes, mysterious universes. In fact the pure mathematician may create universes just by writing down an equation ... he can have a universe of his own."

There will never be another Einstein—just as there will never be another Edison, another Heifetz, another Babe Ruth, figures towering so far above their contemporaries that they stood out as legends, heroes, half-gods in the culture's imagination. There will be, and almost certainly have already been, scientists, inventors, violinists, and baseball players with the same raw genius. But the world has grown too large for such singular heroes. When there are a dozen Babe Ruths, there are none. In the early twentieth century, millions of Americans could name exactly one contemporary scientist. In the late twentieth century, anyone who can name a scientist at all can name a half-dozen or more.

Einstein's publicists, too, belonged to a more naïve era; icons are harder to build in a time of demythologizing, deconstruction, and pathography. Those celebrating Einstein had the will and the ability to remake the popular conception of scientific genius. It seemed that Edison's formula favoring perspiration over inspiration did not apply to this inspired, abstracted thinker. Einstein's genius seemed nearly divine in its creative power: he imagined a certain universe and this universe was born. Genius seemed to imply a detachment from the mundane, and it seemed to entail wisdom. Like sports heroes in the era before television, he was seen exclusively from a distance. Not much of the real person interfered with the myth. By now, too, he had changed from the earnest, ascetic-looking young clerk whose genius had reached its productive peak in the first and second decades of the century. The public had hardly seen that man at all. Now Einstein's image drew on a colorful and absentminded appearance—wild hair, ill-fitting clothes, the legendary socklessness. The mythologizing of Einstein occasionally extended to others. When Paul A. M. Dirac, the British quantum theorist, visited the University of Wisconsin in 1929, the *Wisconsin State Journal* published a mocking piece about "a fellow they have up at the U. this spring ... who is pushing Sir Isaac Newton, Einstein and all the others off the front page." An American scientist, the reporter said, would be busy and active, "but Dirac is different. He seems to have all the time there is in the world and his heaviest work is looking out the window." Dirac's end of the dialogue was suitably monosyllabic. (The *Journal*'s readers must have assumed he was an ancient eminence; actually he was just twenty-seven years old.)

> "Now doctor will you give me in a few words the

low-down on all your investigations?"

"No."

"Good. Will it be all right if I put it this way—'Professor Dirac solves all the problems of mathematical physics, but is unable to find a better way of figuring out Babe Ruth's batting average'?"

"Yes."

...

"Do you go to the movies?"

"Yes."

"When?"

"In 1920—perhaps also 1930."

The genius was otherworldly and remote. More than the practical Americans whose science meant gizmos and machines, Europeans such as Einstein and Dirac also incarnated the culture's standard oddball view of the scientist. "Is he the tall, backward boy ... ?" Barbara Stanwyck's character asked in *The Lady Eve* about Henry Fonda's, an ophiologist roughly Feynman's age.

—He isn't backward, he's a scientist.
—Oh, is that what it is. I knew he was *peculiar*.

"Peculiar" meant harmless. It meant that brilliant men paid for their gifts with compensating, humanizing flaws. There was an element of self-defense in the popular view. And there was a little truth. Many scientists did walk through the ordinary world seeming out of place, their minds elsewhere. They sometimes failed to master the arts of dressing carefully or making social conversation.

Had the *Journal*'s reporter solicited Dirac's opinion of the state of American science, he might have provoked a longer comment.

INDEX