CORNELL

For physics as an enterprise within American culture there were two eras. One ended and the other began in the summer of the atomic bombs. Politicians, educators, newspaper editors, priests, and the scientists themselves began to understand the divide that had been crossed.

"Among the divinities of ancient Greece, there was a Titan named Prometheus," ran a typical essay in *The Christian Century* the next winter. "He stole fire from heaven and gave it to man… . For this act, Prometheus has been held in highest honor as a benefactor of humanity and the divine patron of science and learning." No more. Now, rather to the cleric essayist's delight, the atomic bomb had humbled Prometheus's heirs, the scientists. Their centuries of progress had decisively ended with their invention of a device of human self-destruction. Now it was time for Christian ministers to step in. Even the scientists, he said, "have for the first time in history turned aside from their vocation and become statesmen and evangelists, preaching the grim gospel of damnation unless men repent." Here he was alluding to J. Robert Oppenheimer, for Oppenheimer had already seen the aptness of the Promethean legend—who could have missed it?—and had begun to speak out both to the public and to scientists. What Oppenheimer preached, however, was more subtle than a gospel of damnation. He reminded listeners that the religious had long felt threatened by science, and now the only mildly God-fearing public had something real to fear. He suspected that atomic weapons would scare people more than any scientific development since Darwin's theory of evolution.

Already, in November 1945, with relieved soldiers and sailors streaming home from the Pacific Theater, before fallout shelters, nuclear proliferation, and ban the bomb had a chance to enter the language, Oppenheimer anticipated the time when celebration would give way to dread. "Atomic weapons are a peril which affect everyone in the world," he told his friends and colleagues of the past thirty months. His audience filled the largest assembly hall in Los Alamos, its movie theater. He knew that the newspapers and magazines glorifying the scientists' achievement would soon recognize how little real mystery there had been, how unremarkable, actually, were the problems of nuclear fission (if not implosion), how easy atomic bombs would be to make, and how affordable for many nations.

Prometheus was not the only mythic figure standing in for the scientist; the other was Faust. Lately the Faustian bargain for knowledge and power had not seemed so horrible as it had in medieval times. Knowledge meant washing machines and medicines, and the devil had softened into an amusing character for Saturday cartoons and Broadway musicals. But now the fires in two Japanese cities renewed a primal understanding that the devil was not so tame. It might mean something, after all, to sell him one's soul. Oppenheimer knew, partly from introspection, that the scientists had immediately begun to question their own motives. "It's a terrible thing that we made," Robert Wilson had said to Feynman, surprising him and pricking his ebullient bubble. Others were beginning to agree. Oppenheimer reminded them of what they were reminding themselves: that two years earlier a Nazi bomb had seemed possible and that the American victory had seemed far from inevitable. He acknowledged that these justifications had faded. Some people, he said, might have been driven by a less high-minded motivation, no more than curiosity and a sense of adventure, and he surprised some of them by saying, "and rightly so." He said it again: "And rightly so." Feynman had left Los Alamos several days before, so he did not hear, nor did he need to hear, Oppy's reminder of their shared credo, a credo now being welded to the most painful act of self-justification they had ever had to perform:

> When you come right down to it the reason that we did this job is because it was an organic necessity. If you are a scientist you cannot stop such a thing. If you are a scientist you believe that it is good to find out how the world works; that it is good to find out what the realities are; that it is good to turn over to mankind at large the greatest possible power to control the world… . It is not possible to be a scientist unless you believe that the knowledge of the world, and the power which this gives, is a thing which is of intrinsic value to humanity, and that you are using it to help in the spread of knowledge, and are willing to take the consequences.

Thus spoke a bringer of fire.

The relations between Americans and their scientists had changed. It became an instant truism that science meant power. Science as an institution—"organized science"—ranked second only to the military as a guarantor of what was being called national security. President Harry S Truman told the Congress that fall that America's role in the world would depend directly on research coordinated by universities, industrial companies, and the government: "The events of the past few years are both proof and prophecy of what science can do." In short order the government established an Atomic Energy Commission, an Office of Naval Research, and a National Science Foundation. Permanent national laboratories with no precedent in the prewar world arose at Los Alamos; at Oak Ridge; at Argonne, south of Chicago; at Berkeley; and at Brookhaven, Long Island, on a six-thousand-acre former army site. Money flowed copiously. Before the war the government had paid for only a sixth of all scientific research. By the war's end the proportions had flipped: only a sixth was financed by all nongovernment sources combined. The government and the public gained a new sense of proprietorship over the whole scientific enterprise. As physicists began to speak out about world government and the international control of nuclear arms, so an army of clerics, foundation heads, and congressmen now made the mission and the morality of science a part of their lecture-circuit repertoire.

On the whole, the popular press lionized Oppenheimer and his colleagues. To have worked on the bomb gave a scientist a stature matched only by the Nobel Prize. By comparison it was nothing to have created radar at the MIT Radiation Laboratory, though by a plausible calculus radar had done more to win the war. The word *physicist* itself finally came into vogue. Einstein was now understood to be a physicist, not a mathematician. Even nonnuclear physicists acquired prestige by association. Soon Wilson, Feynman's recruiter, would look back wistfully to "the quiet times when physics was a pleasant, intellectual subject, not unlike the study of Medieval French in its popular interest." The atomic scientists felt the guilt that flowed from the sudden deaths of at least one hundred thousand residents of Hiroshima and Nagasaki; meanwhile the scientists found themselves hailed as hero wizards, and this was a more complex role than many of them realized at first, containing as it did the seeds of darker relationships. In less than a decade Oppenheimer himself would lose his security clearance in the classic McCarthy-era auto-da-fé. The public would find that knowledge created by scientists was a commodity requiring special handling. It could be stamped CLASSIFIED or betrayed to foreign enemies. Knowledge was the grist of secrets and the currency of spies.

Theoretical physicists, too, had learned something about their kind of knowledge. Oppenheimer reminded them of it, in his November 1945 talk at Los Alamos. The nature of the work in theoretical physics before the war had forced a certain recognition on them, he said—the recognition that human language has limits, that people choose concepts that correspond only faintly to things in the real world, like the shadows of ghosts. Before the bomb work began, quantum mechanics had already altered the relations between science and common sense. We make models of experience, and we know that our models fail to meet the reality.

The University at Peace

Their remarkable change in status buffeted every American institution that made a home for physicists. At Cornell, President Edmund Ezra Day was one of the first to feel the force of the transition, in the stark contrast between two budget meetings with his physicists, one during and one after the war.

In the first, he sat down with his chief experimentalist, Robert F. Bacher, who was setting off on his leave of absence; ultimately Bacher led the bomb project's experimental physics division. Bacher pleaded for a cyclotron like those at Berkeley and Princeton. He pressed Day to find a way of providing operating costs that he said might amount to as much as a professor's salary, from four thousand to five thousand dollars a year.

In the second, two months after Hiroshima, Day's physicists told him that a far more powerful accelerator would be required, along with a new laboratory to house it. This time they asked for a capital expenditure of $3,000,000 and an operating budget that would begin at $250,000. They suggested, furthermore, that without this commitment they would have to look elsewhere for a more propitious environment for nuclear science. The trustees had no obvious source of funds, but after a heated meeting with Day they voted unanimously to proceed. Day declared: “The problem is not to control nuclear forces but to control nuclear physicists. They are in tremendous demand, and at a frightful premium.” Bacher himself, after returning to Cornell briefly, left for Washington to serve as the first scientist on the newly formed Atomic Energy Commission. Three years later Cornell had a new accelerator, a synchrotron. The trustees’ leap of faith had been vindicated by generous funding from the Office of Naval Research. Three years after that, the synchrotron had passed into obsolescence and a new version was already under construction.

Feynman’s first glimpse of the postwar university came in the dead of night before the start of classes in the fall of 1945. Ithaca was a village at the dimmest reaches of a New York City boy’s sense of his state’s geography, practically in Ohio. He made the journey by train, using the long hours to begin sketching out a basic graduate course he was supposed to teach in mathematical methods for physicists. He debarked with a single suitcase and a self-conscious sense of being, finally, a professor. He suppressed the urge to sling his bag over his shoulder as usual. Instead he let a porter guide him to the rear seat of a taxicab. He told the driver to take him to the biggest hotel in town.

In Ithaca, as in towns and cities across America that fall, the hotels and short-term apartments were booked. Housing was scarce. With demobilization college enrollments were exploding. Boom was in the air. Even sleepy Ithaca seemed like a Western town amid the gold rush. Cornell was building houses and barracks at emergency speed. The week before Feynman arrived, five new barracks burned down. He tried a second hotel. Then he realized he could not afford to wander by taxicab, so he checked his suitcase and began to walk, past darkened houses and dormitories. He realized he must have found Cornell. Huge raked piles of leaves dotted the campus, and they started to look like beds—if only he could find one out of the glare of the streetlights. Finally he spotted an open building with couches in the lobby and asked the janitor if he could spend the night on one. He explained awkwardly that he was a new professor.

The next morning he washed as well as he could in the public bathroom, checked in at the physics department, and made his way to a campus housing office in Willard Straight Hall, near the center of the sloping campus. There a clerk told him haughtily that the housing situation was so bad that last night a professor had had to sleep in the lobby. "Look, buddy," Feynman snapped back, "I'm that professor. Now do something for me." He was unpleasantly startled to realize that in a town Ithaca's size he could set off a rumor and circle back into its wake within a matter of hours. He also began to realize that he was going to have to readjust his internal clock. The war had left him with a sense of urgency about appointments and deadlines. Even as ten thousand undergraduates arrived, Cornell seemed slack. He was surprised to discover that the administration had scheduled a full week with nothing for him to do but explore the campus and prepare for classes. Speech patterns struck him as slow, with none of the *beep-beep-beep* nervousness he had got used to. People took time to talk about the weather.

His first months were lonely. None of his close colleagues had been in such a hurry to begin postwar life. Even Bethe did not leave Los Alamos for Cornell until December. The school year began late and stayed unsettled. Space ran short. Workers subdivided rooms in Rockefeller Hall. Closets became offices. Outside, three tennis courts gave way to hasty wooden barracks. Feynman soon shared his dingy Rockefeller office with a colleague from Los Alamos, Philip Morrison, who had carried the atomic bomb's plutonium core to Alamogordo in the back seat of an army sedan. Morrison had been lured by the sweet, serious Bethe, so full of integrity—and also by Feynman, though it now seemed, surprisingly, that Feynman was depressed and lonely. Bethe sensed this, too, but few others noticed. Later Bethe noted dryly, "Feynman depressed is just a little more cheerful than any other person when he is exuberant."

He spent time in the library reading the mildly bawdy *Arabian Nights* and staring hopefully at women. Unlike most of the Ivy League universities, Cornell had accepted women as undergraduates since its founding, after the Civil War, though they automatically matriculated in the College of Home Economics. He went to freshman dances and ate in the student cafeteria. He looked younger than his twenty-seven years, and he did not stand out amid all the returning servicemen. His dance partners looked askance at what sounded like a line—that he was a physicist just back from building the atomic bomb. He missed Arline. Even before leaving Los

Alamos he had begun dating other women—especially beautiful women, in what some of his friends saw as a frenetic, razor-edge denial of grief.

A gulf had opened between Feynman and his mother. Lucille, after so adamantly opposing Richard's marriage, had written painfully on Arline's death:

> … now I want you to know that I'm proud and glad you married her & did what you could to make her short life happy. She worshipped you. Forgive me for not seeing things your way. I was frightened for you—for what you would have to bear. But you bore it so well. Now try to face life without her …

Begging him to come home, she promised him piles of rice and sugar buns and gave her word that no one would tell him to comb his hair. He did come, briefly, for a few days in July. Then, in August, the news of the atomic bomb broke over the household like a lightning storm. Friends and relatives called almost continuously. Lucille tried in vain to get through to Santa Fe by telephone. One cousin called from a wire-service office to read a comment of Oppenheimer's that had just come across the ticker. After 11 P.M. the phone rang and a voice said, "This is the Princeton *Triangle*. Is it true that your son R. P. Feynman had more gravy stains on his gown that any other man at the Graduate College in 1940?" It was another cousin.

"I have a sense of humor, too," Lucille wrote to Richard, "but I don't think this is a funny occasion."

> I felt thrilled & frightened at your part in this tremendous thing. No one can be really joyous. It is with horror that I listen to the death & destruction the bomb has caused… . I pray that this horrible destruction of man by man may be the climax of all such destruction… . No wonder I thought you were nervous. Who wouldn't be, playing around in such a dangerous place.

The combination of pride and terror—the scientists, too, were feeling it that night—stirred a remarkable memory. "It reminded me of the time I was playing bridge in the living room & my child prodigy had a little fire in a trash basket he was holding outside the window.

"By the way," she added, "I don't think you ever told me how you put it out."

Feynman did not stop at home on his way to Ithaca from New Mexico that fall. At some point Lucille began to realize how much damage had been done by her opposition to the marriage. Late one night, unable to sleep, she got out of bed and penned an anguished letter—a love letter from mother to son—beginning, "Richard, What has happened between you and your family? What has driven us apart? My heart yearns for you… . My heart is full to bursting & hot tears burn my eyes as I write."

She wrote about his childhood: how much he had been wanted and treasured; how she had read him beautiful stories; how Melville had made patterns for him from colored tiles; how they had tried to invest him with a sense of morality and duty. She reminded him of the pride they had felt in all his achievements, from high school through graduate school.

> More times than I can enumerate here my heart has leaped for joy because of you… . And now—now—strange harvest that I reap. We are as far apart as the poles.

Without mentioning Arline, she said she felt a sense of shame. "The fault must be mine. Some where along the way I lost you." Other mothers, she said, had sons who loved them. Why not her? She closed with as impassioned a plea as any spurned lover could make.

> I need *you*. I want you. I will *never* give you up. Not even death can break the bond between us… . Think of me sometimes & let me know that you are thinking of me. My darling, oh my darling, what more can I say to you. I adore you & *always* will.

He did go home for Christmas in 1945. Gradually the wound began to heal. In the meantime Feynman made some indirect efforts to find his way back into the unfinished theory that had occupied him at Princeton, but they did not lead to anything usable. The culmination of the driven, purposeful work of the past three years had left a void that he could not easily fill. He found it hard to concentrate on research. As spring came he would sit on the grass outdoors and worry about whether he had slipped past his best working years without achieving anything. He had built a reputation among senior physicists, but now, back in a world returning to normal, he realized that he had not done the normal work to go with the reputation. Since his two published papers in college—his squib on cosmic rays with Vallarta and his undergraduate thesis—his only journal publications had been accounts of the work with Wheeler on the absorber theory, already looking short-lived.

Phenomena Complex—Laws Simple

If Feynman was struggling to find his footing, Julian Schwinger was not. Since growing up at opposite ends of New York City, in neighborhoods that might as well have been a thousand miles apart, they had become competitors without either quite acknowledging it. Their routes into physics had remained utterly separate, as had their styles. Schwinger, with heavy owlish eyes and a mild stoop even in his twenties, took as great pains to achieve elegance as Feynman did to remain rough-hewn. He dressed carefully and expensively and drove a Cadillac. He worked nocturnally, usually sleeping until late afternoon.His lectures had already become famous for their seamlessness and uninterruptibility. He prided himself on speaking without notes. A young Englishman who heard him (and who considered Feynman's ebullience slightly tiring, by contrast) thought Schwinger became "a man possessed"—"It seems to be the spirit of Macaulay which takes over, for he speaks in splendid periods, the carefully architected sentences rolling on, with every subordinate clause duly closing." He liked to make his listeners think. He would never announce directly that he had married and taken a honeymoon, when he could say, "I abandoned my bachelor quarters and embarked on an accompanied, nostalgic trip around the country… ." His equations had something of the same style.

His patron had been I. I. Rabi, who never tired of describing their first encounter: Schwinger, a seventeen-year-old waiting quietly in his office, had finally piped up to settle an argument over a controversial foray into quantum-mechanical paradox just published by Einstein, Boris Podolsky, and Nathan Rosen. With the arrogance of a shy young man determined to plow his own course, Schwinger was already in administrative difficulties at City College because he rarely attended classes. Rabi helped him transfer to Columbia and then took devilish pleasure in encouraging his irate instructors to carry out their threats to flunk him. "Are you a mouse or a man? Give him an F," he told one dull chemistry professor; he judged correctly that the grade would come to haunt the professor more than it would the student. Even before Schwinger got his college diploma at the age of nineteen, Rabi was having him fill in as the lecturer in his quantum-mechanics course. Also before graduating, he completed the research that served as his doctoral dissertation. Fermi, Teller, and Bethe each knew him, knew his work, or had collaborated with him. Meanwhile Feynman, barely three months younger, was completing his sophomore year at MIT. Schwinger published a fecund series of research papers, mostly in the *Physical Review*, each highly polished, with a dozen different collaborators. By the time Feynman published his undergraduate thesis, Schwinger was in Berkeley as a National Research Council fellow, working directly with Oppenheimer.

With Rabi, he chose to avoid Los Alamos in favor of radar and the Radiation Laboratory. He never seemed to lose a stride. By the war's end Rabi had him replace Pauli as a special lecturer in charge of bringing the laboratory's scientists up to date with nonwar physics. For the atomic bomb scientists, isolated as they were behind their desert fence, the war brought a more total interruption of normal careers. Physicists Feynman's age were especially aware of it. They had just reached what should have been their crucial, productive years. Schwinger made one tour through Los Alamos in 1945 and met Feynman briefly for the first time. Feynman marveled at how much this contemporary had managed to publish. He had thought Schwinger was older. When he had long since forgotten the content of Schwinger's lecture to the Los Alamos theorists, he still remembered the style: the way Schwinger walked into the room, his head tilted, like a bull into the ring; the way he conspicuously set his notebook aside; the intimidating perfection of his discourse.

Now Schwinger was at Harvard, where he was shortly to become a twenty-nine-year-old full professor. The Harvard committee had seriously considered only Bethe for the same opening and worried meanwhile whether Schwinger would be able to wake up to teach classes that met as early as noon. He managed, and his lectures on nuclear physics quickly became a draw for the entire Harvard and MIT physics community.

Feynman, meanwhile, poured energy into his more mundane course in the methods of mathematical physics. This was a standard course, taught in every physics department, though it occurred to Feynman that he had just lived through a momentous change in physicists' mathematical methods. At Los Alamos mathematical methods had been put through a crucible: refined, clarified, rewritten, reinvented. Feynman thought he knew what was useful and what was mere textbook knowledge taught because it had always been taught. He intended to emphasize nonlinearity more than was customary and to teach students the patchwork of gimmicks and tricks that he used himself to solve equations. Beginning with his jottings on the night train that brought him to Ithaca, he designed a new course from the bottom up.

On the first page of a cardboard notebook like the ones he had used in high school he began with first principles:

> Phenomena complex—laws simple— connection is math-phys—the solution of equ obtained from laws.

He was thinking about how to mold students in his own image. How did *he* solve problems?

> Know what to leave out… . physical insight knowing what can be done by math.

He decided to give the students a blunt summary of what did and did not lie ahead.

> Lots of tricks to introduce—no time for complete study or math rigor demonstration. Lots of work.

He crossed that out.

> Really introduce each subject.

But after all it *would* be lots of work.

Lots of work—practice. Interested in more detail, read books, see me, practice more examples. If no go—OK we slow up. Hand in some problems so I can tell.

He would promise them important mathematical methods left out of ordinary courses, as well as methods that were altogether new. It would be practical, not perfect, mathematics.

Specify accuracy required. Let's go

He scanted some of the laborious traditional techniques, such as contour integration, because he had so often found—winning bets in the process—that he could handle most such integrals directly by frontal assault. Whether he would succeed in conveying such skills to his students was a question that worried some of his colleagues as they watched Feynman plow apart the mathematical-methods syllabus. Nevertheless, during the few years that he taught the course, it drew some of the younger members of the physics and mathematics faculty along with the captive graduate students. The coolest among them had to feel the jolt of an examination problem that began, "In an atom bomb in the form of a cylinder radius *a*, height 2π, the density of neutrons *n* …" The students found themselves in the grip of a theorist whose obsession with mathematical methods concerned the uneasy first principles of quantum mechanics. Again and again he showed his affinity with the purest core issues of the propagation of sound and light. He drove his students through calculations of the total intensity of radiation in all directions when emitted by a periodic source; through the reluctant visualization of vectors, matrices, and tensors; through the summations of infinite series that sometimes converged and sometimes failed to converge, running inconveniently off toward infinity.

Gradually he settled in at Cornell, though he still made no progress on his theoretical research. The atomic bomb was on his mind, and he went on the local radio to speak about it in unadorned language. *Announcer: Last week Dr. Feynman told you what one atom bomb did to Hiroshima, and what one bomb would do to Ithaca …* The interviewer asked about atomic-powered automobiles. Many listeners, he said, were awaiting the day when they could slip a spoonful of uranium into the tank and thumb their noses at the filling stations. Feynman said he doubted the practicality of that—"the rays emitted by the fission of the uranium in the engine would kill the driver." Still, he had spent time working out other applications of nuclear power. At Los Alamos he had invented a type of fast reactor for generating electric power and had patented it (in the government's behalf). He was also thinking about space travel. "Dear Sir," he wrote to a physicist colleague as 1945 came to a close, "I believe that interplanetary travel is now (with the release of atomic energy) a definite *possibility*." He had a radically quirky, almost flaky, proposal. Rocket propulsion would not be the answer, he said. It was fundamentally limited by the temperature and atomic weight of the propulsive gas, the temperature in turn being limited by the ability of metal to withstand heat. He predicted—anticipating the ungainly disposable boosters and giant fuel tanks that became the curse of space travel thirty years in the future—that the weight and bulk of fuel would exceed by too many times the weight and bulk of the vehicle.

Instead he proposed a form of jet propulsion, using air as the propellant. Jet technology had just now reached practicality in airplanes. Feynman's spacecraft would use the outer edges of the earth's atmosphere as a sort of warm-up track and accelerate as it circled the earth. An atomic reactor would power the jet by heating the air that was sucked into the engine. Wings would be used first to provide lift and then, when the speed rose beyond five miles per second, "flying upside down to keep you from going off the earth, or rather out of the atmosphere." When the craft reached a useful escape velocity, it would fly off at a tangent toward its destination like a rock from a slingshot.

Yes, air resistance, heating the ship, would be a problem. But Feynman thought this could be overcome by delicately adjusting the altitude as the craft sped up—"if there is enough air to cause appreciable heating by friction there surely is enough to feed the jet engines." The engines would need impressive engineering to operate in such a wide range of air densities, he admitted. He did not address a problem of symmetry: how such a spacecraft would slow down on reaching an airless destination such as the moon. In any event he could not have anticipated the killing flaw in his idea: that people would lose faith in the innocence of nuclear reactors flying about overhead.

They All Seem Ashes

He visited Far Rockaway just before the fall semester began in 1946 and gave another talk on the atomic bomb at the local Temple Israel the day after Yom Kippur. The synagogue had a glamorous new rabbi, Judah Cahn, who delivered widely admired sermons on modern problems. Feynman's parents, despite their atheism, had started attending from time to time. Melville's health seemed slightly better. His uncontrollable high blood pressure had become a constant source of worry to the family, and in the preceding spring he had traveled out to the Mayo Clinic, in Minnesota, where he was enrolled in an early experiment on the effect of diet. He accepted a strict regimen of rice and fruit. It seemed to work. His blood pressure decreased. He returned home and occasionally sneaked out, in violation of doctors' orders, to play golf with friends. He was fifty-six years old. One day Feynman saw him at the table, staring at a salt shaker. Melville closed one eye, opened it, closed the other eye, and said he had a blind spot. A small blood vessel must have burst in his brain, he said.

The knowledge that sudden death might come at any time hung over the family. Melville and his son almost never wrote each other—Lucille handled the intrafamily correspondence—but when Richard first accepted the Cornell professorship he sent his father a letter expressing twenty-five years of love and gratitude, and Melville, moved, responded in kind. His chest was swelled with pride, he wrote (while Lucille complained that he was wasting paper by writing on only one side):

> It is not so easy for a Dope of a father to write to a son who has already arrived to a state of learning and wisdom beyond his… . That was all right when you were small and I had a great advantage over you—but today it would be more equitable if I could bask in the sunlight of *your* knowledge, and sit by your side and learn from you some of the more wondrous secrets of nature that now are beyond my ken but are known to you.

On October 7 he collapsed from a stroke. He died the next day. Richard signed his second death certificate in two years. Melville Feynman had written him: "The dreams I have often had in my youth for *my* own development, I see coming true in your career… . I envy the life of culture you will have being constantly with so many other big men of equal culture."

The interment took place at Bayside Cemetery nearby in Queens, a vast rolling field of gravestones and monuments as far as the eye could see. Lucille's father had built a mausoleum there, a stone hut like a small bomb shelter. Midway through the ceremony Rabbi Cahn asked Richard, as eldest son, to say the Kaddish with him. Joan watched in anguish as her brother's face froze. He wanted no part of a mourners' prayer in praise of God.

He told the rabbi he did not understand the Hebrew. Cahn merely switched to English. Richard listened to the words and refused to repeat them. He did not believe in God; he knew that his father had not believed in God; and the hypocrisy seemed unbearable. His disbelief had nothing of indifference in it. It was a determined, coolly rational disbelief, a conviction that the myths of religion cheated knowledge. He stood there surrounded by stone and grass near the undersized sepulchral vaults, assembled one atop another, that held the bones of his grandparents. One shelf, too, held the remains of his infant brother, Henry, memorialized now for twenty-two years after his life of one month. On Feynman's face was a look of tension and determination and also, it seemed to Joan at that moment, utter isolation. Leaving his father's coffin, he exploded in a rage. Their mother broke down and wept.

At Cornell the next week he seemed unchanged. Just as at Los Alamos—it had been barely a year before—if he grieved, he showed no one. He was proudly rational as ever—"realistic," he told himself. Classes began. Cornell's 1946 fall-term enrollment was its largest ever, nearly double prewar levels. Feynman was already a draw for young physicists, and he lectured with absolute confidence. Then, a few nights into the term—it was October 17—he took a pen and paper, let realism slip away, and wrote one last letter to the only person who could help him now:

> D'Arline,
>
> I adore you, sweetheart.
>
> I know how much you like to hear that—but I don't only write it because you like it—I write it because it makes me warm all over inside to write it to you.

It is such a terribly long time since I last wrote to you—almost two years but I know you'll excuse me because you understand how I am, stubborn and realistic; & I thought there was no sense to writing.

But now I know my darling wife that it is right to do what I have delayed in doing, and that I have done so much in the past. I want to tell you I love you. I want to love you. I always will love you.

I find it hard to understand in my mind what it means to love you after you are dead—but I still want to comfort and take care of you—and I want you to love me and care for me. I want to have problems to discuss with you—I want to do little projects with you. I never thought until just now that we can do that together. What should we do. We started to learn to make clothes together—or learn Chinese—or getting a movie projector. Can't I do something now. No. I am alone without you and you were the "idea-woman" and general instigator of all our wild adventures.

When you were sick you worried because you could not give me something that you wanted to & thought I needed. You needn't have worried. Just as I told you then there was no real need because I loved you in so many ways so much. And now it is clearly even more true—you can give me nothing now yet I love you so that you stand in my way of loving anyone else—but I want you to stand there. You, dead, are so much better than anyone else alive.

I know you will assure me that I am foolish & that you want me to have full happiness & don't want to be in my way. I'll bet you are suprised that I don't even have a girl friend (except you, sweetheart) after two years. But you can't help it, darling, nor can I—I don't understand it, for I have met many girls & very nice ones and I don't want to remain alone—but in two or three meetings they all seem ashes. You only are left to me. You are real.

My darling wife, I do adore you.

I love my wife. My wife is dead.

Rich.

PS. Please excuse my not mailing this—but I don't know your new address.

That he had written such a letter to the woman he loved, two years after her death, could never become part of the iconography of Feynman, the collection of stories and images that was already beginning to follow him about. The letter went into an envelope, the envelope into a box. It was not read again until after his death. Nor did Feynman speak of his graveside outburst at the burial of his father, even to friends, although they would have recognized at least one of its potential morals, his unwillingness to submit to hypocrisy. The Feynman who could be wracked by strong emotion, the man stung by shyness, insecurity, anger, worry, or grief—no one got close enough any more to see him. His friends heard a certain kind of story instead, in which Feynman was an inadvertent boy hero, mastering a bureaucracy or a person or a situation by virtue of his naïveté, his good humor, his brashness, his commonsense cleverness (not brilliance), and his emperor's-new-clothes honesty. The stories were true, at least in spirit, though like all stories they were selectively incomplete. They were admired, polished, retold, and once in a while even relived.

Many of his friends at Los Alamos had already heard variations of a draft-examination story, in which he needled an army examiner who asked him to hold out his hands. Feynman held them out: one palm up, the other palm down. The examiner asked him to turn them over, and he did, providing a wise-guy lesson in symmetry: one palm down, the other palm up. Shortly after his first year at Cornell, Feynman got a chance to refine the story. The army was still drafting, and his educational deferments had run their course. The Selective Service scheduled a new physical examination. Feynman's version of the story, told countless times in the decades that followed, varied from the half serious to the strictly comic. The basic form went like this:

Stripped to his underwear, he goes from booth to booth, until—"Finally, we get to Booth No. 13, Psychiatrist."

Witch doctor. Baloney. Faker. Feynman held an extreme view of psychiatry. His mind was his bailiwick, and he liked to think himself in control. Sensitive psychiatrists might have noted his tendency to deny the occasional roiling undercurrents; the undercurrents and the denial were their bailiwick. He preferred to stress the unscientific hocus-pocus of their enterprise (conveniently shifting terminology, lack of reproducible experiments), as reflected in a movie he had seen recently, Alfred Hitchcock's *Spellbound*, in which "a woman" (Ingrid Bergman), "her hand is stuck and she can't play the piano … she used to be a great pianist… ." Certainly he never considered whether he (himself at that moment unable to work) might have had any but the most rational of reasons for feeling: "It's boring as hell… ." The woman ducks off-screen with her psychiatrist, comes back, sits down at the piano, and plays. "Well, this kind of baloney, you know, I can't stand it. I'm very anti. Okay?" Apart from everything else, psychiatrists are doctors, and Feynman has his reasons for holding doctors in contempt.

The psychiatrist looks at his file and says with a smile, *Hello, Dick! Where do you work?* ("Well, what the hell is he calling me *Dick* for? You know, he don't know me that well.")

Feynman says coldly, Schenectady. (This is temporarily true. He and Bethe are supplementing their Cornell salaries by working that summer at General Electric.)

Where at Schenectady, Dick?

Feynman tells him.

You like your work, Dick? "I couldn't like him less, you know? Like a guy bothering you in a bar."

Now a fourth question—*Do you think people talk about you?*—and Feynman detects that this is the routine: three innocent questions and then down to business.

"So I say, Yeah …" At this point Feynman, relating the story, takes on a tone of misunderstood innocence. He is scrupulously honest. If only the psychiatrist would forget the formulas, forget the mumbo jumbo, and try to understand him. "I wasn't trying to fake it… . I meant in the sense that my mother talks to her friends… . I tried to explain—honest… ." The psychiatrist makes a note.

Do you think people stare at you? Feynman would say no—honest—but the psychiatrist adds, *For example, do you think that any of the fellows sitting on the benches are looking at us now.* Well, Feynman has sat on one of those benches, and there was not much else to look at. He does some mental arithmetic. "So I figure … there are about twelve guys in the thing and about three of them are looking—well, that's all they've got to do—so I say, to be conservative, 'Yeah, maybe two of them are looking at us.'"

He turns around to check, and sure enough. But the psychiatrist, "this nincompoop, this nincompoop … doesn't bother to turn around and find out if it's true or not." (No scientist he.)

Do you talk to yourself? "I admitted that I do… ." ("Incidentally, I didn't tell him something which I can tell you, which is I find myself sometimes talking to myself in quite an elaborate fashion … : 'The integral will be larger than this sum of the terms, so that would make the pressure higher, you see?' 'No, you're crazy.' 'No, I'm not! No, I'm not!' I say. I argue with myself… I have two voices that work back and forth.")

I see you lost a wife recently. Do you talk to her? (The resentment that this question must stir goes beyond the comic bounds of the anecdote.)

Do you hear voices in your head? "No," Feynman says. "Very rarely." He admits a few occasions. Sometimes, in fact, just as he was falling asleep, he would hear Edward Teller, with a distinctive Hungarian accent, in Chicago giving him his first briefing on the atomic bomb.

There was much more: an argument about the nature of insanity, an argument about the value of life—Feynman in both cases continuing to get under the examiner's skin. Feynman acknowledged that one of his mother's sisters was mentally ill. And then the punch line, more serious than Feynman's audiences tended to realize.

Well, Dick, I see you have a Ph.D. Where did you study?

MIT and Princeton. Where did *you* study?

Yale and London. And what did you study, Dick?

Physics. And what did you study?

Medicine.

And *this* is medicine?

The story never included several plausible points. Feynman never pleaded that, having contributed three years of wartime service in the Manhattan Project, he ought to be exempt from a further contribution. Nor did he mention how destructive it would have been to his career as a theoretical physicist if he had been conscripted now, at the age of twenty-eight. He had to walk a narrow line. There was nothing amusing or stylish in the summer of 1946 about evading the draft. For most people, to be declared mentally deficient by one's draft board was a more frightening possibility than army service—far more damaging to one's civilian prospects. So the Selective Service established few safeguards against fakery in the psychiatric examination. It did not expect to see records of a previous history of mental illness, for example; in any case private psychiatric treatment was far more unusual than it became in the next generation. Examiners felt they could rely on a subject's naïve self-description to answer their checklist questions. Feynman repeated his answers to a second psychiatrist. His ability to conjure the voice of Teller was recorded as *hypnagogic hallucinations*. It was noted that the subject had a *peculiar stare*. ("I think it was probably when I said, 'And *this* is medicine?'") He was rejected.

It occurred to him that the Selective Service would examine its own files and discover a series of official letters requesting deferment so that Feynman could conduct essential research in physics during the war. More recent letters stated that he was performing an important service educating future physicists at Cornell. Might someone conclude that he was deliberately trying to deceive the examiners? To protect himself, he wrote a letter, carefully phrased, stating for the record that he believed no weight should be given to the finding of psychiatric deficiency. The Selective Service replied with a new draft card: 4-F.

Around a Mental Block

Princeton was celebrating the bicentennial of its founding with a grand explosion of pomp that fall: parties, processions, and a series of formal conferences that drew scholars and dignitaries from long distances. Dirac had agreed to speak on elementary particles as part of a three-day session on the future of nuclear science. Feynman was invited to introduce his one-time hero and lead a discussion afterward.

He disliked Dirac's paper, a restatement of the now-familiar difficulties with quantum electrodynamics. It struck him as backward-looking in its Hamiltonian energy-centered emphasis—a dead end. He made so many nervous jokes that Niels Bohr, who was due to speak later in the day, stood up and criticized him for his lack of seriousness. Feynman made a heartfelt remark about the unsettled state of the theory. "We need an intuitive leap at the mathematical formalism, such as we had in the Dirac electron theory," he said. "We need a stroke of genius."

As the day wore on—Robert Wilson speaking about the high-energy scattering of protons, E. O. Lawrence lecturing on his California accelerators—Feynman looked out the window and saw Dirac lolling on a patch of grass and gazing at the sky. He had a question that he had wanted to ask Dirac since before the war. He wandered out and sat down. A remark in a 1933 paper of Dirac's had given Feynman a crucial clue toward his discovery of a quantum-mechanical version of the *action* in classical mechanics. "It is now easy to see what the quantum analogue of all this must be," Dirac had written, but neither he nor anyone else had pursued this clue until Feynman discovered that the "analogue" was, in fact, exactly proportional. There was a rigorous and potentially useful mathematical bond. Now he asked Dirac whether the great man had known all along that the two quantities were proportional.

"Are they?" Dirac said. Feynman said yes, they were. After a silence he walked away.

Feynman's reputation was traveling around the university circuit. Job offers floated his way. They seemed perversely inappropriate and did nothing to help his mood of frustration. Oppenheimer had invited him to California for the spring semester; now he turned the invitation down. Cornell promoted him to associate professor and raised his salary again. The chairman of the University of Pennsylvania's physics department needed a new chief theorist. Here Bethe stepped in paternalistically: he had no intention of letting go of Feynman, and he was sensitive to his protégé's mood. He thought it would be harmful for this suddenly unproductive twenty-eight-year-old to take on the psychological responsibility of a lead role in a university theory group. More than anything, he thought Feynman needed shelter. (He told the Pennsylvania administrator that Feynman was the second-best young physicist around: second to Schwinger.) For Feynman the most surprising—and oppressive—offer came from the Institute for Advanced Study, Einstein's institute in Princeton, in the spring. Oppenheimer had now been named as the institute's director, and he wanted Feynman. H. D. Smyth, Feynman's old chairman at Princeton, wanted him, too, and the two institutions had sounded him out about a special joint appointment. His anxiety about failing to live up to such expectations was reaching a peak. He experimented with various tactics to break his mental block. For a while he got up every morning at 8:30 and tried to work. Looking in the mirror one morning as he shaved, he told himself the Princeton offer was absurd—he could not possibly accept, and furthermore he could not accept the responsibility for their impression of him. He had never claimed to be an Einstein, he told himself. It was their mistake. For a moment he felt lighter. Some of his guilt seemed to lift away.

His old friend Wilson had just arrived to direct the nuclear laboratory. Along with Bethe, he caught Feynman's mood and invited him in for a talk. Don't worry so much, he told Feynman. We are responsible. We hire professors; we take the risks; as long as they teach their classes satisfactorily they fulfill their part of the bargain. It made Feynman think wistfully about the days before *the future of science* had begun to seem like his mission—the days before physicists changed the universe and became the most potent political force within American science, before institutions with fast-expanding budgets began chasing nuclear physicists like Hollywood stars. He remembered when physics had been a game, when he could look at the graceful narrowing curve in three dimensions that water makes as it streams from a tap, and he could take the time to understand why.

A few days later he was eating in the student cafeteria when someone tossed a dinner plate into the air—a Cornell cafeteria plate with the university seal imprinted on one rim—and in the instant of its flight he experienced what he long afterward considered an epiphany. As the plate spun, it wobbled. Because of the insignia he could see that the spin and the wobble were not quite in synchrony. Yet just in that instant it seemed to him—or was it his physicist's intuition?—that the two rotations were related. He had told himself he was going to *play*, so he tried to work the problem out on paper. It was surprisingly complicated, but he used a Lagrangian, least-action approach and found a two-to-one ratio in the relationship of wobble and spin. That was satisfyingly neat. Still, he wanted to understand the Newtonian forces directly, just as he had when he was a sophomore taking his first theory course and he provocatively refused to use the Lagrangian approach. He showed Bethe what he had discovered.

But what's the importance of that? Bethe asked.

It doesn't have any importance, he said. I don't *care* whether a thing has importance. Isn't it fun?

It's fun, Bethe agreed. Feynman told him that was all he was going to do from now on—have fun.

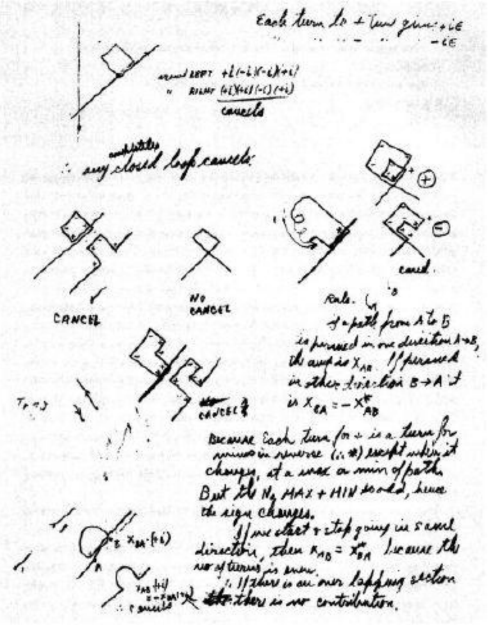
Sustaining that mood took deliberate effort, for in truth he had given up none of his ambition. If he was floundering, so were far more distinguished theoretical physicists, committed to resolving the flaws in quantum mechanics. He had not forgotten his painful disagreement with Dirac that fall—his conviction that Dirac had turned squarely back toward the past and that an alternative approach must surely be possible. Early in 1947 Feynman let his friend Welton know how grand his plans had become. (Welton was now working at the permanent plant at Oak Ridge; many years later he would finish his career there, still affected by the peculiar disappointment that hobbled so many others who had crossed Feynman's path at the wrong time.) Feynman said nothing about having fun. "I am engaged now in a general program of study—I want to understand (not just in a mathematical way) the ideas of all branches of theor. physics," he wrote. "As you know I am now struggling with the Dirac Equ." Despite what he told Bethe, he did make a connection between the axial wobble of a cafeteria plate and the abstract quantum-mechanical notion of spin that Dirac had so successfully incorporated in his electron.

Many years later Feynman and Dirac met one more time. They exchanged a few awkward words—a conversation so remarkable that a physicist within earshot immediately jotted down the Pinteresque dialogue he thought he heard drifting his way:

> I am Feynman.
>
> I am Dirac. (Silence.) It must be wonderful to be the discoverer of that equation.
>
> That was a long time ago. (Pause.) What are you working on? Mesons.
>
> Are you trying to discover an equation for them? It is very hard.
>
> One must try.

More than anyone else, Dirac had made the mere discovery of an equation into a thing to be admired. To aficionados the Dirac equation never did quite lose its rabbit-out-of-a-hat quality. It was relativistic—it survived without strain the manipulations required to accommodate near-light velocities. And it made spin a natural property of the electron. Understanding spin meant understanding the deceptive unreality of some of physics' new language. Spin was not yet as whimsical and abstract as some of the particle properties that followed it, properties called *color* and *flavor* in a half-witty, half-despairing acknowledgment of their unreality. It was still possible, barely, to understand spin literally: to view the electron as a little moon. But if the electron was also an infinitesimal point, it could hardly rotate in the classical fashion. And if the electron was also a smear of probabilities and a wave reverberating in a constraining chamber, how could these objects be said to *spin*? What sort of spin could come only in unit amounts or half-unit amounts (as quantum-mechanical spin did)? Physicists learned to think of spin not so much as a kind of rotation, but as a kind of symmetry, a way of stating mathematically that a system could undergo a certain rotation.

Spin was a problem for Feynman's theory as he had left it in his Princeton thesis. The quantity of action in ordinary mechanics contained no such property. And his theory would be useless if he could not apply it to a spinning, relativistic electron—the Dirac electron. Among the obstacles blocking his path, this was one of the heaviest. No wonder his eye might have been drawn to things that spun—a cafeteria plate, for example, wobbling in a split-second trajectory. His next step was peculiar and characteristic. He reduced the problem to a skeleton, a universe with just one dimension (or two: one space and one time). This universe was merely a line, and in it a particle could take just one kind of path, back and forth, reversing direction like a crazed insect. Feynman's goal was to begin with the method he had invented at Princeton—the summing of all possible paths a particle could take—and see whether he could derive, in this one-dimensional world, a one-dimensional Dirac equation. He jotted:



Feynman considered the path a particle would take in a one-dimensional universethat is, a particle restricted to moving back and forth on a line , always at the speed of light. He diagrammed the back-and-forth motion by visualizing the space dimension horizontally and the time dimension vertically: the passage of time is represented as motion upward on the page. In this toy model, he found that he could derive a central equation of quantum mechanics by adding the contributions made by all the possible paths a particle could take.

Geometry of Dirac Equ. 1 dimension
Prob = squ. of sum of contrib. each path
Paths zig zag at light velocity.

And he added something new—a diagram, purely schematic, for keeping track of the zigs and zags. The horizontal dimension represented his one spatial dimension, and the vertical dimension represented time. He successfully negotiated the details of this one-dimensional shadow theory. The spin of his particles implied a phase, like the phase of a wave, and he made some assumptions, only partly arbitrary, about what would happen to the phase each time a particle zagged. Phase was crucial to the mathematics of summing the paths, because paths would either cancel or reinforce one another, depending on how their phases overlapped. Feynman did not attempt to publish this fragment of a theory, excited though he was by the progress. The challenge was to extend the theory to more dimensions—to let the space unfold—and this he could not do, though he spent long hours in the library, for once reading old mathematics.

Shrinking the Infinities

Feynman's frustration in these first postwar years mirrored a growing sense of impotence and defeat among established theoretical physicists. The feeling, at first private and then shared, remained invisible outside their small community. The contrast with the physicists' public glory could hardly have been greater.

The cause was abstruse. The single difficulty at the core of this anguish was a mathematical tendency of certain quantities to diverge as successive terms of an equation were computed—terms that should have been vanishing in importance. Physically it seemed that the closer one stood to an electron, the greater its charge and mass would appear. The result: the infinities with which Feynman had been struggling since Princeton. It meant that quantum mechanics produced good first approximations followed by a Sisyphean nightmare. The harder a physicist pushed, the less accurate his calculations became. Such quantities as the mass of the electron became—if the theory were taken to its limit—infinite. The horror of this was hard to comprehend, and no glimmer of it appeared in popular accounts of science at the time. Yet it was not merely a theoretical knot. A pragmatic physicist eventually had to face it. "Thinking I understand geometry," Feynman said later, "and wanting to fit the diagonal of a five foot square, I try to figure out how long it must be. Not being very expert I get infinity—useless… ."

> It is not philosophy we are after, but the behavior of real things. So in despair, I measure it directly—lo, it is near to seven feet—neither infinity nor zero. So, we have measured these things for which our theory gives such absurd answers… .

Experimental yardsticks for the electron were not so easy to come by, and it was a tribute to the original theory of Heisenberg, Schrödinger, and Dirac that first approximations matched any experimental results that the laboratories had produced so far. Better results were on the way, however.

Meanwhile, the scientists contemplating the state of theoretical physics descended into a distinct gloominess; in the aftermath of the bomb, their mood seemed postcoital.

"The last eighteen years"—the period, that is, since the quick birth of quantum mechanics—"have been the most sterile of the century," remarked I. I. Rabi to a colleague over lunch in that spring of 1947, though Rabi himself was thriving as head of a fruitful group at Columbia.

"Theoreticians were in disgrace"—so it seemed to one especially precocious student of physics, Murray Gell-Mann.

"The theory of elementary particles has reached an impasse," Victor Weisskopf wrote. Everyone had been struggling futilely, he said, especially since the war, and everyone had had enough of "knocking a sore head against the same old wall."

Merely a few dozen men in mathematical difficulty—or the generation's deepest crisis in theoretical physics. It was all the same. Weisskopf was preparing for an unusual gathering. A former president of the New York Academy of Sciences, Duncan MacInnes, had been nursing a conviction that modern-day conferences were growing too unwieldy. Hundreds of people would appear. Speakers were starting to cater to these diffuse audiences by delivering generalized and retrospective talks. As an experiment, MacInnes proposed an intimate meeting restricted to twenty or thirty invited guests, to take place in a relaxed, country-inn setting. With "Fundamental Problems of Quantum Mechanics" as a topic, he managed —though it took more than a year—to draw a select group in early June to an inn called the Ram's Head, just opening for the summer season on New York's Shelter Island, between the forks of eastern Long Island. Weisskopf was one of those charged with setting the agenda. Other participants were Oppenheimer, Bethe, Wheeler, Rabi, Teller, and several representatives of the younger generation, including Julian Schwinger and Richard Feynman.

So two dozen suit-jacketed physicists met on a Sunday afternoon on the East Side of New York and motored across Long Island in a rickety bus. Somewhere along the way a police escort picked them up, sirens wailing, and a banquet was arranged by a local chamber of commerce official who had been serving in the Pacific when, he felt, the atomic bomb saved his life. A ferry carried them across to Shelter Island, and to some of the physicists there was an air of unreality about it all. When they gathered for breakfast the next morning, they noticed the phrase "restricted clientele" on the menus and performed a quick head count: their group contained more Jews, they decided, than the inn's dining room had ever seen. One New York newspaper reporter had come along, and he telephoned his report to the *Herald Tribune*: "It is doubtful if there has ever been a conference quite like this one… . They roam through the corridors mumbling mathematical equations, eat their meals amid the fury of technical discussions… ." Island residents, he wrote,

> are reasonably confused about this sudden descent of science among them. The principal theory is that the scientists are busy making another type of atomic bomb, and nothing could be farther from the truth… .
>
> Quantum mechanics is the never-never land of science, a world in which matter and energy become confused and where all the verities of day-to-day life become meaningless… .

To those sensitive to small breezes, it was beginning to seem that two of the younger men in particular, Schwinger and Feynman, were engaged in a gestation of fresh ideas. Schwinger mostly kept his own counsel during these three days. Feynman tried his methods out on a few people; a young Dutch physicist, Abraham Pais, watched him derive results at lightning speed with the help of sketchy pictures that left Pais baffled. On the last morning, after some words by Oppenheimer, Feynman was asked to give the whole group an informal description of his work, and he did, happily. No one really understood, but he left the memory of—as one listener recorded in his diary—"a clear voice, great rush of words and illustrative gestures sometimes ebullient."

Above all, however, it was a conference dominated by news from experimenters, and particularly experimenters in the furnace Rabi was stoking at Columbia. The Columbia groups favored techniques that seemed homely and unspectacular in this era of the burgeoning particle accelerator, though their arsenal also included technologies fresh from the wartime Radiation Laboratory, magnetrons and microwaves. Willis Lamb had just shined a beam of microwaves onto a hot wisp of hydrogen blowing from an oven. He was trying to measure the precise energy levels of electrons in the hydrogen atom. He succeeded—the art of spectroscopy had never seen such precision—and he found a distinct gap between two energy levels that should have been identical. *Should have been*, that is, according to the clearest existing guide to hydrogen atoms and electrons, the theory of Dirac. That was in April. Lamb had gone to bed thinking about knobs and magnets and a bouncing spot of light from the galvanometer and the clear discrepancy between his experiment and Dirac's theory, and he had awakened the next day thinking (accurately, as it turned out): *Nobel Prize*. News of what would soon be called the Lamb shift had already reached most of the Shelter Island participants before Lamb made a detailed report the first day. The theorists present had often repeated the truism that progress in science comes when experiments contradict theory. Rarely had any of them seen such a clean example (more often it was theory that contradicted theory). To Schwinger, listening, the point was that the problem with quantum electrodynamics was neither infinite nor zero: it was a number, now standing before them, finite and small. The alumni of Los Alamos and the Radiation Laboratory knew that the task of theoretical physics was to justify such numbers. The rest of the conference fed off a nervous euphoria, as it seemed to Schwinger: "The facts were incredible—to be told that the sacred Dirac theory was breaking down all over the place.” As the meeting adjourned, Schwinger left with Oppenheimer by seaplane.

Quantum electrodynamics was a “debacle,” another physicist said. Harsh assessments of a theory accurate enough for all but this delicate experiment. But after all, the physicists had known that the theory was fatally pocked with infinities. The experiment gave them real numbers to calculate, numbers marking the exact not-quite-rightness of the world according to Dirac.

Dyson

That fall Freeman Dyson arrived at Cornell. Some of Cornell’s mathematicians knew the work of a Briton by that name. It was hardly a common name, and mathematics was certainly known for its prodigies, but surely, they thought, this small, hawk-nosed twenty-three-year-old joining the physics department could not be the same man. Other graduate students found him genial but inscrutable. He would sleep late, bring his *New York Times* to the office, read it until lunch time, and spend the afternoon with his feet up and perhaps his eyes closed. Just occasionally he would wander into Bethe’s office. What they did there, no one knew.

Indeed, Dyson was one of England’s two or three most brilliant mathematical prodigies. He was the son of two supremely cultured members of the middle class who were late to marry and entering middle age when he was born. His father, George, composed, conducted, and taught music at a boys’ college in the south. Eventually he became director of England’s Royal College of Music. His mother, Mildred, trained as a lawyer, though she did not practice, and passed on to Freeman her deep love of literature, beginning with Chaucer and the poets of ancient Greece and Rome. As a six-year-old he would sit with encyclopedia volumes spread open before him and make long, engrossing calculations on sheets of paper. He was intensely self-possessed even then. His older sister once interrupted him to ask where their nanny was and heard him reply, “I expect her to be in the absolute elsewhere.” He read a popular astronomy book, *The Splendour of the Heavens*, and the science fiction of Jules Verne, and when he was eight and nine wrote a science-fiction novel of his own, *Sir Phillip Roberts's Erolunar Collision*, with a maturely cadenced syntax and an adult sense of literary flow. His scientist hero has a knack for both arithmetic and spaceship design. Freeman, who did not favor short sentences, imagined a scientist comfortable with public acclaim, yet solitary in his work:

> "I, Sir Phillip Roberts, and my friend, Major Forbes," he began, "have just unravelled an important secret of nature; that Eros, that minor planet that is so well-known on account of its occasional proximity with the Earth, Eros, will approach within 3,000,000 miles of the Earth in 10 years 287 days hence, instead of the usual 13,000,000 miles every 37 years; and, therefore it may, by some great chance fall upon the Earth. Therefore I advise you to calculate the details of this happening!" …
>
> When the cheers were over, and everybody had gone home, it did not mean that the excitement was over; no, not at all; everybody was making the wildest calculations; some reasonable, some not; but Sir Phillip only wrote coolly in his study rather more than usual; nobody could tell what his thoughts were.

He read popular books about Einstein and relativity and, realizing that he needed to learn a more advanced mathematics than his school taught, sent away to scientific publishers for their catalogs. His mother finally felt that his interest in mathematics was turning into an obsession. He was fifteen and had just spent a Christmas vacation working methodically, from six each morning until ten each evening, through the seven hundred problems of H. T. H. Piaggio's *Differential Equations*. That same year, frustrated at learning that a classic book on number theory by I. M. Vinogradov existed only in Russian, he taught himself the language and wrote out a full translation in his careful hand. As Christmas vacation ended, his mother went for a walk with him and began a cautionary lecture with the words of the Latin playwright Terence: "I am human and I let nothing human be alien to me." She continued by telling him Goethe's version of the Faust story, parts one and two, rendering Faust's immersion in his books, his lust for knowledge and power, his sacrifice of the possibility of love, so powerfully that years later, when Dyson happened to see the film *Citizen Kane*, he realized that he was weeping with the recognition of his mother's Faust incarnate once again on the screen.

As the war began, Dyson entered Trinity College, Cambridge. At Cambridge he heard intimate lectures by England's greatest mathematicians, Hardy, Littlewood, and Besicovitch. In physics Dirac reigned. Dyson's war could hardly have been more different from Feynman's. The British war organization wasted his talents prodigiously, assigning him to the Royal Air Force bomber command in a Buckinghamshire forest, where he researched statistical studies that were doomed, when they countered the official wisdom, to be ignored. The futility of this work impressed him. He and others in the operational research section learned—contrary to the essential bomber command dogma—that the safety of bomber crews did not increase with experience; that escape hatches were too narrow for airmen to use in emergencies; that gun turrets slowed the aircraft and bloated the crew sizes without increasing the chances of surviving enemy fighters; and that the entire British strategic bombing campaign was a failure. Mathematics repeatedly belied anecdotal experience, particularly when the anecdotal experience was colored by a lore whose purpose was to keep young men flying.

Dyson saw the scattershot bomb patterns in postmission photographs, saw the Germans' ability to keep factories operating amid the rubble of civilian neighborhoods, worked through the firestorms of Hamburg in 1943 and Dresden in 1945, and felt himself descending into a moral hell. At Los Alamos a military bureaucracy worked more successfully than ever before or since with independent-minded scientists. The military bureaucracy of Dyson's experience embodied a routine of petty and not-so-petty dishonesty, and the scientists of the bomber command were unable to challenge it.

These were black days for the combination of science and machinery called technology. England, which had invented so much, had always been prone to misgivings. Machines disrupted traditional ways of living. In the workplace they seemed dehumanizing. At the turn of the century, amid the black soot clouds of the English industrial city, it was harder to romanticize the brutal new working conditions of the factory than the brutal old working conditions of the peasant farm. America, too, had its Luddites, but in the age of radio, telephone, and automobile few saw a malign influence in the progress that technology brought. For Americans the loathing of technology that would become a theme of late-twentieth-century life began with fears born amid the triumph of 1945. Among the books that had most influenced Dyson was a children's tale called *The Magic City*, written in 1910 by Edith Nesbit. Among its lessons was a bittersweet one about technology. Her hero—a boy named Philip—learns that in the magic city, when one asks for a machine, he must keep using it forever. Given a choice between a horse and a bicycle, Philip wisely chooses the horse, at a time when few in England or America were failing to trade their horses for bicycles, motorcars, or tractors. Dyson remembered *The Magic City* when he learned about the atomic bomb—remembered that new technology, once acquired, is always with us. But nothing is simple, and Dyson also took to heart a remark of D. H. Lawrence's about the welcome minimal purity of books, chairs, bottles, and an iron bedstead, all made by machines: "My wish for something to serve my purpose is perfectly fulfilled… . Wherefore I do honour to the machine and to its inventor." The news of Hiroshima came partly as a relief to Dyson. It released him from his own war. Yet he knew that the strategic bombing campaign had killed four times as many civilians as the atomic bombs. Years later, when Dyson had a young son, he woke the boy in the middle of the night because he—Freeman—had awakened from an unbearable nightmare. A plane had crashed to the ground in flames. People were nearby, and some ran into the fire to rescue the victims. Dyson, in his dream, could not move.

He sometimes struck people as shy or diffident, but his teachers in England had learned that he had enormous self-possession. As a high-school student he had worked on the problem of pure number theory known as partitions—a number's partitions being the ways it can be subdivided into sums of whole numbers: the partitions of 4 are 1 + 1 + 1 + 1, 1 + 1 + 2, 1 + 3, 2 + 2, and 4. The number of partitions rises fairly rapidly—14 has 135 partitions—and the question of just how rapidly has all the hallmarks of classic number theory. It is easy to state. A child can work out the first few cases. And from its contemplation arises a glorious world with the intricacy and beauty of origami. Dyson followed a path trod earlier by the Indian prodigy Srinivasa Ramanujan at the beginning of the century. By his sophomore year at Cambridge he arrived at a set of conjectures about partitions that he could not prove. Instead of setting them aside, he made a virtue of his failure. He published them as only his second paper. “Professor Littlewood,” he wrote of one of his famous professors, “when he makes use of an algebraic identity, always saves himself the trouble of proving it; he maintains that an identity, if true, can be verified in a few lines by anybody obtuse enough to feel the need of verification. My object … is to confute this assertion… .” Dyson promised to state a series of interesting identities that he could not prove. He would also, he boasted, “indulge in some even vaguer guesses concerning the existence of identities which I am not only unable to prove but unable to state… . Needless to say, I strongly recommend my readers to supply the missing proofs, or, even better, the missing identities.” Routine mathematical discourse was not for him.

One day an assistant of Dirac’s told Dyson, “I am leaving physics for mathematics; I find physics messy, unrigorous, elusive.” Dyson replied, “I am leaving mathematics for physics for exactly the same reasons.” He felt that mathematics was an interesting game but not so interesting as the real world. The United States seemed the only possible place to pursue physics now. He had never heard of Cornell, but he was advised that Bethe would be the best person in the world to work with, and Bethe was at Cornell.

He went with the attitude of an explorer to a strange land, eager to expose himself to the flora and fauna and the possibly dangerous inhabitants. He played his first game of poker. He experienced the American form of “picnic,” which surprisingly involved the frying of steak on an open-air grill. He ventured forth on automobile excursions. “We go through some wild country,” he wrote his parents shortly after his arrival—the wild country in this case being the stretch of exurban New York lying between Ithaca and Rochester. He traveled with a theoretician called Richard Feynman: “the first example I have met of that rare species, the native American scientist.”

> He has developed a private version of the quantum theory … ; in general he is always sizzling with new ideas, most of which are more spectacular than helpful, and hardly any of which get very far before some newer inspiration eclipses them… . when he bursts into the room with his latest brain-wave and proceeds to expound it with the

most lavish sound effects and waving about of the arms, life at least is not dull.

Although Dyson was nominally a mere graduate student, for his first assignment Bethe had handed him a live problem: a version of the Lamb shift, fresh from Shelter Island. Bethe himself had already made the first fast break in the theoretical problem posed by Lamb's experiment. On the train ride home, using a scrap of paper, he made a fast, intuitive calculation that soon made a dozen of his colleagues say, *if only I had …* He telephoned Feynman when the train reached Schenectady, and he made sure his preliminary draft was in the hands of Oppenheimer and the other Shelter Island alumni within a week. It was a blunt Los Alamos–style estimate, ignoring the effects of relativity and evading the infinities by arbitrarily cutting them off. Bethe's breakthrough was sure to be superseded by a more rigorous treatment of the kind Schwinger was known to have in the works. But it gave the right number, almost exactly, and it lent weight to the conviction that a proper quantum electrodynamics would account for the new, precise experiments.

The existing theory "explained" the existence of different energy levels in the atom. It gave physicists their only workable means of calculating them. The different energies arose from different combinations of crucial quantum numbers, the angular momentum of the electron orbiting the nucleus, and the angular momentum of the electron spinning around itself. A certain symmetry built into the equation made it natural for a pair of the resulting energy levels to coincide exactly. But they did not coincide in Willis Lamb's laboratory, so something must be missing and, as Bethe surmised, that something was the theorists' old bugbear, the self-interaction of the electron.

This extra energy or mass was created by the snake-swallowing-its-tail interplay of the electron with its own field. This quantity had been a tolerable nuisance when it was theoretically infinite and experimentally negligible. Now it was theoretically infinite and experimentally real. Bethe had in mind a suggestion that the Dutch physicist Hendrik Kramers had made at Shelter Island: that the "observed" mass of the electron, the mass the theorists tended to think of as a fundamental quantity, should be thought of as a combination of two other quantities, the self-energy and an “intrinsic” mass. These masses, intrinsic and observed, also known as “bare” and “dressed,” made an odd couple. The intrinsic mass could never be measured directly, and the observed mass could not be computed from first principles. Kramers proposed a method by which the theorists would pluck a number from experimental measurements and correct it, or “renormalize” it. This Bethe did, crudely but effectively. Meanwhile, as the mass went, so went the charge—this formerly irreducible quantity, too, had to be renormalized. Renormalization was a process of adjusting terms of the equation to turn infinite quantities into finite ones. It was almost like looking at a huge object through an adjustable lens, and turning a knob to bring it down to size, all the while watching the effect of the knob turning on other objects, one of which was the knob itself. It required great care.

From one perspective, renormalization amounted to subtracting infinities from infinities, with a silent prayer. Ordinarily such an operation could be meaningless: *infinity* (the number of integers, 0, 1, 2, 3, …) minus *infinity* (the number of even integers, 0, 2, 4, …) equals *infinity* (the remaining, odd integers, 1,3, 5, …), and all three of those infinities are the same, unlike, for example, the distinctly greater infinity representing the number of real numbers. The theorists implicitly hoped that when they wrote *infinity – infinity = zero* nature would miraculously make it so, for once. That their hope was granted said something important about the world. For a while it was not clear just what.

Bethe assigned Dyson a stripped-down, toy version of the Lamb shift, asking him to calculate the Lamb shift for an electron with no spin. It was a way for Dyson to find a quick way into a problem of the most timely importance and for Bethe to continue his own prodding. Dyson could see that the calculation Bethe had published was both a swindle and a piece of genius, a bad approximation that somehow coughed up the right answer. More and more, too, Dyson talked with Feynman, who gradually began to come into clearer focus for him. He watched this wild American dash from the dinner table at the Bethes’ to play with their five-year-old son, Henry. Feynman did have an extraordinary affinity for his friends’ children. He would entertain them with gibberish, or with juggling tricks, or with what sounded to Dyson like a one-man percussion band. He could enthrall them merely by borrowing someone’s eyeglasses and slowly putting them on, taking them off, and putting them on. Or he would engage them in conversation. He once asked Henry Bethe, “Did you know there are twice as many numbers as numbers?”

“No, there are not!” Henry said.

Feynman said he could prove it. “Name a number.”

“One million.”

Feynman said, “Two million.”

“Twenty-seven!”

Feynman said, “Fifty-four,” and kept on countering with the number that was twice Henry’s, until suddenly Henry saw the point. It was his first real encounter with infinity.

For a while, because Feynman did not seem to take his work seriously, neither did Dyson. Dyson wrote his parents that Feynman was “half genius and half buffoon” (a description he later regretted). Just a few days later Dyson heard an account from Weisskopf, visiting Cornell, of Schwinger’s progress at Harvard. He sensed a connection with the very different notions he was hearing from Feynman. He had begun to see a method beneath Feynman’s flash and wildness. The next time he wrote his parents, he said:

> Feynman is a man whose ideas are as difficult to make contact with as Bethe’s are easy; for this reason I have so far learnt much more from Bethe, but I think if I stayed here much longer I should begin to find that it was Feynman with whom I was working more.

A Half-Assedly Thought-Out Pictorial Semi-Vision Thing

By the physicists’ own lights their difficulties were mathematical: infinities, divergences, unruly formalisms. But another obstacle lay in the background, rarely surfacing in the standard published or unpublished rhetoric: the impossibility of visualization. How was one to perceive the atom, or the electron in the act of emitting light? What mental picture could guide the scientist? The first quantum paradoxes had so shattered physicists’ classical intuitions that by the 1940s they rarely discussed visualization. It seemed a psychological issue, not a scientific one.

The atom of Niels Bohr, a miniature solar system, had become an embarrassingly false image. In 1923, on the tenth anniversary of Bohr's conception, the German quantum physicist Max Born hailed it: "the thought that the laws of the macrocosmos in the small reflect the terrestrial world obviously exercises a great magic on mankind's mind"—but already he and his colleagues could see the picture fading into anachronism. It survived in the language of *angular momentum* and *spin*—as well as in the standard high-school physics and chemistry curriculums—but there was no longer anything plausible in the picture of electrons orbiting a nucleus. Instead there were waves with modes of resonance, particles that smeared out probabilistically, operators and matrices, malleable spaces with extra dimensions, and physicists who forswore the idea of visualization altogether. Bohr himself had set the tone. In accepting the Nobel Prize for his atomic model, he said it was time to give up the hope of explanations in terms of analogies with everyday experience. "We are therefore obliged to be modest in our demands and content ourselves with concepts which are formal in the sense that they do not provide a visual picture of the sort one is accustomed to require… ." This progress had not been altogether free of tension. "The more I reflect on the physical portion of Schrödinger's theory, the more disgusting I find it," was Heisenberg's 1926 comment to Pauli. "Just imagine the rotating electron whose charge is distributed over the entire space with axes in 4 or 5 dimensions. What Schrödinger writes on the visualizability of his theory … I consider trash." As much as physicists valued the conceptualizing skill they called intuition, as much as they spoke of a difference between physical understanding and formal understanding, they had nevertheless learned to mistrust any picture of subatomic reality that resembled everyday experience. No more baseballs, artillery shells, or planetoids for the quantum theorists; no more idle wheels or wavy waves. Feynman's father had asked him, in the story he told so many times: "I understand that when an atom makes a transition from one state to another, it emits a particle of light called a photon… . Is the photon in the atom ahead of time? … Well, where does it come from, then? How does it come out?" No one had a mental image for this, the radiation of light, the interaction of matter with the electromagnetic field: the defining event of quantum electrodynamics.

Where this image should have been, instead there was a void, as frothy and alive with possibility as the unquiet vacuum of the new physics. Unable to let their minds fix on even a provisional picture of quantum events, some physicists turned to a new kind of philosophizing, characterized by paradoxical thought experiments and arguments about *reality*, *consciousness*, *causality*, and *measurement*. Such arguments grew to form an indispensable part of the late twentieth century's intellectual atmosphere; they trailed the rest of physics as a cloud of smoke and flotsam trails a convoy. They were provocative and irresolvable. The paper of Einstein, Podolsky, and Rosen in 1935—the paper that provided the seventeen-year-old Schwinger with his first opportunity to impress Rabi—became an enduring example. It posed the case of two quantum systems—atoms, perhaps—linked by a particle interaction in their past but now separated by a great distance. The authors showed that the plain act of measuring one atom of this pair would affect what one could measure about the other atom, and the effect would be instantaneous—faster than light and thus retroactive, as it were. Einstein considered this a damning commentary on the laws of quantum mechanics. Bohr and younger theorists maintained a more sanguine attitude, noting that Einstein himself had already placed *past* and *distance* into the class of concepts about which one could no longer speak with comfortable, classical certainty. In the same vein was Schrödinger's famous cat: a poor hypothetical animal sitting in a box with a vial of poisonous gas attached to a detector, its fate thus linked to that same quantum-mechanical event, the emission of a photon from an atom. Schrödinger's point was that, while physicists now glibly calculated such events as probabilities—half yes and half no, perhaps—they still could not visualize a cat as anything but alive or dead.

Physicists made a nervous truce with their own inability to construct unambiguous mental models for events in the very small world. When they used such words as *wave* or *particle*—and they had to use both—there was a silent, disclaiming asterisk, as if to say: *not really*. As a consequence, they recognized that their profession's relationship to reality had changed. Gone was the luxury of supposing that a single reality existed, that the human mind had reasonably clear access to it, and that the scientist could explain it. It was clear now that the scientist's work product—a theory, a model—interpreted experience and construed experience in a way that was always provisional. Scientists relied on such models as intensely as someone crossing a darkened room relies on a conjured visual memory. Still, physicists now began to say explicitly that they were creating a language—as though they were more like literary critics than investigators. "It is wrong to think that the task of physics is to find out how nature is," said Bohr. "Physics concerns only what we can *say* about nature." This had always been true. Never before, though, had nature so pointedly rubbed physicists' noses in it.

Yet in the long run most physicists could not eschew visualization. They found that they needed imagery. A certain kind of pragmatic, working theorist valued a style of thinking based on a kind of seeing and feeling. That was what *physical intuition* meant. Feynman said to Dyson, and Dyson agreed, that Einstein's great work had sprung from physical intuition and that when Einstein stopped creating it was because "he stopped thinking in concrete physical images and became a manipulator of equations." Intuition was not just visual but also auditory and kinesthetic. Those who watched Feynman in moments of intense concentration came away with a strong, even disturbing sense of the physicality of the process, as though his brain did not stop with the gray matter but extended through every muscle in his body. A Cornell dormitory neighbor opened Feynman's door to find him rolling about on the floor beside his bed as he worked on a problem. When he was not rolling about, he was at least murmuring rhythmically or drumming with his fingertips. In part the process of scientific visualization is a process of putting oneself in nature: in an imagined beam of light, in a relativistic electron. As the historian of science Gerald Holton put it, "there is a mutual mapping of the mind … and of the laws of nature." For Feynman it was a nature whose elements interacted with palpable, variegated, fluttering rhythms.

He thought about it himself. Once—uninterested though he was in fiction or poetry—he carefully copied out a verse fragment by Vladimir Nabokov: "Space is a swarming in the eyes; and time a singing in the ears."

"Visualization—you keep repeating that," he said to another historian, Silvan S. Schweber, who was trying to interview him.

> What I am really trying to do is bring birth to clarity, which is really a half-assedly thought-out pictorial semi-vision thing. I would see the

jiggle-jiggle-jiggle or the wiggle of the path. Even now when I talk about the influence functional, I see the coupling and I take this turn—like as if there was a big bag of stuff—and try to collect it away and to push it. It's all visual. It's hard to explain.

"In some ways you see the answer——?" asked Schweber.

——the character of the answer, absolutely. An inspired method of picturing, I guess. Ordinarily I try to get the pictures clearer, but in the end the mathematics can take over and be more efficient in communicating the idea of the picture.

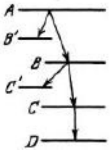
In certain particular problems that I have done it was necessary to continue the development of the picture as the method before the mathematics could be really done.

The field itself presented the ultimate challenge. Feynman once told students, "I have no picture of this electromagnetic field that is in any sense accurate." In seeking to analyze his own way of visualizing the unvisualizable he had learned an odd lesson. The mathematical symbols he used every day had become entangled with his physical sensations of motion, pressure, acceleration … Somehow he invested the abstract symbols with physical meaning, even as he gained control over his raw physical intuition by applying his knowledge of how the symbols could be manipulated.

When I start describing the magnetic field moving through space, I speak of the *E*- and *B*- fields and wave my arms and you may imagine that I can see them. I'll tell you what I see. I see some kind of vague, shadowy, wiggling lines … and perhaps some of the lines have arrows on them—an arrow here or there which disappears when I look too closely… . I have a terrible confusion between the symbols I use to describe the objects and the objects themselves.

Yet he could not retreat into the mathematics alone. Mathematically the field was an array of numbers associated with every point in space. That, he told his students, he could not imagine at all.

Visualization did not have to mean diagrams. A complex, halfconscious, kinesthetic intuition about physics did not necessarily lend itself to translation into the form of a stick-figure drawing. Nor did a diagram necessarily express a physical picture. It could merely be a chart or a memory aid. At any rate diagrams had been rare in the literature of quantum physics. One typical example used a ladder of horizontal lines to represent the notion of energy levels in the atom:



The “quantum jump” visualized as a sort of ladder.

The quantum jump from one level down to another accompanied the emission of a photon; the absorption of a photon would bring a jump upward. No depiction of the photons appeared in these diagrams; nor in another, more awkward schematic for the same process.

Feynman never used such diagrams, but he often filled his note pages with drawings of a different sort, recalling the space-time paths that had been so crucial a feature of his Princeton work with Wheeler. He drew the paths of electrons as straight lines, moving across the page to represent motion through space and up the page to represent progress through time. At first he, too, left the emission of a photon out of his pictures: that event would appear as the deflection of an electron from one path to another. The absence of photons did reflect an implicit choice from among the available pictorial landscapes: Feynman was still thinking mainly in terms of electrons interacting with the electromagnetic field as a field, rather than with the field as incarnated in the form of particles, photons.

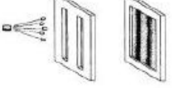
In mid-1947 friends of Feynman persuaded him—threats and cajoling were required—to write for publication the theoretical ideas they kept hearing him explain. When he finally did, he used no diagrams. The result was partly a reworking of his thesis, but it also showed the maturing and broadening of his command of the issues of quantum electrodynamics. He expressed the tenets of his new vision with an unabashed plainness. For some physicists this would be the most influential set of ideas Feynman ever published.

He said he had developed an alternative formulation of quantum mechanics to add to the pair of formulations produced two decades before by Schrödinger and Heisenberg. He defined the notion of a *probability amplitude for a space-time path*. In the classical world one could merely add probabilities: a batter's on-base percentage is the 30 percent probability of a base hit plus the 10 percent probability of a base on balls plus the 5 percent probability of an error … In the quantum world probabilities were expressed as complex numbers, numbers with both a quantity and a phase, and these so-called *amplitudes* were squared to produce a probability. This was the mathematical procedure necessary to capture the wavelike aspects of particle behavior. Waves interfered with one another. They could enhance one another or cancel one another, depending on whether they were in or out of phase. Light could combine with light to produce darkness, alternating with bands of brightness, just as water waves combining in a lake could produce doubly deep troughs and high crests.

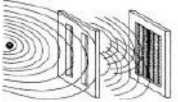
Feynman described for his readers what they already knew as the canonical thought experiment of quantum mechanics, the so-called two-slit experiment. For Niels Bohr it had illustrated the inescapable paradox of the wave-particle duality. A beam of electrons (for example) passes through two slits in a screen. A detector on the far side records their arrival. If the detector is sensitive enough, it will record individual events, like bullets striking; it might be designed to click as a Geiger counter clicks. But a peculiar spatial pattern emerges: the probabilities of electrons arriving at different places vary in the distinct manner of diffraction, precisely as though waves were passing through the slit and interfering with one another. Particles or waves? Sealing the paradox, quantum mechanically, is a conclusion that one cannot escape: that each electron "sees," or "knows about," or somehow *goes through* both slits. Classically a particle would have to go through one slit or the other. Yet in this experiment, if the slits are alternately closed, so that one electron must go through A and the next through B, the interference pattern vanishes. If one tries to glimpse the particle as it passes through one slit or the other, perhaps by placing a detector at a slit, again one finds that the mere presence of the detector destroys the pattern.

Probability amplitudes were normally associated with the likelihood of a particle's arriving at a certain place at a certain time. Feynman said he would associate the probability amplitude "with an entire motion of a particle"—with a path. He stated the central principle of his quantum mechanics: *The probability of an event which can happen in several different ways is the absolute square of a sum of complex contributions, one from each alternative way.* These complex numbers, these amplitudes, were written in terms of the classical action; he showed how to calculate the action for each path as a certain integral. And he established that this peculiar approach was mathematically equivalent to the standard Schrödinger wave function, so different in spirit.

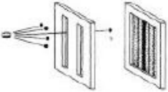
The central mystery of quantum mechanics—the one to which all others could ultimately be reduced.



A gun (obeying the classical laws) sprays bullets toward a target. First they must pass through a screen with two slits. The pattern they make shows how their *probability* of arrival varies from place to place. They are likeliest to strike directly behind one of the slits. The pattern happens to be simply the sum of the patterns for each slit considered separately: if half the bullets were fired with only the left slit open and then half were fired with just the right slit open, the result would be the same.



With waves, however, the result is very different, because of *interference*. If the slits were opened one at a time, the pattern would resemble the pattern for bullets: two distinct peaks. But when the slits are open at the same time, the waves pass through both slits at once and interfere with each other: where they are in phase they reinforce each other; where they are out of phase they cancel each other out.



Now the quantum paradox: Particles, like bullets, strike the target one at a time. Yet, like waves, they create an interference pattern. If each particle passes individually through one slit, with what does it "interfere"? Although each electron arrives at the target at a single place and a single time, it seems that each has passed through—or somehow felt the presence of—both slits at once.

The Physical Review had printed nothing by Feynman since his undergraduate thesis almost a decade before. To his dismay, the editors now rejected this paper. Bethe helped him rewrite it, showing him how to spell out for the reader what was old and what was new, and he tried the more retrospective journal *Reviews of Modern Physics*, where finally it appeared the next spring under the title "Space-Time Approach to Non-Relativistic Quantum Mechanics." He plainly admitted that his reformulation of quantum mechanics contained nothing new in the way of results, and he stated even more plainly where he thought the merit lay: "There is a pleasure in recognizing old things from a new point of view. Also, there are problems for which the new point of view offers a distinct advantage." (For example, when two particles interacted, it became possible to avoid the laborious bookkeeping of two different coordinate systems.) His readers—

and at first they were few—found no fancy mathematics, just this shift of vision, a bit of physical intuition laid atop a foundation of clean, classical mechanics.

Few immediately recognized the power of Feynman's vision. One who did was the Polish mathematician Mark Kac, who heard Feynman describe his path integrals at Cornell and immediately recognized a kinship with a problem in probability theory. He had been trying to extend the work of Norbert Wiener on Brownian motion, the herky-jerky random motion in the diffusion processes that so dominated Feynman's theoretical work at Los Alamos. Wiener, too, had created integrals that summed many possible paths a particle could take, but with a crucial difference in the handling of time. Within days of Feynman's talk, Kac had created a new formula, the Feynman-Kac Formula, that became one of the most ubiquitous of mathematical tools, linking the applications of probability and quantum mechanics. He later felt that he was better known as the K in F-K than for anything else in his career.

Even to physicists well accustomed to theoretical constructions with awkward philosophical implications, Feynman's summings of paths—path integrals—seemed bizarre. They conjured a universe where no potential goes uncounted; where nothing is latent, everything alive; where every possibility makes itself felt in the outcome. He had expressed his conception to Dyson:

> The electron does anything it likes. It just goes in any direction at any speed, forward or backward in time, however it likes, and then you add up the amplitudes and it gives you the wave function.

Dyson gleefully retorted that he was crazy. Still, Feynman had caught the intuitive essence of the two-slit experiment, where an electron seems aware of every possibility.

Feynman's path-integral view of nature, his vision of a "sum over histories," was also the principle of least action, the principle of least time, reborn. Feynman felt that he had uncovered the deep laws that gave rise to the centuries-old principles of mechanics and optics discovered by Christiaan Huygens, Pierre de Fermat, and Joseph-Louis Lagrange. How does a thrown ball know to find the particular arc whose path minimizes action? How does a ray of light know to find the path that minimizes time? Feynman answered these questions with images that served not only for the novel mysteries of quantum mechanics but for the treacherously innocent exercises posed for any beginning physics student. Light seems to angle neatly as it passes from air to water. It seems to bounce like a billiard ball off the surface of a mirror. It seems to travel in straight lines. These paths—the paths of least time—are special because they tend to be where the contributions of nearby paths are most closely in phase and most reinforce one another. Far from the path of least time—at the distant edge of a mirror, for example—paths tend to cancel one another out. Yet light does take every possible path, Feynman showed. The seemingly irrelevant paths are always lurking in the background, making their contributions, ready to make their presence felt in such phenomena as mirages and diffraction gratings.

Optics students learned alternative explanations for such phenomena in terms of waves like those undulating through water and air. Feynman was—with finality—eliminating the wave viewpoint altogether. Waviness was built into the phases carried by amplitudes, like little clocks. Once, with Wheeler, he had dreamed of eliminating the field itself. That idea had proved fanciful. The field had lodged itself deeply in the consciousness of physicists. It was indispensable and it was multiplying—a new particle, such as the meson, meant a new field, like a new plastic overlay, of which the particle was a quantized manifestation. Still, Feynman's theory retained the mark of its original scaffolding, though the scaffolding was long discarded. The actors were, more clearly than ever, particles. That became an attractive feature for physicists seeking help in visualization, in an experimental world dominated more and more by the cloud trails, the nomenclature, the behaviorism of particles.

Schwinger's Glory

Feynman's path integrals belonged to a loose kit of ideas and methods, a private physics that he had assembled but not organized. Much relied on guesswork or, as he said, "semi-empirical shenanigans." It was all hodgepodge and purpose-driven, and he could barely communicate it, let alone prove it, even to his most sympathetic listeners, Bethe and Dyson. In the fall of 1947 he attended a formal lecture by Bethe on his approach to the Lamb shift. When Bethe concluded by stressing the need for a more reliable way of making the theory finite, a way that would observe the requirements of relativity, Feynman realized that he could compute the necessary correction. He promised Bethe an answer by the next morning.

By morning he realized that he did not know enough about Bethe's calculation of the electron's self-energy to translate his correction into the normal language of physics. They stood together at the blackboard for a while, Bethe explaining his calculation, Feynman trying to translate his technique, and the best answer they could reach diverged not modestly, like Bethe's, but horrendously. Feynman, thinking about the problem physically, was sure it should not diverge at all.

In the days that followed, he taught himself about self-energy all over again. When he reexpressed his equations in terms of the observed, "dressed" mass of the electron instead of the theoretical, "bare" mass, the correction came out just as he had thought, converging to a finite answer. Meanwhile, glowing news of Schwinger's progress was reaching Ithaca from Cambridge via Weisskopf and Bethe. When Feynman heard late in the fall that Schwinger had worked out a calculation for the magnetic moment of the electron—another tiny experimental anomaly newly found in Rabi's laboratory—he solved the problem, too. Schwinger's elaborate piece of calculating gave leading physicists a conviction that theory was once again on the march. "God is great!" Rabi wrote Bethe with characteristic wryness, and Bethe replied: "It is certainly wonderful how these experiments of yours have given a completely new slant to a theory and how the theory has blossomed out in a relatively short time. It is as exciting as in the early days of quantum mechanics."

Feynman felt increasingly competitive about Schwinger, and increasingly frustrated. He had his quantum electrodynamics, he believed, and what he now thought of as "the Schwinger-Weisskopf-Bethe camp" had another. In January the American Physical Society met in New York, and Schwinger was the star. His program was not complete, but he had integrated the new idea of renormalization into the standard quantum mechanics in a way that let him demonstrate a series of impressive derivations. He showed how the anomalous magnetic moment, like the

Lamb shift, came from the electron's interaction with its own field. His lecture drew a crowd that packed the hall. Too many physicists were forced to stand out in the corridors to hear the bursts of applause (and the embarrassed laughter that came when Schwinger finally said, "It is quite clear that …"). Hasty arrangements were made for Schwinger to repeat the lecture later the same day in Columbia's McMillin Theater. Dyson attended. Oppenheimer smoked his pipe conspicuously in the front row. Feynman rose during the question period to say that he, too, had reached these results and that, in fact, he could offer a small correction. Immediately he regretted it. He thought he must have sounded like a little boy piping up with "I did it too, Daddy." Few people that winter realized the depths of the rivalry he felt, but he made a bitter remark to a girlfriend, who understood the drift of his disappointment if not the exact circumstances.

"I'm so sorry that your long worked-on experiment was more or less stolen by someone else," she wrote back. "I know it just makes you feel sick. But Dick dear, how could life or things be interesting if there was not competition?" She wondered, why couldn't he and his competitor combine their ideas and work together?

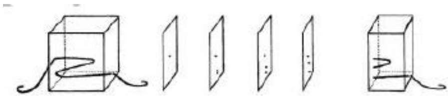
Schwinger and Feynman were not alone in trying to produce the calculations—the explanation—required by the immediate experiments on the Lamb shift and the electron's magnetic moment. Other theorists followed the lead provided by Bethe's back-of-the-envelope approach. They saw no need to create a monumental new quantum electrodynamics, when they might generate the right numbers merely by patching the technique of renormalization onto the existing physics. Independently, two pairs of scientists succeeded in this, producing solutions that went beyond Bethe's in that they took into account the way masses fattened at relativistic speeds. Before publishing, one team, Weisskopf and a graduate student, Bruce French, committed a fatal act of indecision by consulting both Schwinger and Feynman. Engrossed in their more ambitious programs, Schwinger and Feynman each warned Weisskopf off, saying that he was in error by a small factor. Weisskopf decided it was inconceivable that these brilliant upstarts could both be wrong, independently, and delayed his manuscript. Months passed before Feynman called apologetically to say that Weisskopf's answer had been correct.

For Feynman's own developing theory, a breakthrough came when he confronted the ticklish area of antimatter. The first antiparticle, the negative electron, or positron, had been born less than two decades earlier as a minus sign in Dirac's equations—a consequence of a symmetry between positive and negative energy. Dirac had been forced to conceive of holes in a sea of energy, noting in 1931 that "a hole, if there were one, would be a new kind of particle, unknown to experimental physics." Unknown for the next few months—then Carl Anderson, at Caltech, found the trail of one in a cloud chamber built to detect cosmic rays. It looked like an electron, but it swerved up through a magnetic field when it should have swerved down.

The vivid photographs, along with the lively name coined by a journal editor against Anderson's will, gave the positron a legitimacy that theorists found hard to ignore. The collision of an electron with its antimatter cousin released energy in the form of gamma rays. Alternatively, in Dirac's picture of the vacuum as a lively sea populated by occasional holes, or bubbles, one could say that the electron fell into a hole and filled it, so that both the hole and the electron would disappear. As experimentalists continued to study their cosmic-ray photographs, they also found the reverse process: a gamma ray, nothing more than a high-frequency particle of light, could spontaneously produce a pair of particles, one electron and one positron.

Dirac's picture had difficulties. As elsewhere in his physics, unwanted infinities arose. The simplest description of the vacuum, empty space at absolute zero, seemed to require infinite energy and infinite charge. And from the practical perspective of anyone trying to write proper equations, the infinitude of presumed particles caused infernal complications. Feynman, seeking a way out, turned again to the forward- and backward-flowing version of time in his work with Wheeler at Princeton. Once again he proposed a space-time picture in which the positron was a time-reversed electron. The geometry of this vision could hardly have been simpler, but it was so unfamiliar that Feynman strained for metaphors:

"Suppose a black thread be immersed in a cube of collodion, which is then hardened," he wrote. "Imagine the thread, although not necessarily quite straight, runs from top to bottom. The cube is now sliced horizontally into thin square layers, which are put together to form successive frames of a motion picture." Each slice, each cross-section, would show a dot, and the dot would move about to reveal the path of the thread, instant by instant. Now suppose, he said, the thread doubled back on itself, "somewhat like the letter N." To the observer, seeing the successive slices but not the thread's entirety, the effect would resemble the production of a particle-antiparticle pair:



> In successive frames first there would be just one dot but suddenly two new ones would appear when the frames come from layers cutting the thread through the reversed section. They would all three move about for a while then two would come together and annihilate, leaving only a single dot in the final frames.

The usual equations of electron motion covered this model, he said, though it did require "a more tortuous path in space and time than one is used to considering." He remained dissatisfied with the analogy of the thread and kept looking for more intuitive ways to express his view, capturing as it did the essence of the distinction between seeing paths in time-bound slices and seeing them whole. A Cornell student who had served as a wartime bombardier had a suggestion, and the bombardier metaphor, the one Feynman finally published, became famous.

> A bombardier watching a single road through the bomb-sight of a low flying plane suddenly sees three roads, the confusion only resolving itself when two of them move together and disappear and he realizes he has only passed over a long reverse switchback of a single road. The reversed section represents the positron in analogy, which is first created along with an electron and then moves about and annihilates another electron.

That was the broad picture. His path-integral method suited the model well: he knew from his old work with Wheeler that the summing of the phases of nearby paths would apply to "negative time" as well. He also found a shortcut past complications that had arisen because of the Pauli exclusion principle, the essential law of quantum mechanics that forbade two electrons from inhabiting the same quantum state. He granted himself a bizarre dispensation from the exclusion principle on the basis that, where earlier calculations had seen two particles, there was actually just one, taking a zigzag back and forth through a slice of time. "Usual theory says no, because then at time between *ty*, *tx* can't have 2 electrons in same state," he jotted in a note to himself. "We say it is same electron so Pauli exclusion doesn't operate." It sounded like something from the science fiction of time travel—hardly a notion designed for ready acceptance. He knew well that he was proposing a radical departure from the commonsense experience of time. He was violating the everyday intuition that the future does not yet exist and that the past has passed. All he could say was that time in physics had already departed from time in psychology—that nothing in the microscopic laws of physics seemed to mandate a distinction between past and future, and that Einstein had already ruined the notion of absolute time, independent of the observer. Yet Einstein had not imagined a particle's history reversing course and swerving back against the current. Feynman could only resort to an argument from utility: "It may prove useful in physics," he wrote, "to consider events in all of time at once and to imagine that we at each instant are only aware of those that lie behind us."

My Machines Came from Too Far Away

Schwinger and Feynman were both looking ahead to the inevitable sequel to the elite Shelter Island meeting. A new gathering was planned for late March at a resort in the Pocono Mountains of Pennsylvania: again the setting was to be pastoral, the roster intimate, the agenda profound. Success had enhanced the already high-status guest list. Fermi, Bethe, Rabi, Teller, Wheeler, and von Neumann were returning, along with Oppenheimer as chairman, and now they would be joined by two giants of prewar physics, Dirac and Bohr.

They gathered on March 30, 1948, in a lounge under a tarnished green clock tower with a view over a golf course and fifty miles of rolling woodlands. The presentations opened with the latest news of particle tracks in cosmic-ray showers and in the accelerator at Berkeley. With its sixteen-foot magnet the Berkeley synchrotron promised to push protons up to energies of 350 million electron volts by fall, enough to re-create copious bursts of the new elementary (so it seemed) particle called the meson, the cosmic-ray particle of most current topical interest. Instead of waiting for the cosmos to send samples down into their cloud chambers, experimenters would finally be able to make their own.

There had been a problem with the cosmic-ray data, an enormous discrepancy between the expected and the observed strengths of the mesons' interactions with other particles. At Shelter Island a young physicist, Robert Marshak, had proposed a solution requiring more courage and ingenuity in 1947 than such solutions would need in decades to come: namely, that there must be a second species of particle mixed in with the first. Not one meson but two—it seemed so obvious once someone dared break the ice. Feynman gleefully said they would have to call the new particle a marshak. Abetted by technology, the roster of elementary particles was climbing toward double digits. As the Pocono meeting opened, experimentalists warmed up the audience by showing pictures of an increasingly characteristic sort. Particles made impressive chicken-claw tracks in the photographs. No one could see fields, or matrices, or operators, but the geometry of particle scattering could not have been more vivid.

The next morning Schwinger took the floor. He began to present for the first time a complete theory of quantum electrodynamics that, as he stressed at the outset, met the dual criteria of "relativistic invariance" and "gauge invariance." It was a theory, that is, whose calculations looked the same no matter what velocity or phase its particles chose. These invariances assured that the theory would be unchanged by the arbitrary perspective of the observer, just as the time from sunrise to sunset does not depend on whether one has set one's clock forward to daylight saving time. The theory would have to make sure that calculations never tied themselves to a particular reference system, or "gauge." Schwinger told his listeners that he would consider a quantized electromagnetic field in which "each small volume of space is now to be handled as a particle"—a particle with more mathematical power and less visual presence than those of the previous day. He introduced a difficult new notation and set about to derive a sampling of specific results for such "applications" as the interaction of an electron with its own field. If his distinguished listeners found themselves in darkness, they were nevertheless not so easily cowed as Schwinger's customary audiences, and the usual express train found itself halted by interruptions. Bohr himself broke in with a question—Schwinger hated this and cut him off abruptly. Finally he managed to move forward, promising that all would be made clear in due course. As always, he made a point of lecturing without notes, and nearly all of his presentation was formal, deriving one equation after another. His talk became a marathon, lasting late into the afternoon. Bethe noticed that the formal mathematics silenced the critics, who raised questions only when Schwinger tried to express plainly physical ideas. He mentioned this to Feynman, suggesting that he, too, take a mathematical approach to his presentation. Fermi, glancing about at his famous colleagues, noticed with some satisfaction that one by one they had let their attention drift away. Only he and Bethe managed to stay with Schwinger to the end, he thought.

Then it was Feynman's turn. He was uneasy. It seemed to him that Schwinger's talk, though a bravura performance, had not gone well (but he was wrong—everyone, and crucially Oppenheimer, had been impressed). Bethe's warning made him reverse his planned presentation. He had meant to stay as closely as possible to physical ideas. He did have a mathematical formalism, as private though not as intricate as Schwinger's, and he could show how to derive his rules and methods from the formalism, but he could not justify the mathematics itself. He had reached it by trial and error. He knew it was correct, because he had tried it now on so many problems, including all of Schwinger's, and it worked, but he could not prove that it worked and he could not connect it to the old quantum mechanics. Nevertheless he took Bethe's advice and began with equations, saying, "This is a mathematical formula which I will now show you produces all the results of quantum mechanics."

He had always told his friends that once he started talking about physics he did not care who his audience was. One of his favorite stories was about Bohr, who had singled him out at Los Alamos as a young man unafraid to dispute his elders. Bohr had consulted Feynman privately there from time to time, often through his physicist son, Aage. Still, he had never fully warmed to Feynman, with his overeager, American, working-class style. Now Bohr waited, at the end of a long day, in this formidable audience of twenty-six men. Not even at Princeton, when he lectured to Einstein and Pauli, had Feynman stood before such a concentration of the great minds of his science. He had created a new quantum mechanics almost without reading the old, but he had made two exceptions: he had learned from the work of Dirac and Fermi, both now seated before him. His teachers Wheeler and Bethe were there. So were Oppenheimer, who had built one bomb, and Teller, who was building the next. They had known him as a promising, fearless young light. His thirtieth birthday was seven weeks away.

Schwinger himself was hearing Feynman's theory for the first time. He thought it intellectually repulsive, though he did not say so (and afterward they cordially compared techniques and found themselves in nearly perfect agreement). He could see that Feynman was offering a patchwork of guesses and intuition. It struck him as engineering, all I-beams and T-beams. Bethe interrupted once, sensing that the audience was numbed with detail, and tried to return Feynman to fundamentals. Feynman explained his path integrals, an alien idea, and his positrons moving backward in time, even more disturbing. Teller caught the apparent infringement of the exclusion principle and refused to accept Feynman's unrigorous justification. It struck Feynman that everyone had a favorite principle or theorem and he was violating them all. When Dirac asked, "Is it unitary?" Feynman did not even know what he meant. Dirac explained: the matrix that carries one from the past to the future had to maintain an exact bookkeeping of total probability. But Feynman had no such matrix. The essence of his approach was a view of past and future together, with the freedom to go forward or backward in time at will. He was getting almost nothing across. Finally, as he sketched diagrams on the blackboard—schematic trajectories of particles—and tried to show his method of summing the amplitudes for different paths, Bohr rose to object. Had Feynman ignored the central lesson of two decades of quantum mechanics? It was obvious, Bohr said, that such trajectories violated the uncertainty principle. He stepped to the blackboard, gestured Feynman aside, and began to explain. Wheeler, taking notes, quickly jotted, "Bohr Has Raised The Question As To Whether This Point Of View Has Not The

Same Physical Content As The Theory Of Dirac, But Differs In A Manner Of Speaking Of Things Which Are Not Well-Defined Physically." Bohr continued for long minutes. That was when Feynman knew he had failed. At the time, he was in anguish. Later he said simply: "I had too much stuff. My machines came from too far away."

There Was Also Presented (by Feynman) …

Wheeler had arranged as rapid a news service as the available technology permitted. On his first day back in Princeton he pressed his graduate students into service as scribes. They reproduced his notes page by page onto mimeograph blanks and printed dozens of copies, turning their forearms magenta. For months this samizdat document served as the only available introduction to the new Schwingerian covariant quantum electrodynamics. Only a few pages were devoted to Feynman, with his "alternative formulation" and curious diagrams. Dyson read the Wheeler notes avidly. Bethe had tried to get him an invitation to Pocono ("you can imagine that I was highly pleased and flattered," Dyson wrote his parents), but Oppenheimer refused to consider someone whose current caste was student.

Feynman himself was assigned the task of writing a nontechnical account of the Pocono meeting for a new trade journal for physicists, *Physics Today*—anonymously, he hoped. He explained renormalization à la Schwinger, concluding:

> A major portion of the conference was spent in hearing and discussing these results of Schwinger. (((One conferee put it: "We did not have time to discuss a great deal, for we had to take time out to learn some physics." He was referring to this work of Schwinger.)))
>
> There was also presented (by Feynman) a theory in which the equations of electrodynamics are artificially altered so that all quantities including the inertia of the electron turn out finite. The results of this theory are in essential agreement with those of Schwinger, but they are not as complete.

In the same runner-up vein Feynman was asked to help select a winner for a new prize the National Academy of Sciences was awarding for "an outstanding contribution to our knowledge of the nature of light." When Schwinger saw Feynman's name on the list of judges, he inferred correctly that the prize was meant for him. What was quantum electrodynamics about, if not light, in all its many dresses?

No one had been more definitively impressed by Schwinger, and unimpressed by Feynman, than Oppenheimer. Awaiting him back in Princeton was a startling confirmation of Schwinger's theory, in the form of a letter from a Japanese theorist, Shin'ichirō Tomonaga, whose claim to glory began with the words: "I have taken the liberty of sending you copies of several papers and notes …"

Japan's physicists had just begun making significant contributions to the international community in the 1930s—it had been Hideki Yukawa at Kyōto University who first proposed that a massive, short-lived, undiscovered particle might act as a "carrier" of the nuclear force, binding protons together in the atom's core—when the war isolated them utterly. Even with the war's end, channels to occupied Japan opened slowly. News of the Lamb shift reached Kyōto and Tokyo not through American physicists and not through journals, but from a squib in a newsmagazine.

Tomonaga, a native of Tokyo and a graduate of Kyōto University, a classmate and friend of Yukawa, had been deeply influenced by Dirac; he belonged to a small group that translated Dirac's famous textbook into Japanese. In 1937 he traveled to Germany to study with Heisenberg; returning at the war's onset in 1939, he stopped briefly in New York to visit the World's Fair. He worked out what he called a "super many time" theory, in which every point in the field had its own clock—a workable notion, he found, despite the seeming absurdity of trying to manipulate infinitely many time variables. In his thoughts on physics he traversed much of the ground covered by his European and American counterparts, but with a far greater sense of solitude, hardly diminished by his time in Germany. He recorded a dark mood in his diary from time to time:

> After supper I took up my physics again, but at last I gave up. Ill-starred work indeed! … Recently I have felt very sad without any reason, so I went to a film… . Returning home I read a book on

> physics. I don't understand it very well… . Why isn't nature clearer and more directly comprehensible? … As I went on with the calculation, I found the integral diverged—was infinite. After lunch I went for a walk. The air was astringently cold… . All of us stand on the dividing line from which the future is invisible. We need not be too anxious about the results, even though they may turn out quite different from what you expect… .

His occasional emotional desolation paled in light of what faced him in the months after the surrender, when shortages of food and housing overshadowed all else in Japan. He made a home and an office in a battered Quonset hut on the Tokyo University grounds. He furnished it with mats.

Although Oppenheimer knew nothing of Tomonaga's personal circumstances, he knew what he and his Los Alamos compatriots had wrought on Japan, and he also wished to preserve the internationalism of physics in the face of what suddenly seemed an American hegemony. He could hardly have been better placed to appreciate Tomonaga's letter—clear evidence that a Japanese physicist had not just matched the essentials of Schwinger's work but had anticipated it. Tomonaga had not published, and he had not created the entire Schwingerian tapestry, but he had been first. Oppenheimer immediately gave Tomonaga his imprimatur in a letter to each of the Pocono participants. "Just because we were able to hear Schwinger's beautiful report," he wrote, "we may better be able to appreciate this independent development." For Dyson, working in Pocono's aftermath to understand the new theories, the revelation of Tomonaga's papers lay in what seemed a simple beauty. He thought that he now understood Schwinger and that not all Schwinger's complications were necessary. Graduate students poring over the Pocono notes already suspected this, despite the acclaim their elders were awarding. Later Dyson quoted "an unkind critic" as having said, "Other people publish to show how to do it, but Julian Schwinger publishes to show you that only he can do it." He seemed to strive for an exceptional ratio of equations to text, and the prose posed serious challenges to the *Physical Review*'s typesetters.

Schwinger occasionally heard what sounded like carping amid the applause: comments to the effect that he was a soulless Paganini, all flash and technique instead of music; that he was more mathematician than physicist; that he too carefully smoothed the rough edges. “I gather I stand accused,” Schwinger said later, “of presenting a finished elaborate mathematical formalism from which had been excised all the physical insights that provide signposts to its construction.”

He had removed the signposts. He never liked to show the rough pathways of his thinking, any more than he liked to let his audiences see notes when he lectured. Yet all his mathematical power could not have produced his joining of relativity and quantum electrodynamics if he had lacked the intuition of a physicist. Beneath the formalism lay a profound—and historically minded—conviction about the nature of particles and fields. To Schwinger renormalization was not just a mathematical trick. Rather it marked a mutation in physicists’ understanding of what a particle was. His central physical insight, had he expressed it in the compromised language of everyday speech, might have sounded like this:

Are we talking about particles or are we talking about waves? Until now, everyone has thought that their equations—the Dirac equation, for example, which is supposed to describe the hydrogen atom—referred directly to the physical particles. Now, in a field theory, we recognize that the equations refer to a sublevel. Experimentally we are concerned with particles, yet the old equations describe fields. When you talk about fields, you presume that you can describe, and somehow experience, exactly what goes on at every point in space at every time; when you talk about particles, you merely sample the field with measurements at occasional instants.

A particle is a cohesive thing. We know we have a particle only when the same thing stays there as time goes on. The very language of particles implies phenomena with continuity over space and time. Yet if you make measurements at only disconnected instants, how do you know there is a particle? Experiments probe the field only crudely—they look at large spaces over long times.

The essence of renormalization is to make the transition from one level of description to the next. When you begin with field equations, you operate at a level when particles are not there from the start. It is when *you solve the field equations that you see the emergence of particles. But the properties—the mass and the charge—that you ascribe to a particle are not those inherent in the original equations.*

Other people say, "Oh, the equations have divergences, you have to cancel them out." That is only the form, not the essence of renormalization. The essence lies in recognizing that the theories of Maxwell and Dirac are not about electrons, positrons, and photons but about a deeper level.

Cross-Country with Freeman Dyson

Feynman had a tendency to vanish with the end of the school year, leaving behind a vacuum populated by uncorrected papers, ungraded tests, unwritten letters of recommendation. Often Bethe covered for his lapses in the paperwork of teaching. Still, June might bring a tirade from Lloyd Smith, the department chairman:

> Your sudden departure from Ithaca without completing the grades in your courses, especially those involving seniors who may thus be prevented from graduating, has caused the Department considerable embarrassment. I have begun to be somewhat apprehensive over what would appear to be a feeling of indifference concerning the obligations and responsibilities to the University …

Feynman would jot some grades—round numbers, none higher than 85—and then start doodling equations.

This June found him at the wheel of his secondhand Oldsmobile, rushing across the country at a constant 65 miles per hour. In the passenger seat Freeman Dyson eyed the scenery and occasionally wished Feynman would slow down. Feynman thought Dyson was a bit dignified. Dyson liked the role of foreign observer of the American scene: here was his chance to play Tocqueville peering at the wild West from the vantage point of Route 66. Missouri, the Mississippi River (thick and reddish-brown, just as he had imagined it), Kansas, Oklahoma—none of this struck him as very Western, actually. In fact it looked not unlike his rural corner of New York.

He had decided that modern America resembled Victorian England, particularly in the attention devoted to furnishing middle-class homes and women. His destination was Ann Arbor, Michigan, where he intended to pursue Schwinger, who was presenting his work in a series of summer-school lectures. Feynman, meanwhile, was heading for Albuquerque to resolve an entanglement with a woman he had known at Los Alamos. (She was Rose McSherry, a secretary whom he dated after Arline's death. Another of Feynman's current attachments was needling him by calling McSherry his "movie queen." Dyson's guess was that he would marry her.)

Dyson realized that he was not taking the direct route to Ann Arbor, but he relished the chance to spend time with Feynman. No one interested him as much. In the months since Pocono, he had begun to think that his mission might be to find a synthesis of the difficult new theories of quantum electrodynamics—rival theories, as he saw it, though to most of the community the rivalry seemed lopsided. He had heard Feynman's theory in informal blackboard sessions, and it still troubled him that Feynman was, as it seemed, merely writing down answers instead of solving equations in the normal manner. He wanted to understand more.

They drove, sometimes stopping for hitchhikers, more often maintaining a determined pace, and Feynman confided more in Dyson than he had done with any friend in his adult life. He startled Dyson with a grim outlook on the future. He felt certain that the world had seen only the beginning of nuclear war. The memory of Trinity, sheer ebullient joy at the time, haunted him now. Philip Morrison, his Cornell colleague, had published an admonitory description of an atomic blast on East 20th Street in Manhattan—Morrison had witnessed the Hiroshima aftermath and wrote this account in a horrifyingly vivid past tense—and Feynman could not meet his mother at a midtown restaurant without thinking about the radius of destruction. He could not shake a feeling that normal people, without the burden of his accursed knowledge, were living a pitiful illusion, like ants tunneling and building before the giant's boot comes down. This was a classic danger sign—the feeling of being the only sane man, the only man who truly sees—but Dyson suddenly felt that Feynman was as sane as anyone he knew. This was not the jester he had first described to his parents. Dyson wrote later: "As we drove through Cleveland and St. Louis, he was measuring in his mind's eye distances from ground zero, ranges of lethal radiation and blast and fire damage… . I felt as if I were taking a ride with Lot through Sodom and Gomorrah."

As they drew closer to Albuquerque, Feynman was also thinking about Arline. Sometimes it occurred to him that her death might have left him with a feeling of impermanence. Spring flooding in the Oklahoma prairie closed the highway. Dyson had never seen rain fall in such dense curtains—nature as raw as these plainspoken Americans, he thought. The car radio reported people trapped in cars, drowned or rescued by boats. They pulled off the road in a town called Vinita and found lodging in a hotel of the kind Feynman knew all too well from his weekend trips to visit Arline: an "office" on the second floor, a sign reading, "This hotel is under new management, so if you're drunk you came to the wrong place," a hanging cloth covering the doorway to the room he shared with Dyson for fifty cents apiece. That night he told Dyson more about Arline than ever before. Neither of them forgot it.

They talked about their aspirations for science. Feynman cared far less than Dyson about his still-patchwork scheme for renormalizing quantum electrodynamics. It was his sum-over-histories theory of physics that claimed his passion. As Dyson saw, it was a grand vision and a unifying vision—too ambitious, he thought. Too many physicists had already stumbled in pursuit of this grail, including Einstein, notoriously. Dyson—more than anyone who heard Feynman at Pocono or attended his occasional seminars at Cornell, more even than Bethe—was beginning to see just how far Feynman sought to reach. He was not ready to concede that his friend could out-Einstein Einstein. He admired Feynman's gall, the largeness of his dream, the implicit attempt to unify realms of physics that were more distant from one another than anything in human experience. On the largest scale, the scale of solar systems and galactic clusters, gravity reigned. On the smallest scale, particles still awaiting discovery bound the atom's nucleus with unimaginably strong forces. Dyson considered it enough to walk the "middle ground," the realm that after all encompassed everything in between: the furniture of everyday life, the foundations underlying chemistry and biology. The middle ground, where quantum theory ruled, extended to all phenomena that could be seen and studied without the help of either a mammoth telescope or a behemoth particle accelerator. Yet Feynman wanted more.

> It was essential to his view of things that it must be universal. It must describe everything that happens in nature. You could not imagine the sum-over-histories picture being true for a part of nature and untrue for another part. You could not imagine it being true for electrons and untrue for gravity. It was a unifying principle that would either explain everything or explain nothing.

Many years later each man recalled their night in Vinita, Dyson showing how unshakably he revered his friend still, Feynman showing how he could use storytelling as a strategy—a dagger and a cloak. Dyson wrote:

> In that little room, with the rain drumming on the dirty window panes, we talked the night through. Dick talked of his dead wife, of the joy he had had in nursing her and making her last days tolerable, of the tricks they had played together on the Los Alamos security people, of her jokes and her courage. He talked of death with an easy familiarity which can come only to one who has lived with spirit unbroken through the worst that death can do. Ingmar Bergman in his film *The Seventh Seal* created the character of the juggler Jof, always joking and playing the fool, seeing visions and dreams that nobody else believes in, surviving at the end when death carries the rest away. Dick and Jof have a great deal in common.

And Feynman:

> The room was fairly clean, it had a sink; it wasn't so bad. We get ready for bed.
>
> He says, "I've got to pee."
>
> "The bathroom is down the hall."
>
> We hear girls giggling and walking back and forth in the hall outside, and he's nervous. He doesn't want to go out there.
>
> "That's all right; just pee in the sink," I say.
>
> "But that's unsanitary."

> "Naw, it's okay; you just turn the water on."
>
> "I can't pee in the sink," he says.
>
> We're both tired, so we lie down. It's so hot that we don't use any covers, and my friend can't get to sleep because of the noises in the place. I kind of fall asleep a little bit.
>
> A little later I hear a creaking of the floor nearby, and I open one eye slightly. There he is, in the dark, quietly stepping over to the sink.

And Dyson:

> That stormy night in our little room in Vinita, Dick and I were not looking thirty years ahead. I knew only that somewhere hidden in Dick's ideas was the key to a theory of quantum electrodynamics simpler and more physical than Julian Schwinger's elaborate construction. Dick knew only that he had larger aims in view than tidying up Schwinger's equations. So the argument did not come to an end, but left us each going his own way.

They reached Albuquerque, Dyson seeing for the first time the deceptively clear air and the red desert beneath still snowy peaks. Feynman bore into town at 70 miles per hour and was immediately arrested for a rapid sequence of traffic violations. The justice of the peace announced that the fine he handed down was a personal record. They parted—Feynman to find Rose McSherry (marriage was impossible, as it happened, in part because she was determinedly Roman Catholic and he could not be), Dyson to find a bus back toward Ann Arbor and Schwinger.

Oppenheimer's Surrender

With Bethe's blessing Dyson moved to the Institute for Advanced Study in Princeton in the fall of 1948. Oppenheimer had taken over as director the year before. Dyson was eager to impress him, and he immediately sensed he was not alone. "On Wednesday Oppenheimer returns," he wrote his parents. "The atmosphere at the Institute during these last days has been rather like the first scene in 'Murder in the Cathedral' with the women of

Canterbury awaiting the return of their archbishop."

He did not wait for Oppenheimer's blessing, however, before mailing off to the *Physical Review*a manuscript representing a cathartic outpouring of work during the last days of the summer. He proudly told his parents that the concentration had nearly killed him. Inspiration came most snappily on the fifty-hour bus ride east to Princeton, he told colleagues. (When Oppenheimer heard this he retorted with a sarcastic allusion to the lightning-from-the-blue legend of Fermat's last theorem: "There wasn't enough room in the margin to write down the proof.") Dyson had found the mathematical common ground he was sure must exist. He, too, created and reshaped terminology to suit his purpose. His chief insight was to focus on a so-called scattering matrix, or *S* matrix, a mustering of all the probabilities associated with the different routes from an initial state to a given end point. He now advertised "a unified development of the subject"—more reliable than Feynman and more usable than Schwinger. His father said that Feynman-Schwinger-Dyson reminded him of a clause in the Athanasian Creed: "There is the Father incomprehensible, and the Son incomprehensible, and the Holy Ghost incomprehensible, yet there are not three incomprehensibles but one incomprehensible."

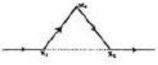
It occurred to Dyson that he was rushing into print with accounts of theories not yet published by their inventors and that the inventors themselves might take offense. He visited Bethe, temporarily in New York visiting Columbia, and they took a long walk in Riverside Park as the sun set over the Hudson River. Bethe warned him that there could be problems. Dyson said it was Schwinger's and Feynman's own fault that they had not published "any moderately intelligible account": Schwinger, he suspected, was polishing obsessively, while Feynman simply couldn't be bothered with paperwork. It was irresponsible. They were retarding the development of science. By publicizing their work Dyson was performing a service to humanity, he argued. He and Bethe ended up agreeing that Feynman would not mind but that Schwinger might, and that it would be poor tactics for an ambitious young physicist to irritate Schwinger. "So the result of all this," Dyson wrote his parents,

> is that I am reversing the tactics of Mark Antony, and saying very loud at various points in my paper, "I come to praise Schwinger, not to

bury him." I only hope he won't see through it.

Still, he made his judgment clear. The distinctions he drew and the characterizations he set down soon became the community's conventional wisdom: that Schwinger's and Tomonaga's approach was the same, while Feynman's differed profoundly; and that Feynman's method was original and intuitive, while Schwinger's was formal and laborious.

Dyson well understood that he was reaching out to an audience that wanted tools. When he showed a Schwinger formula with commutators threatening to subdivide like branches on a tree and remarked that "their evaluation gives rise to long and rather difficult analysis," he knew that his readers would not suspect him of overstating the difficulty. Ease of use was the Feynman virtue he stressed. To "write down the matrix elements" for a certain event, he explained, one need only take a certain set of products, replace them by sums of matrix elements from another equation, reassemble the various terms in a certain form, and undertake a certain type of substitution. Or, he said, one could simply draw a graph.



The simplest Dyson graph.

Graph was the mathematician's word for a network of points joined by lines. Dyson showed that there was a graph for every matrix and a matrix for every graph—the graphs provided a means of cataloging these otherwise-misplaceable arrays of probabilities. So alien did this conceit seem that Dyson left it to his readers to draw the graphs in their minds. The journal editors made room for just one figure. Dyson called the solid lines, with an implicit direction, electron lines. The directionless dotted lines were photon lines. Feynman, he mentioned, had something more in mind than the mere bookkeeping of matrices: "a picture of the physical process." For

Feynman the points represented the actual creation or annihilation of particles; the lines represented paths of electrons and photons, not through a measurable real space but through the history from one quantum event to another.

Oppenheimer depressed Dyson with a coolness bordering on animosity. It was the last response he had expected: a defeatist Oppenheimer, a lethargic Oppenheimer, an Oppenheimer hostile to new ideas and unwilling to listen. He had been in Europe, where he had summarized the present state of the theory at two international conferences. It was "Schwinger's theory" and "Schwinger's program." There were developments "the first largely, the second almost wholly, due to Schwinger." In passing, there were "Feynman's algorithms"—an exotically disdainful phrase.

Dyson decided that there would be no prize for timidity and—still in his first weeks at the institute—sent Oppenheimer by interoffice mail an aggressive manifesto. He argued that the new quantum electrodynamics promised to be more powerful, more self-consistent, and more broadly applicable than Oppenheimer seemed to think. He did not mince words.

> From Mr. F. J. Dyson.
>
> Dear Dr. Oppenheimer:
>
> As I disagree rather strongly with the point of view expressed in your Solvay Report (not so much with what you say as with what you do not say) …
>
> I… . I am convinced that the Feynman theory is considerably easier to use, understand, and teach.
>
> II. Therefore I believe that a correct theory, even if radically different from our present ideas, will contain more of Feynman than of Heisenberg-Pauli. …
>
> V. I do not see any reason for supposing the Feynman method to be less applicable to meson theory than to electrodynamics… .
>
> VI. Whatever the truth of the foregoing assertions may be, we have now a theory of nuclear fields which can be developed to the point where it can be compared with experiment, and this is a challenge to be accepted with enthusiasm.

Enthusiasm was not immediately forthcoming, but Oppenheimer did set up a series of forums to let Dyson make his case. They became an occasion. Bethe came down from New York to listen and lend moral support. As the seminars went on, Oppenheimer was a dramatically nerve-tightening presence. He interrupted continually, criticizing, jabbing, pouncing on errors. To Dyson he seemed uncontrollably nervous—always chain-smoking and fidgeting in his chair. Feynman himself was following Dyson's progress by long-distance as he continued his own work. Dyson visited him at Cornell one weekend and watched, amazed, as he rattled off two new fundamental calculations in a matter of hours. Then Feynman fired off a hasty letter: "Dear Freeman: I hope you did not go bragging about how fast I could compute the scattering of light by a potential because on looking over the calculations last night I discovered the entire effect is zero. I am sure some smart fellow like Oppenheimer would know such a thing right off."

In the end Bethe turned Oppenheimer around. He cast his vote explicitly with the Feynman theory and let the audience know that he felt Dyson had more to say. He took Oppenheimer aside privately, and the mood shifted. By January, the war had been won. At the American Physical Society meeting Dyson found himself almost as much a hero as Schwinger had been the year before. Sitting in the audience with Feynman beside him, he listened as a speaker talked admiringly of "the beautiful theory of Feynman-Dyson." Feynman said loudly, "Well, Doc, you're in." Dyson had not even got a doctoral degree. He went on an excited lecture tour and told his parents that he was a certified big shot. The reward that lasted, however, was a handwritten note that had appeared in his mailbox in the dying days of the fall, saying simply, "*Nolo contendere. R. O.*"

Dyson Graphs, Feynman Diagrams

It was the affair of Case and Slotnick at the same January meeting that brought home to Feynman the full power of his machinery. He heard a buzz in the corridor after an early session. Apparently Oppenheimer had devastated a physicist named Murray Slotnick, who had presented a paper on meson dynamics. A new set of particles, a new set of fields:

would the new renormalization methods apply? With physicists looking inward to the higher-energy particles implicated in the forces binding the nucleus, meson theories were now rising to the fore. The flora and fauna of meson theories did seem to resemble quantum electrodynamics, but there were important differences—chief among them: the counterpart of the photon was the meson, but mesons had mass. Feynman had not learned any of the language or the special techniques of this fast-growing field. Experiments were delivering data on the scattering of electrons by neutrons. Infinities again seemed to plague many plausible theories. Slotnick investigated two species of theory, one with "pseudoscalar coupling" and one with "pseudovector coupling." The first gave finite answers; the second diverged to infinity.

So Slotnick reported. When he finished Oppenheimer rose and asked, "What about Case's theorem?"

Slotnick had never heard of Case's theorem—and could not have, since Kenneth Case, a postdoctoral fellow at Oppenheimer's institute, had not yet publicized it. As Oppenheimer now revealed, Case's theorem proved that the two types of coupling would have to give the same result. Case was going to demonstrate this the next day. For Slotnick, the assault was unanswerable.

Feynman had not studied meson theories, but he scrambled for a briefing and went back to his hotel room to begin calculating. No, the two couplings were not the same. The next morning he buttonholed Slotnick to check his answer. Slotnick was nonplussed. He had just spent six intensive months on this calculation; what was Feynman talking about? Feynman took out a piece of paper with a formula written on it.

"What's that *Q* in there?" Slotnick asked.

Feynman said that was the momentum transfer, a quantity that varied according to how widely the electron was deflected.

Another shock for Slotnick: here was a complication that he had not dared to confront in a half-year of work. The special case of no deflection had been challenge enough.

This was no problem, Feynman said. He set *Q* equal to zero, simplified his equation, and found that indeed his night's work agreed with Slotnick. He tried not to gloat, but he was afire. He had completed in hours a superior version of a calculation on which another physicist had staked a major piece of his career. He knew he now had to publish. He possessed a crossbow in a world of sticks and clubs.

He went off to Case's lecture. At the end he leapt up with the question he had ready: "What about Slotnick's calculation?"

Schwinger, meanwhile, found the spotlight sliding away. Dyson's paper carried a sting—Dyson, who had seemed such an eager student the summer before. Now this strange wave of Dyson-Feynman publicity. As Schwinger said later with his incomparably sardonic obliqueness, "There were visions at large, being proclaimed in a manner somewhat akin to that of the Apostles, who used Greek logic to bring the Hebrew god to the Gentiles."

Feynman now presented his own logic in his own voice. He and Dyson appeared at a third and last small gathering of physicists, this time at Oldstone-on-the-Hudson, New York, the final panel of the triptych that had begun at Shelter Island two years earlier. He published an extended set of papers—they would stretch over three years and one hundred thousand words—that defined the start of the modern era for the next generation of physicists. After his path-integrals paper came, in the *Physical Review*, "A Relativistic Cut-Off for Classical Electrodynamics," "Relativistic Cut-Off for Quantum Electrodynamics," "The Theory of Positrons," "Space-Time Approach to Quantum Electrodynamics," "Mathematical Formulation of the Quantum Theory of Electromagnetic Interaction," and "An Operator Calculus Having Applications in Quantum Electrodynamics." As they appeared, the younger theorists who devoured them realized that Dyson had given only a bare summary of Feynman's vision. They felt invigorated by his images—beginning with the unforgettable bombardier metaphor in the positron paper—and by his way of insisting on the plainest statements of physical principles in physical language:

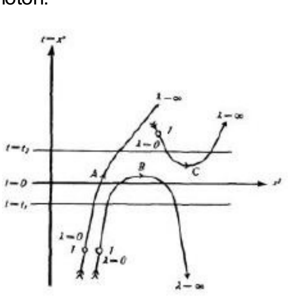
The rest mass particles have is simply the work done in separating them against their mutual attraction after they are created. . . .

How would such a path appear to someone whose future gradually became past through a moving present? He would first see …

No aspiring physicist could read these papers without thinking about what space was, what time was, what energy was. Feynman was helping physics live up to the special promise it made to its devotees: that this most fundamental of disciplines would bring them face to face with the primeval questions. Above all, however, to young physicists the diagrams spoke loudest.

Feynman had told Dyson, with a slight edge, that he had not bothered to read his papers. “Feynman and I really understand each other,” Dyson wrote home cheerily. “I know that he is the one person in the world who has nothing to learn from what I have written; and he doesn’t mind telling me so.” Feynman’s students, however, sometimes noticed what seemed to them an undercurrent of anger in the pointed comments he would make about Dyson. He had started hearing about Dyson’s graphs—irritating. Why *graphs*? he asked Dyson. Was that the mathematician in him, putting on airs?

Feynman’s space-time method had other antecedents besides Dyson’s graphs, as it happened. A 1943 German textbook by Gregor Wentzel contained a parallel depiction of a particle exchange process in beta decay. A Swiss student of Wentzel’s, Ernst Stückelberg, had developed a diagrammatic approach that even embraced the conception of time-reversed positrons; parts of this he published, in French, and parts were returned as unpublishable. (Wentzel himself was the unimpressed referee.) Their diagrams showed glimmerings of the style of visualization that Feynman now brought to fruition. His own full-dress version finally appeared in a paper he sent off in late spring 1949. “The fundamental interaction”—an image that would burn itself into the brains of the next generation of field theorists—showed two electrons interacting by exchanging a single photon.



Adiagram from a little-known 1941 paper of Ernst Stuckelberg, showing aversion of time reversal in particle trajectories.

He drew electrons as solid lines with arrows. For photons he used wavy lines without arrows: no directionality needed because the photon's anti-particle is itself. "The fundamental interaction" reinterpreted the basic textbook process of electromagnetic repulsion. Two negative charges, electrons, repel. A standard picture, showing lines of force or merely two balls pressing apart from each other, would beg the question of how an entity feels the force of another entity at a distance. It would imply that force can be transmitted instantly, when in truth, as Feynman's diagrams automatically made explicit, whatever carries force can move only as fast as light. In the case of electromagnetism, it is light—in the form of fugitive "virtual" particles that flash into existence just long enough to help quantum theorists balance their books.

These were space-time diagrams, of course, representing time as one direction on the page. Typically the past sat at the bottom and the future at the top; one way to read the diagram would be to cover it with a sheet of paper, pull the paper slowly upward, and watch the history unfold. An electron changes course as it emits a photon. Another electron changes course when it absorbs the photon. Yet even the idea that the earlier event is *emission* and that the later is *absorption* represented a prejudice about time. It was built into the language. Feynman stressed how free his approach was from customary intuitions: these events are interchangeable.

$$[(P_\mu - K_\mu)g^{\mu\nu}(P_\nu - K_\nu) + m^2c^2]\psi = 0.\text{''}$$

The Feynman diagram: "The fundam ental interaction." It is a space-time diagram: the progress of time is shown upward on the page. If one covers it with a sheet of paper and then draws the paper slowly upward:

•A pair of electrons-their paths shown as solid lines-move toward each other.

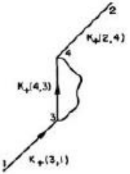
•When (6) is reached , a virtual photon is emitted by the right-hand electron (wiggly line), and the electron is deflected outward.

•At (5) the photon is reabsorbed by the other electron , and it, too, is deflected outward.

Thus this diagram depicts the ordinary force of repulsion between two electrons as a force carried by a quantum of light. Because it is a *virtual* particle, coming into existence for a mere ghostly instant, it can temporarily violate the laws that govern the system as a whole—the exclusion principle or the conservation of energy, for example. And Feynman noted that it is arbitrary to think of the photon as being emitted in one place and absorbed in the other: one can say just as correctly that it is emitted at (5), travels *backward* in time, and is then (earlier) absorbed at (6).

The diagram is an aid to visualization. But it serves physicists mainly as a bookkeeping device. Each diagram is associated with a complex number, an *amplitude* that is squared to produce a probability for the process shown.

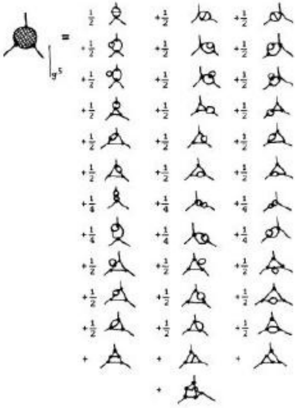
In fact each diagram represented not a particular path, with specified times and places, but a sum of all such paths. There were other simple diagrams. He represented the self-energy of an electron—its interaction with itself—by showing a photon line returning to the same electron that spawned it. There was a grammar of permissible diagrams, corresponding, as Dyson had emphasized, to the permissible mathematical operations. Still, the diagrams could grow arbitrarily complicated, virtual particles appearing and disappearing in an intricate, recursive mesh. Feynman's first H-shaped diagram for interacting electrons was the only such diagram with one virtual photon. Drawing all the possible diagrams with two virtual photons showed how quickly the permutations grew. Each made a contribution to the final computation, and more complicated diagrams became enormously difficult to calculate. Fortunately the greater the complication the less the probability and the smaller, therefore, the effect on the answer. Even so, physicists would shortly find themselves agonizing over pages of diagrams resembling catalogs of knots. They found it was worth the effort; each diagram could replace an effective lifetime of Schwingerian algebra.



Self-interaction. It is necessary to sum the amplitudes corresponding tomany Feynman diagrams to add the contributions for every way an event can occur. The continual possibility of virtual particles materializing and vanishing causes increasing complexity. Here an electron interacts with itself, in effect- the self-energy problem that first troubled Feynman in his work with Wheeler. It emits and absorbs its own virtual photon.

Feynman diagrams seemed to depict particles, and they had sprung from a mind focused on a particle-centered style of visualization, but the theory they anchored—quantum field theory—gave center stage to the field. In a sense the paths of the diagrams, and the paths summed in the path integrals, were the paths of the field itself. Feynman read the *Physical Review* more avidly than ever in the past, watching for citations. For a while it was all Schwinger—a paper would be pages of glyphs and would culminate in a neat expression that Feynman felt he could simply have written down as a starting point. He was sure this could not last. It did not. Feynman's method, Feynman's rules, began to take over. In the summer of 1950 a paper appeared with small "Feynman diagrams" on the first page —"following the simplified methods introduced by Feynman." A month later came another: "a technique due to Feynman… . The calculation of matrix elements can be simplified greatly by use of the Feynman-Dyson methods." The unreasonable power of the diagrams in the hands of students frustrated some of the elders, who felt that physicists were waving a sword that they did not understand. As the flood of papers began to cite Feynman, Schwinger went into what he described as his retreat. "Like the silicon chip of more recent years, the Feynman diagram was bringing computation to the masses," he said. Later, people who overlooked the note of hoi polloi quoted this remark as though Schwinger had intended a tribute. He had not. This was "pedagogy, not physics."

> Yes, one can analyze experience into individual pieces of topology. But eventually one has to put it all together again. And then the piecemeal approach loses some of its attraction.



Making the increasingly precise calculations for which quantum electrodynamics became famous requi red formidable exercises in combinatorics.

Schwinger's students at Harvard were put at a competitive disadvantage, or so it seemed to their fellows elsewhere, who suspected them of surreptitiously using the diagrams anyway. This was sometimes true. (They revered him, though—his night-owl ways, his Cadillac, his theatrically impeccable lecture performances. They emulated his way of saying, "We can effectively regard …" and they tried to construct the perfect Schwinger sentence: one graduate student, Jeremy Bernstein, liked a prototype that began, "Although 'one' is not perfectly 'zero,' we can effectively regard …" They also worried about Schwinger's ability to materialize silently beside them at the lunch table; a group of his graduate students protected themselves with a conversational convention in which

Schwinger meant *Feynman* and *Feynman* meant *Schwinger*.)

Murray Gell-Mann later spent a semester staying in Schwinger's house in Cambridge and loved to say afterward that he had searched everywhere for the Feynman diagrams. He had not found any, but one room had been locked …

Away to a Fabulous Land

Bethe worried that Feynman was growing restless after four years at Cornell. There were entanglements with women: Feynman pursued them and dropped them, or tried to, with increasingly public frustration—so it seemed even to undergraduates, who knew him as the least professorial of professors, likely to be found beating a rhythm on a dormitory bench or lying supine and greasy beneath his Oldsmobile. He had never settled into any house or apartment. One year he lived as faculty guest in a student residence. Often he would stay nights or weeks with married friends until these arrangements became sexually volatile. He seemed to think that Cornell was alternately too large and too small—an isolated village with only a diffuse interest in science outside the confines of its physics department. Furthermore, Hans Bethe would always be the great man of physics at Cornell.

An old Los Alamos acquaintance, Robert Bacher, after serving on the new Atomic Energy Commission, was moving to Caltech, where he was charged with rebuilding an obsolete-looking physics program. He was swimming in a lake during a summer vacation in northern Michigan when Feynman's name came into his head. He rushed back to shore, tracked Feynman down by telephone, and within a few days had him there visiting.

Feynman agreed to consider Pasadena, but he was also thinking about possibilities even more faraway, exotic, and warm. South America was on his mind. He had gone so far as to study Spanish. Pan American Airways had opened the continent to American tourists on a large scale, jumping from New York to Rio de Janeiro in thirty-four hours for roughly the price of the fortnight-long ocean voyage, and the popular magazines were filling with sensual images: palms and plantations, hot beaches and gaudy nights. Carmen Miranda and bananas still dominated the travel writing.

There was a new note, too, of the apocalyptic fear that had dogged Feynman: the Soviet Union had demonstrated its first working atomic bomb in September 1949, and worries about nuclear war were entering the national consciousness and spurring a panicky civil defense movement. Emigrations to South America became an odd symptom. One of Feynman's girlfriends told him seriously that he might be safer there. John Wheeler said—by way of imploring Feynman to join work on a thermonuclear bomb—that he was estimating "at least a 40 percent chance of war by September."

When a Brazilian physicist visiting Princeton, Jayme Tiomno, heard that Feynman was flirting with Spanish, he had suggested a switch to Portuguese and invited him to visit the new Centro Brasiliero de Pesquisas Físicas in Rio for several weeks in the summer of 1949. Feynman accepted, applied for a passport, and left the continental United States for the first time. He did learn enough Portuguese to teach physicists and beseech women in their native language. (By the end of the summer he had persuaded one of them, a Copacabana resident named Clotilde, who called him *meu Ricardinho* in her mellifluous Portuguese, to come live with him in Ithaca—briefly.) Late the next winter he impulsively asked the centro to hire him permanently. Meanwhile he was negotiating seriously with Bacher. He had endured one too many days kneeling in cold slush as he tried to wrap chains around his tires. Caltech appealed to him. It reminded him of the other Tech, such a pure haven for the technically minded. Four years at a liberal-arts university had not softened his outlook. He was tired of "all the ins and outs of the small town and the bad weather," he wrote Bacher, and added, "The theoretical broadening which comes from having many humanities subjects on the campus is offset by the general dopiness of the people who study these things and by the Department of Home Economics." He warned Bacher about one of his weaknesses: he did not like having graduate students. At Cornell "poor Bethe" had ended up covering for him again and again.

> I do not like to suggest a problem and suggest a method for its solution and feel responsible after the student is unable to work out the problem by the suggested method by the time his wife is going to have a baby so that he cannot get a job. What happens is that I find

> that I do not suggest any method that I do not know will work and the only way I know it works is by having tried it out at home previously, so I find the old saying that "A Ph.D. thesis is research done by a professor under particularly trying circumstances" is for me the dead truth.

He had a sabbatical year coming. He was going to make his escape, one way or another.

Once (and it was not yesterday), a diligent student of field theory wrote later at Niels Bohr's institute in Copenhagen, *there lived a very young mole and a very young crow who, having heard of the fabulous land called Quefithe, decided to visit it. Before starting out, they went to the wise owl and asked what Quefithe was like.*

Owl's description of Quefithe was quite confusing. He said that in Quefithe everything was both up and down. Physicists need more than ideas and methods. They need a version of history, too, a narrative cabinet for ordering their bits of knowledge. So they create a legend of search and discovery on the fly; they turn hearsay and supposition into instant lore. They discover that it is hard to teach a pure concept without clothing it in at least a fragment of narrative: who discovered it; what problem needed solving; what path led from not knowing to knowing. Some physicists learn that there is such a thing as physicists' history, necessary and convenient but often different from real history. The fable of Quefithe—"*qu*antum *fi*eld *the*ory"—with a Schwinger mole and a Feynman crow, an owl resembling Bohr, and a fox like Dyson, lovingly satirized a story that had entered the community's store of self-knowledge as rapidly as the path integrals and Feynman diagrams: *If you knew where you were, there was no way of knowing where you were going and conversely, if you knew where you were going, there was no way of knowing where* you *were. . . .*

Clearly, if they were ever going to learn anything about Quefithe, they had to see it for themselves. And that is what they did.

After a few years had passed, the mole came back. He said that Quefithe consisted of lots of tunnels. One entered a hole and wandered through a maze, tunnels splitting and rejoining, until one found the next hole and got out. Quefithe sounded like a place only a mole would like, *and nobody wanted to hear more about it.*

Not much later the crow landed, flapping its wings and crowing excitedly. Quefithe was amazing, it said. The most beautiful landscape with high mountains, perilous passes and deep valleys. The valley floors were teeming with little moles who were scurrying down rutted paths. The crow sounded like he had taken too many bubble baths, and many who heard him shook their heads. The frogs kept on croaking "It is not rigorous, it is not rigorous!" … But there was something about crow's enthusiasm that was infectious.

The most puzzling thing about it all was that the mole's description of Quefithe sounded nothing like the crow's description. Some even doubted that the mole and the crow had ever gotten to the mythical land. Only the fox, who was by nature very curious, kept running back and forth between the mole and the crow and asking questions, until he was sure that he understood them both. Nowadays, anybody can get to Quefithe—even snails.