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Richard Feynman and the Pleasure Principle

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"Energy is eternal delight," the poet and painter William Blake declared, and the consummate physicist Richard Feynman—born in May 1918—embodied that credo as far as a human being can in his allotted earthly span. The modern world is sometimes called disenchanted, denuded of magic, because science has annihilated the invisible homeland of the spirits, where angels, demons, and God himself were believed to dwell. But Feynman spoke unabashedly of the wonders and miracles to be found in nature as modern science describes it; the physical world enchanted him because it gave him so much to think about. His mind cavorted as he unlocked some of nature's most daunting puzzles. The quantum world with its intricate bizarrerie, which upended the established order of classical physics indisputable since Newton, flummoxed an intelligence as monumental as Einstein's. But Feynman made himself comfortable there, as though it were his native habitat.

The secrets Feynman uncovered of the infinitesimal clarified the world of objects we can see and feel. He was a signature contributor to the theory of quantum electrodynamics (QED), describing the interaction of subatomic particles with light. From QED, one could derive "the basic rules for all ordinary phenomena except for gravitation and nuclear processes," as he explained in his *Lectures on Physics*, the text of the two-year introductory course he taught at Caltech in the early 1960s:

> …out of quantum electrodynamics come all known electrical, mechanical, and chemical laws: the laws for the collision of billiard balls, the motions of wires in magnetic fields, the specific heat of carbon monoxide, the color of neon signs, the density of salt, and the reactions of hydrogen and oxygen to make water are all consequences of this one law.

The world apparent to all is the starting point for the most arcane investigations of the privileged few. To look hard at every scene as it passes before your eyes, to examine every phenomenon and unpack its inner

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workings—physics unfolds from such boundless elemental curiosity. In the *Lectures*, Feynman describes the complex of sights and sounds that a person standing on the seashore experiences, and he proceeds to ask the consequent questions that constitute science's fundamentals:

> Is the sand other than the rocks? That is, is the sand perhaps nothing but a great number of very tiny stones? Is the moon a great rock? If we understood rocks, would we also understand the sand and the moon? Is the wind a sloshing of the air analogous to the sloshing motion of the water in the sea? What common features do different movements have? What is common to different kinds of sound? How many different colors are there?

These are the unsophisticated questions an intelligent child might ask; and Feynman as a child asked precisely such questions. A ball lying in his little red wagon would roll to the back when he pulled the wagon forward, and it would roll to the front when the wagon stopped. The little boy wanted to know why this happened. His father, a uniform salesman, who according to family lore said that if his first child were a boy he would be a scientist, explained to his son what inertia is, but added that nobody knows why it works as it does.

Feynman would learn not to trouble himself with the unanswerable question of why things ultimately are as they are, leaving that to philosophers and religious operatives, whom he thought pretty much useless. Describing what things are and how they work provided excitement enough, and truth enough, for a scientific devotee. The intellectual thrill of seeking—and sometimes discovering—the truth was the medium in which he thrived. He proselytized for the modern scientific project, not as the conquest of nature for the relief of man's estate but as the effort to understand nature for the joy of knowing. As he insisted in *The Meaning of It All: Thoughts of a Citizen-Scientist*, a series of lectures given in 1963, "You cannot understand science and its relation to anything else unless you understand and appreciate the great adventure of our time. You do not live in your time unless you understand that this is a tremendous adventure and a wild and exciting thing." The great adventure had nothing to do with social, moral, or medical benefit; it gloried in exploration for its own sake. Feynman fairly scoffed at the journalistic proclivity to relate every scientific advance to a possible cure for cancer. Even after he was diagnosed with two rare types of cancer whose combined strength would bring him down, he never resorted to special pleading for himself or his fellow sufferers, and there was no evident change in his thinking about the ultimate purpose of science. He would recall the nonpareil mathematician John von Neumann, a colleague on the Manhattan Project, telling him that he was not responsible for the condition of the world. He found this insight—apolitical, perhaps even amoral, and inimical to the beliefs of such scientific colossi as Einstein and J. Robert Oppenheimer, Marie Curie and Linus Pauling and James D. Watson—profoundly liberating. He was free to search the universe for whatever knowledge it might yield, and there was nothing else that drove him with a comparable passion.

As much as he despised philosophy, and especially ancient philosophy, Feynman was willy-nilly a descendant of Epicurus, the philosophical champion of pleasure. Though Feynman's pursuit of pleasure was more frenetic than that of the tranquil garden-dweller, both found political life deeply displeasing compared to the joys of the life of the mind and the liberating thought that all is matter. Feynman begins his famous lectures on physics by noting that "all things are made of atoms"—a characteristically Epicurean doctrine, and to Feynman the most important single statement of scientific knowledge. And like the ancient philosopher, he saw in natural science a way to refute received religious ideas and to accept the inherent meaninglessness of the universe. In a 1959 television interview that the station deemed morally objectionable and decided not to air, Feynman offered this perspective of the moral conflicts and travails of humanity:

> It doesn't seem to me that this fantastically marvelous universe, this tremendous range of time and space and different kinds of animals, and all the different plants, and all these atoms with their motions and so on, all this complicated thing can merely be a stage so that God can watch human beings struggle for good and evil—which is the view that religion has. The stage is too big for the drama.

Religion held no appeal for Feynman, to put it delicately. Displays of piety could provoke him to rage. At his father's graveside, he fell into a snit at the rabbi's prayers, which he believed went unheard by the God who wasn't there. Afterward he fulminated at the hypocrisy of observing religious proprieties for a man who was an atheist. Despite Feynman's transportive rapture at the wonder and miracle of nature, nature's God never entered the picture. Feynman believed in the mind, not in the soul.

And yet he was given to raptures that were not purely intellectual. He was no thinking engine but a man of acute sensibility. In the *Lectures on Physics*, he exults in "the most remarkable discovery in all of astronomy… that *the stars are made of atoms of the same kind as those on the earth.*" Then he jumps to a footnote that berates modern poets for ignoring the beauty of the universe as revealed by science:

> Poets say science takes away from the beauty of the stars—mere globs of gas atoms. Nothing is "mere." . . . For far more marvelous is the truth than any artists of the past imagined! Why do the poets of the present not speak of it? What men are poets who can speak of Jupiter if he were like a man, but if he is an immense spinning sphere of methane and ammonia must be silent?

A modern poetry adequate to the task must do justice to the achievement of the modern scientific mind, which in Feynman's view has allowed us to understand and thus to truly appreciate nature for the first time. When a sensitive lady took exception to some derogatory remarks about poetry that Feynman made in the *Los Angeles Times*, she sent him W. H. Auden's poem "After Reading a Child's Guide to Modern Physics" to prove that poets pay attention to science:

> This passion of our kind
> For the process of finding out
> Is a fact one can hardly doubt,
> But I would rejoice in it more
> If I knew more clearly what
> We wanted the knowledge for.

Feynman, a self-confessed and unapologetic philistine, responded with a crisp dismissal, accusing Auden of aesthetic malfeasance—"lack of response to Nature's wonders." "We want [scientific knowledge] so we can love Nature more. Would you not turn a beautiful flower around in your hand to see it from other directions as well?"

"Whither is fled the visionary gleam?" Wordsworth asked about the fleeting glories of childhood amazement at nature's beauty. Feynman enjoyed the immense good fortune of never losing that childlike wonder, even as he pursued a vocation of surpassing intellectual rigor. Physics was the greatest fun in the world. Feynman was *homo ludens*, the man at play even in his most serious undertakings, his work unalloyed pleasure, its difficulties sporting challenges eagerly embraced.

The Magic of Thinking, Simply

Feynman started young and never stopped. As a small boy in Far Rockaway, New York, he put together a makeshift "laboratory," a "collection of wires, batteries and other electrical bits and pieces," as John and Mary Gribbin describe it in their biography *Richard Feynman: A Life in Science* (1997). Not only did he hire his three-year-old sister, Joan, as his lab assistant for two cents a week, he made her "his first student," as she put it—teaching the young girl arithmetic, later introducing her to astronomy, and schooling her in centrifugal force by whipping around a glass of water without spilling. His inspired student would earn a Ph.D. in physics and become a researcher for NASA. For Feynman, teaching was a natural extension of learning, and he would be renowned as a master lecturer at Caltech.

Feynman had to know how things work, for the physical world was a splendid puzzle that demanded solving. Not averse to earning some pocket change with his passion for mechanical things, the young boy fixed radios for his neighbors. One radio that started up with a tremendous roar and wobble before calming itself and playing right required more than the usual consideration. The customer saw Feynman walking back and forth instead of taking the radio apart right away, and he told the kid that he must not know what he was doing. The imperturbable boy answered, "I'm thinking!" Feynman thought some more, then proceeded to reverse the order of the tubes—and the radio played perfectly. The skeptic was now a true believer. As Feynman tells the story in his bestselling memoir of vignettes, *"Surely You're Joking, Mr. Feynman!": Adventures of a Curious Character* (1985), the neighbor then "got me other jobs, and kept telling everybody what a tremendous genius I was, saying, 'He fixes radios by *thinking!*' The whole idea of thinking, to fix a radio—a little boy stops and thinks, and figures out how to do it—he never thought that was possible."

Young Feynman performed feats of mind, especially with numbers, that many thought impossible—and that *were* impossible, for them. In high school, he derived proofs by methods quite different from the provided textbooks—a practice he would uphold throughout his career, often not troubling to read the published literature on a question but beginning his inquiries from first principles, conducting his investigations along his own lines. He became the superstar of the high school algebra team, adept at solving knotty problems against the stopwatch's unforgiving minute. "It was practically impossible to do the problem in any conventional, straightforward way.... So you had to think, 'Is there a way to *see* it?' Sometimes you could see it in a flash, and sometimes you'd have to invent another way to do it and then do the algebra as fast as you could." Early on, Feynman developed the habit of approaching every problem in his own way, and he would be known for seeing in a flash what other quite brilliant minds had tried and failed to grind out slowly. He was a prodigy of intuition, and he honed his skills by practice: He trained himself to be preternaturally intuitive, exercising his phenomenal ability to envision spatial and numerical relationships until it worked like sorcery.

Feynman's magic was later memorialized by his awestruck colleagues, to whom "reasoning" hardly sounded like the word to describe his uncanny approach to settling intractable questions. He would summon the answers from the vasty deep, and they would come. A Cornell colleague, the mathematician Mark Kac, would later write,

> ...there are two kinds of geniuses: the "ordinary" and the "magicians." An ordinary genius is a fellow that you and I would be just as good as, if we were only many times better. There is no mystery as to how his mind works....It is different with the magicians. They are, to use mathematical jargon, in the orthogonal complement of where we are and the working of their minds is for all intents and purposes incomprehensible. Even after we understand what they have done, the process by which they have done it is completely dark....Richard Feynman is a magician of the highest caliber.

In *Genius: The Life and Science of Richard Feynman* (1992)—as elegantly written a scientific biography as one will ever read—James Gleick relates a comic homage to Feynman's gifts by Nobel laureate Murray Gell-Mann, who for years had an office down the hall at Caltech from Feynman: "Dick's methods are not the same as the methods used here....Dick's method is this. You write down the problem. You think very hard. (He shuts his eyes and presses his knuckles parodically to his forehead.) Then you write down the answer." Magic.

As a college student at M.I.T.—Feynman's first choice, Columbia, with its odious Jewish quota, turned him down—he performed superbly. He went in thinking he would be a math major but decided the only careers such a degree would prepare him for were teaching the subject or working as an insurance actuary. He then considered electrical engineering before finally settling on physics. While still an undergraduate, he secured his first publication with an article on cosmic rays, which he co-wrote with a professor. He was also a most extraordinary mathematician, recruited to join the three-man M.I.T. team for the prestigious intercollegiate Putnam competition. Feynman was back in his fraternity house while the other competitors were still sweating it out. He scored so much higher than anyone else that the examiners' jaws dropped. As the top finisher, he won a scholarship to Harvard for graduate school, but turned it down for Princeton.

Princeton had its doubts about accepting Feynman. His math score on the GRE was the best the admissions committee had ever seen, and his physics score perfect—but the history, literature, and fine arts scores bordered on the imbecile.

And then there was the question of what may euphemistically be called his character. Waspish Princetonians had little love in their hearts for Jews. The M.I.T. professors writing Feynman's testimonials took pains to emphasize that he was the *right* kind of Jew, or at least not the wrong kind: his "physiognomy and manner" were unexceptionable, one of his referees felt obliged to attest.

The danger with a Jew as talented and single-minded as Feynman was of course that he would be offensively ambitious. Thomas Wolfe, a leading novelist of the era (not to be confused with Tom Wolfe of *The Right Stuff* fame), weighed in on the Jewish problem in American science: as relayed by Gleick, "Wolfe, himself despising the ambition of 'the Jew boy,' nevertheless understood the attraction of the scientific career: 'Because, brother, he is burning in the night. He sees the class, the lecture room, the shining apparatus of gigantic laboratories, the open field of scholarship and pure research, certain knowledge and the world distinction of an Einstein name.'" In the end, Princeton made the right intellectual and moral choice—and now ambitious young scientists burn for the world distinction of a Feynman name.

Advancing Waves

At Princeton, Feynman would lay the groundwork for his later achievements in the theory of quantum electrodynamics, and in so doing would perform the signal service of making quantum mechanics almost intelligible to ordinary minds. His doctoral thesis adviser, John Wheeler—a "theoretical gunslinger unafraid of the most outrageous ideas—told Einstein even before the thesis was finished that his student had seen his way to the most lucid and elegant description of the most elusive phenomena: "How could one ever want a simpler way to see what quantum theory is all about!"

The biography by John and Mary Gribbin provides a gracefully succinct account of Feynman's doctoral work, which I will condense. At M.I.T., Feynman had already been richly perplexed by the question of the "self-energy" of the electron—the way an electron interacts with itself because of its own field of force. All-but-indisputable theory had it that the strength of the interaction between particles is inversely proportional to the square of the distance between them. This is the same mathematical relation that governs how a light brightens as you draw near it: Every time you halve your distance, the light appears twice as bright. The perplexity occurs because the electron is a point charge, with a radius of zero. To calculate the strength of the field at the electron itself—its self-energy—one would divide by zero, and get an answer of infinity. In the light analogy, to fully reach the light source, you would halve your distance an infinite number of times—meaning the light would double in brightness an infinite number of times, and be infinitely bright. If the electron has infinite energy, it would also, because $E = mc^2$, have infinite mass. Both conclusions are impossible.

As the Gribbins write, "even though the field concept lay at the heart of physics"—and dictated that every particle interacts with itself—Feynman's initial move was to reject it. But he realized that he could not readily do so, for to eliminate the field, and thereby an electron's self-interaction, would also eliminate its *radiation resistance.* Radiation resistance describes how a particle's charge gives it greater inertia, meaning it is harder to move than if the particle had no charge. This is an observed reality—it is part of what makes radio possible—and some type of action on the particle was needed to account for it. Aiming to get rid of self-interaction in a field while saving radiation resistance, Feynman imagined "a universe in which there were only two electrons," which interact at a distance. If one electron shakes, the second electron shakes in response. The second electron's shaking then causes the first electron to shake some more—so there is an interaction between the electrons that might explain radiation resistance.

But Wheeler pointed out the fatal flaw with Feynman's theory: Like light shining from a bulb to a mirror and then bouncing back, the forces would have to travel the distance between the two electrons. It would thus take some time for the first shaking electron to eventually affect its own motion. But radiation resistance, like inertia, is instantaneous. Feynman's theory had a delay that somehow must be closed.

So Wheeler suggested an unconventional modification of Feynman's theory. James Clerk Maxwell's fundamental equations for electromagnetic waves have two possible solutions. The common solution describes a wave that moves away from its source at the speed of light. The other solution also describes a wave that moves away from its source at the speed of light—but *backward* in time. This solution can also be described—if no less strangely—using normal forward time: Instead of beginning at the time and place of emission, the wave begins in the past and at a distance, then moves *toward* the source, arriving at the source at the time of emission. The common kind of waves are called "retarded waves," as they arrive at a destination after they are emitted, as one might naturally expect them to do. The time-defying waves, which arrive *before* they are emitted, are called "advanced waves." One has to bend one's natural reason into an unnatural shape to think about, if not quite accept, advanced waves—and understandably, the Gribbins write, they were "usually ignored" as a solution to Maxwell's equations.

But Wheeler proposed that advanced and retarded waves together might close the vexing time gap in Feynman's theory. Feynman set about determining the precise combination that would be necessary to produce the right amount of radiation resistance. The answer, once revealed, was simple: When an electron is shaken, it emits advanced and retarded waves of equal amplitude. This mind-bending answer works because the advanced wave caused by shaking the electron arrives at the second electron *before* the first electron is shaken. This advanced wave shakes the second electron, creating another advanced wave and another retarded wave. The retarded wave travels to the first electron, forward in time—traversing the distance over the exact same span of time as the original advanced wave. Thus the retarded wave arrives at the precise moment that the first electron is shaken, creating the force that causes the instantaneous radiation resistance effect. The overall combination of waves also generates the common solution to Maxwell's equations, a wave that propagates from first electron to second electron and back in normal delayed forward time. Meanwhile, the two time-reversed waves, which are a half-cycle out of phase, cancel each other out at all prior points. So causality is violated in theory—but the total amount of violation is zero, allowing causality to be preserved in reality.

As the Gribbins summarize, the Wheeler–Feynman theory of radiation—sometimes called the "absorber theory," because the absorbing electron might be said to govern radiation emission—"describes the interaction between two charged particles in terms of waves moving forwards and backwards through time." The theory works not only for the special case of the imaginary two-particle universe but for the universe as it really exists. "All of conventional electrodynamics could be written in this new and mathematically simple way, without involving electromagnetic waves or fields at all, provided you were open-minded enough to accept the reality of interactions that travelled backwards in time."

The next step for Feynman was configuring a quantum-mechanical form of the theory, which also dispensed with fields and dealt with interaction at a distance between electrons. Wheeler was working on this as well—but found himself stymied where his student roared along. Feynman would reconceive quantum mechanics by adapting a method of calculation from classical mechanics that he had learned in high school: the Lagrangian method, named after the French mathematician Joseph-Louis Lagrange. The Lagrangian method was founded on the "principle of least action," which holds that an object moving through space follows the path that requires the least *action*, with "action" roughly describable as the total amount that the object interchanges its kinetic and potential energy as it moves. (More precisely, action is the integral over time of an object's kinetic energy minus its potential energy.)

Imagine throwing a baseball to a friend who's the same height as you, and think back for a moment to the high-school physics concepts of kinetic and potential energy. At the moment you first toss the ball, it has entirely kinetic energy and no potential energy. As the ball travels, it slows down, losing kinetic energy, which transfers into greater potential energy as the ball rises higher. At the highest point, when the ball is suspended for an infinitesimal moment, it has no kinetic energy and entirely potential energy. The process plays out in reverse as the ball falls into your friend's hand. Throughout, the energy is changing back and forth between kinetic and potential. But why does the ball follow the particular arcing path that it does? Why not, say, a shallower arc initially, then a steeper arc at the end? Or a pyramid-shaped path? Roughly speaking, the principle of least action explains the ball's actual path—a parabola—in terms of its smoothness. The other kinds of paths would be too jerky and abrupt, involving more "effort" by nature than necessary to transfer the kinetic and potential energy back and forth. The principle explains why a baseball thrown—or any moving object in classical physics—seems to "know" from the start the only path it must travel.

The vexing problem was that, to solve this equation generally for all particle motion, you not only have to solve an integral for some known path, but to *find* the path with the smallest integral. That means figuring out how to solve integrals not to produce a single numerical quantity, but a mathematical description of an entire path, selected out of all possible paths. "That," Feynman later said in his lectures, "is a completely different branch of mathematics. It is not the ordinary calculus."

Feynman's penetrating revelation, which followed his discovery of an inconclusive but suggestive article by Paul Dirac, and which came when he was lying sleepless in bed, translated the Lagrangian method into the language of spacetime. To calculate the path a particle takes from one point in spacetime to another, you must indeed reckon every possible path (or "history") the particle could take. To do this, Feynman used what would become known as the "sum over histories" or "path integrals" approach. The Gribbins explain it this way: Where, roughly speaking, the least action in Lagrangian mechanics yields the integral (or sum) of all individual parts along one trajectory, "the path integral approach extends this to include all possible trajectories" and sums them up.

Feynman's novel approach yielded the same mathematical results as the two other established approaches to quantum mechanics (by Schrödinger and Heisenberg) but was more widely useful in some respects. And, as the Gribbins write, "It is also both relatively simple to use and clearly tied… to the understanding of classical mechanics developed since the time of Newton." Feynman's innovative thesis, his proud advisor, Wheeler, declared, defined the watershed where "quantum theory for the first time became simpler than classical theory." Of course, there is simple and then there is simple. The mathematics involved is impossibly abstruse to someone with only a nodding acquaintance with calculus. But to the well-schooled mind Feynman's work is said to be of a pristine clarity.

The Bomb, and a Love Lost

War would intrude on Feynman's ivory-tower idyll, as his knowledge of the subatomic world was commandeered to serve a world-altering purpose few had foreseen. When physicist Leo Szilard explained to Einstein how a nuclear chain reaction could be harnessed to make a bomb of devastating force, the innocent wizard exclaimed, "I never thought of that!" Some of the most gifted physicists in the world would presently be thinking of little else.

Modern warfare is fought with the most modern machinery, and physicists were indispensable to its design; by December 1941, when the United States entered the Second World War, "one-fourth of the nation's seven-thousand-odd physicists had joined a diffuse but rapidly solidifying military-research establishment," Gleick writes. The previous summer, Feynman had already been employed on a project at the Frankford Arsenal to sharpen the aim of artillery fire. The work hadn't excited him. So when the Princeton physicist Robert Wilson sought to recruit Feynman for the project to make a nuclear bomb, Feynman told him he wasn't interested—his doctoral dissertation was his priority.

It took Feynman only a few hours to change his mind. The threat to civilization was too grave to allow him to shirk his duty. He shortly began work as the smarter half of a two-man team on Wilson's operation at Princeton to manufacture the volatile isotope uranium-235 from the stable uranium-238. The authorities shut down the Princeton project a year later, judging a competing device developed at Berkeley to be superior. In fact, Gleick contends, the Princeton team's idea "promised a yield many times greater. Feynman had produced detailed calculations for the design of a vast manufacturing plant.... He took into account everything from wall-scrapings to uranium that would be lost in workers' clothing. He conceived arrays of several thousand machines—yet that proved a modest scale, in light of the later reality."

Feynman would prove an integral agent in the development of the later reality, taking significant part in the Manhattan Project at Los Alamos under the scientific direction of J. Robert Oppenheimer. In December 1942, Enrico Fermi had successfully run the first artificial nuclear chain reaction at the University of Chicago—an exceedingly slow reaction, taking four and a half minutes, while the bomb would have to go off in less than a millionth of a second. To proceed from Fermi's ponderous pile of uranium and graphite to the compact, fast-twitch explosive could not be done by gradual increments. Superb and daring theoretical minds would have to calculate the essential dynamics of an explosion that could not be iteratively tested by experiment. Gleick summarizes Feynman's own summary of the questions needing answers, including the size of the two bomb types to be designed; the critical mass of uranium for the first type and plutonium for the second; the optimal materials for the tamper, the device that would reflect released neutrons back into the core, intensifying the explosion; the necessary purity of the radioactive materials; the heat, light, and shock the blast would produce. "Most of what was to be done was to be done for the first time," Feynman would write anonymously in the bomb's official history.

Feynman was assigned to the Theory Division under the German-Jewish exile Hans Bethe, the world's leading authority on nuclear physics, whose 1938 description of the fusion reactions that keep the sun burning would win him the Nobel Prize. The Bethe–Feynman formula for determining the energy released by a nuclear weapon became canonical. In the early going, Bethe set Feynman the problem of pre-detonation—the possibility of a premature chain reaction that would cause a chunk of fissile material to tear itself apart instead of reaching a full detonation. Naturally, no one had given much thought before to the dynamics of how matter holds together when it's on the verge of a nuclear explosion that will blow it apart. When a problem appeared insoluble, Feynman was the man to turn to. He identified the crucial factor as intermittent sudden outbursts of neutron activity, rising to a crescendo and then petering out. As Gleick writes, “He arrived at a practical method that reliably computed the chances of any premature reaction taking hold.”

Working on a closely related problem, he also headed the group in charge of understanding diffusion—the question of how neutrons scatter and collide to set off fission. This also unprecedented question turned out to have a characteristic Feynman answer. Using an approach he had worked out for his doctoral dissertation and to which he would again return, Feynman found that the course each particle takes could be computed as the sum of all possible paths the particle could take.

The endlessly resourceful Feynman made himself indispensable; Bethe once declared that “Feynman could do anything, anything at all.” He went on to tell how Feynman took over a group in charge of using IBM “calculating machines” and made the computers give swift and correct answers where others had failed. Moreover, Feynman and a colleague put the calculators together—the parts for each one arrived in about ten boxes—and astonished the IBM specialists who had never seen laymen do that job, much less do it perfectly. Edward Teller, later the founding father of the hydrogen bomb, tapped Feynman to lecture his colleagues on the theoretical and practical fundamentals of atomic bomb design and construction. Oppenheimer himself praised Feynman lavishly: “He is by all odds the most brilliant young physicist here, and everyone knows this. He is a man of thoroughly engaging character and personality, extremely clear, extremely normal in all respects, and an excellent teacher with a warm feeling for physics in all its aspects.”

As Oppenheimer’s encomium suggests, Feynman was more than a brilliant scientist; he was a charming figure, and his playful temperament was essential to his success and the success of the project. The group leader encouraged inventive unorthodoxy in his subordinates, always trying to figure out the shrewdest angle from which to attack a problem, however unlikely the double bank shot might at first appear. While he inculcated the habit of successful innovation, he also came down hard on any but the best work. And the mood of intellectual play found its place in the fifteen-hour work days of this most solemn enterprise. He loved every challenge, and all could see and share his pleasure. Superior rank never intimidated him: He would laugh and tell Bethe and Niels Bohr they were crazy when they proposed wrong-headed ideas, and the grandees were often grateful to have a junior colleague not only so devastatingly acute but also so audacious.

Feynman got away with his antic irreverence because he was almost always right. Bohr, grand panjandrum of the quantum world, reportedly said of Feynman (as Feynman recalled it in his own characteristic style), "He's the only guy who's not afraid of me, and will say when I've got a crazy idea. So *next* time when we want to discuss ideas, we're not going to be able to do it with these guys who say everything is yes, yes, Dr. Bohr. Get that guy first, we'll talk with him first." To Feynman the sole recognized authority was the truth, and he accorded every participant in a conversation only the deference his or her latest idea merited.

Feynman did it all while his beloved wife was dying of lymphatic tuberculosis in an Albuquerque sanitarium a hundred miles away. Arline Greenbaum had been his one true love since he was fifteen years old, and he had married her despite the strenuous opposition of his mother, who feared Arline's illness would so burden Feynman that his work would suffer. Nearly every weekend he would borrow a car or hitchhike to see his wife. Writing to each other almost daily, they would relate the day's small events, taunt the censors with clever end-runs around the regulations, rhapsodize about the wonderful life they would have together when Arline recovered, speak passionately of love and death when it became apparent she would not.

Streptomycin came into use just too late to save Arline. Feynman was with her during her final hours in June 1945. When she died, the nurse wrote down the time, 9:21 p.m., and Feynman noticed that the clock on the bedside table had stopped precisely then. While many people would be dumbstruck by this apparent manifestation of the uncanny or the supernatural, Feynman reasoned coolly that he had already had to repair the clock several times, and it must have just broken down suddenly when the nurse picked it up for a close look in the dimly lit room.

Cool reason informed his part in the general jubilation at the triumphant test of the bomb, a month to the day after Arline's death. He was the only person to view the explosion with the naked eye. Everyone else put on dark welder's glasses, but he sat in a truck knowing that the windshield provided adequate protection against ultraviolet light. In a letter to his mother about the test, written three weeks later (just after Hiroshima), he described a ravishing aesthetic experience of almost hallucinatory intensity, which he elucidated by scientific observation. The sight quickly gave way to cheers and business: "When we got back I had the fun of telling lots of people about it.…They were all proud as hell of what they had done. Maybe we can end the war soon. It was too much to hope. We went back to work."

They did end the war in a hurry, but later that year the fear that cataclysmic nuclear war was inevitable struck him as he was sitting in a New York City restaurant: "I looked out at the buildings and I began to think, you know, about how much the radius of the Hiroshima bomb damage was and so forth.... All those buildings, all smashed—and so on. And I would go along and I would see people building a bridge, or they'd be making a new road, and I thought, they're *crazy*, they just don't understand, they don't *understand*. Why are they making new things? It's so useless."

QED—Or, How to See the Wiggle of the Path

The war over, Feynman took a teaching job at Cornell, as Bethe was there. Grief over the deaths of his wife and his father, as well as the prospect of universal annihilation, inhibited his customary irrepressible brio. Bethe, however, would say, "Feynman depressed is just a little more cheerful than any other person when he is exuberant." All the same, Feynman began to doubt his powers.

When in 1946 the Institute for Advanced Study in Princeton, the most exclusive intellectual enclave in the known world, offered him a position, he turned it down, convinced of his unworthiness, believing himself weighed down under other people's unrealistic expectations. Brooding did not suit him, however, and he made the decision not to concern himself about doing path-breaking work. As he writes in *"Surely You're Joking, Mr. Feynman!"*:

> Then I had another thought: Physics disgusts me a little bit now, but I used to *enjoy* doing physics. Why did I enjoy it? I used to *play* with it. I used to do whatever I felt like doing—it didn't have to do with whether it was important for the development of nuclear physics, but whether it was interesting and amusing for me to play with.... So I got this new attitude.... I'm going to *play* with physics, whenever I want to, without worrying about any importance whatsoever.

Days after this avowal, in the cafeteria he saw someone toss a plate into the air. Noticing how the plate wobbled as it spun, he set to calculating the relation between wobble and rotation, just for fun—and the wobbling plate led him back to the questions his doctoral thesis had raised about the "principle of least action" that governs the paths of moving objects, including subatomic particles under quantum mechanics. "It was effortless. It was easy to play with these things. It was like uncorking a bottle: Everything flowed out effortlessly." Significance was irrelevant; ambition was irrelevant; there was no burning for a name like Einstein's; what mattered was the pleasure of figuring things out. Feynman's renewed sense of play directed him in Nobel Prize–winning work for his contribution to the theory of quantum electrodynamics, or QED, which describes the interaction between matter and light in the subatomic realm.

The experimental impetus for reconsidering the path of particles in quantum mechanics came from a 1947 discovery by Willis Lamb, a Columbia University physicist who would be awarded a Nobel Prize of his own. Lamb had tried to measure the energy of the hydrogen atom's electrons and found a gap between energy levels that the prevailing quantum theory predicted should not exist—a gap that came to be known as the Lamb shift.

The young Harvard marvel Julian Schwinger, Feynman's most precocious contemporary, produced in short order a blockbuster theory to fit the new findings—a construction of the most forbidding mathematics. But Feynman had his own ways of handling mathematical difficulty that relied on intuitive apprehension of physical reality, even when the physics seemed unreal on the face of it. Gleick cites an interview in which Feynman described the connection between visualizing the path of an electron or photon and translating the motion into mathematical notation:

> 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.... 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.

For Feynman, coming to clarity involved febrile intuition approaching visionary delirium. He would also see "the character of the answer.... 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." Yet he also devised the most efficient method of compacting the mathematics of subatomic particle motion into a picture: Feynman diagrams.

In *QED: The Strange Theory of Light and Matter*, a lecture series Feynman gave at UCLA in 1983 that describes the QED theory without the incomprehensible equations, Feynman states that there are three basic actions in physics that account for "all the phenomena of light and electrons": A photon goes from point to point in spacetime; an electron goes from point to point in spacetime; and "an electron emits or absorbs a photon—it doesn't make any difference which. I will call this action a 'junction,' or 'coupling.'"

Feynman diagrams are able to depict all of these basic actions, rendering the complex interactions of subatomic particles with simple visual cues. A particle's movement in space is drawn on the horizontal axis, its movement in time on the vertical axis. Line segments, often with directional arrows, depict the motions of electrons and positrons, sometimes careening off into the void; wiggly lines intersecting with the straight ones show photons given off or absorbed by the electrons or positrons. Positrons? How can those enter in? The positron—its existence first hinted at by Paul Dirac in 1928, then proved experimentally by Carl Andersen in 1932—is the antimatter counterpart to the electron, and has a positive charge equal to the electron's negative one. Confoundingly and ingeniously, Feynman pictured it in the diagrams as an electron traveling backward in time.

In quantum physics, the probability that an event *might* happen has superseded the classical certainty that it *will* happen. "Yet science has not collapsed," Feynman insists, with a wink. Describing his diagrams, he exclaimed, "It is absolutely ridiculous: All we do is draw little arrows on a piece of paper—that's all!" But his arrows made possible a way of representing the sum over histories, or path integral, of all possible paths by which particles and photons interact in a given system, so that calculating the probabilities of their paths can be done with an ease that seems almost impossible. QED expresses the quantum-theoretical principle that a beam of light traverses every possible path; yet it also upholds as predictively accurate the classical model—that a light wave travels in straight lines, that it reflects off a mirror at the same angle that it came in, and that a lens focuses it.

Feynman called QED "the jewel of physics—our proudest possession." His version of it demonstrated a method of describing and computing the phenomena far simpler than Schwinger's, and the Feynman diagrams would become the accepted tools for QED and much besides. Of course, nothing in quantum theory can stay so simple. Newly discovered interactions—and there were many more—added loops upon loops to the configurations, whose complexity increased precipitously. As Gleick writes, "physicists would shortly find themselves agonizing over pages of diagrams resembling catalogs of knots." Yet "they found it was worth the effort; each diagram could replace an effective lifetime of Schwingerian algebra." Schwinger would later say derisively that "like the silicon chip of more recent years, the Feynman diagram was bringing computation to the masses." For his work, Feynman would share the 1965 Nobel Prize in Physics with Schwinger and the Japanese theorist Shinichiro Tomonaga.

In 1951 Feynman moved on from Cornell—where he found the winters disagreeably frigid and the liberal arts professoriate intellectually shriveled—to Caltech, where he found the weather and the company always agreeable, and where he would remain as a professor for the rest of his life. His biographers agree that his work there on at least three other theories was of Nobel quality—in Gleick's words, "a theory of superfluidity, the strange, frictionless behavior of liquid helium; a theory of weak interactions, the force at work in radioactive decay; and a theory of partons, hypothetical hard particles inside the atom's nucleus, that helped produce the modern understanding of quarks."

Feynman's mind was one of improbably fecund restlessness, and he turned it to questions that flew at him from every direction. Gleick eulogizes the untiring energies with which Feynman went about investigating most any problem that bounced his way: He studied "friction on highly polished surfaces" in a mostly unsuccessful effort to understand friction plain and simple; theorized inconclusively about the effect of wind on ocean waves; peered into atomic forces that affected the elasticity of crystals; contended mightily with turbulence in gases and liquids, but was defeated; and made significant headway on the quantum theory of gravitation, but like Einstein before him failed to crack the problem. He also did important work in molecular biology on viral mutations "that suppressed each other within the same gene," and as early as 1959 foresaw immense possibilities for nanotechnology, offering thousand-dollar prizes from his own pocket, one for "the first microscope-readable book page shrunk 25,000 times in each direction, and one for the first operating electric motor no larger than a 1/64th-inch cube."

The eclectic list of partial victories, honorable draws, and decisive failures serves to highlight the scope of his interests and the abundance of his talents. In an age of intellectual specialization to the point of sclerosis, Feynman was the rare universal man of science, an unabashed cerebral hedonist out for all the pleasure that knowing the physical world would yield to him.

The Scientist Versus the Bureaucrats

On January 28, 1986, the space shuttle *Challenger* exploded in mid-air seventy-three seconds after takeoff from the Kennedy Space Center in Florida. It carried a crew of seven people, including Christa McAuliffe, a schoolteacher who, as Gleick puts it, had been "the winner of a NASA public-relations program meant to encourage the interest of children and also congressmen." The government was rattled and roused by this catastrophe, and President Reagan appointed a commission to investigate the failure of the craft and to recommend correction. The fourteen-person panel included William P. Rogers, the chairman and a former attorney general and secretary of state; such high-flying celebrities as Neil Armstrong, Sally Ride, and Chuck Yeager, the former test pilot (indeed of *The Right Stuff* fame); a host of airspace industry executives; Air Force Major General Donald J. Kutyna, shuttle program director for the Department of Defense; and Richard Feynman.

Feynman, an eleventh-hour addition, had been asked to serve by NASA's acting administrator, William R. Graham, who had been a student of his at Caltech thirty years earlier and had also attended his regular Wednesday afternoon lectures at the Hughes Aircraft Company. Feynman's first impulse was to decline the request—weakened by cancer, he knew he didn't have much time left, and preferred to spend it with his family and his chosen work rather than in a government job in Washington, a place he sedulously avoided. As he recounts the story, he told his wife, Gweneth (they had married in 1960), that anyone else could do the job as well as he, but she countered that no one else would be able to do what he could. She was right. (Tragically, Gweneth too fell ill with cancer around the time of Richard's death in 1988, and she died the following year.)

He vowed to lay all his other projects aside while he served on the commission. Setting to work the very next day, he consulted experts at the Jet Propulsion Laboratory in Pasadena, who briefed him rapidly, intensely, and thoroughly on the shuttle program. Already he was being nudged toward what would become the breakthrough recognition of the fatal problem: As he writes in his second anecdotal memoir, *"What Do* You *Care What Other People Think?": Further Adventures of a Curious Character* (1988), "The second line of my notes says 'O-rings show scorching in clevis check.' It was noticed that hot gas occasionally burned past the O-rings in booster-rocket field joints."

The commission met in Washington presently, and Feynman identified right away a kindred spirit in General Kutyna, who despite his military finery did not have a special car and driver but typically traveled around D.C. via the Metrorail. When General Kutyna, who had a degree from M.I.T., described to the commission the procedure the Air Force had followed to investigate the failure of an unmanned Titan rocket, Feynman found himself pleased by the lines of inquiry—which resembled those he had sketched out for his own use the night before—and the rigor with which they were pursued, which even exceeded his own expectations. "I'm all excited. I want to do this kind of investigation, and figure we can get started right away—all we have to do is decide who will do what."

Chairman Rogers immediately dampened Feynman's enthusiasm, saying the commission wouldn't be able to use General Kutyna's methodology because the members couldn't expect to gather as much information as that would require. Feynman was puzzled by this, because there were superabundant data about the shuttle flight. Neil Armstrong chimed in that they wouldn't be doing a technical investigation like the one the general described. "This bothered me a lot," Feynman wrote, "because the only things I pictured myself doing were technical!"

Thus the scene was set for the drama of Feynman's technical acumen and invincible reasonableness taking on the bureaucratic rigmarole of NASA and the commission. When he wanted to talk with NASA engineers directly rather than sit and listen to mass briefings, he had to push against Rogers's determination "to proceed in an orderly manner." Feynman wanted the opportunity to meet on his own with experts so he could direct the course of the conversation and pepper the honchos with the necessary questions: "It's the only way I know to get technical information quickly: you don't just sit there while they go through what *they* think would be interesting; instead, you ask a lot of questions, you get quick answers, and soon you begin to understand the circumstances and learn just what to ask to get the next piece of information you need."

He pushed hard enough on Rogers to eventually get his way. Soon he spent a Saturday with the engineers from NASA, hearing all about the shuttle's rocket boosters, the engines, and more, before finally getting to the seals experts, who he knew from his earlier conversations at the Jet Propulsion Laboratory would have the information he needed. The two O-rings, each a quarter-inch thick and about 37 feet around—they spanned the whole circumference of the rocket's shell—formed "the ultimate seal" for the rocket boosters. They were supposed to prevent hot gases from leaking out of the side of the rocket. But they didn't work as reliably as the engineers had hoped. The joints that the O-rings were supposed to seal would bend as the walls of the rockets expanded under pressure during liftoff. If the rubber in the O-rings expanded fast enough to close the gaps created by this bending of the joints, the seals could be maintained—but this meant that the elasticity of the rubber "became a very essential part of the design." Under most conditions the O-rings would work, but there was always the possibility that the seals could leak or fail completely—a possibility about which NASA had a curious complacency. "So NASA had developed a peculiar kind of attitude: if one of the seals leaks a little and the flight is successful, the problem isn't so serious. Try playing Russian roulette that way: you pull the trigger and the gun doesn't go off, so it must be safe to pull the trigger again."

A telephone call from General Kutyna tightened Feynman's grip on the problem. The general had been working on his car's carburetor when a sidelong thought occurred to him: The average ambient air temperature for the fatal shuttle launch had been 36 degrees—estimates for the air temperature around the joint itself were as low as 23 degrees—while the coldest temperature for any previous launch had been 53 degrees. This led him to ask Feynman, rhetorically, "You're a professor; *what, sir, is the effect of cold on the O-rings?*" Feynman knew well that cold stiffens rubber. When stiffened by cold, the O-rings might be unable to expand fast enough to fill the gap in the joint caused by the increase of pressure in the rocket, meaning they could not maintain the seal that kept the hot gases from leaking out of the rocket.

The general had given Feynman "a clue for which I got a lot of credit later, but it was his observation. A professor of theoretical physics always has to be told what to look for. He just uses his knowledge to explain the observations of the experimenters!" Feynman later found out that a NASA astronaut had told the general that NASA had known about the O-rings' tendency to fail more often at lower temperatures and had buried the information. To save that astronaut's career, the general had gotten the word out indirectly, through Feynman. (In an interview for a 2016 article marking the thirtieth anniversary of the disaster, General Kutyna identified the astronaut as Sally Ride herself, one of the members of the commission.)

The mire proved ever deeper. Photographs not only showed a plume of flame shooting out of the right rocket booster starting fifteen seconds before the explosion, but also showed that during ignition, puffs of smoke had come from the same area—the part of the joint near a strut that connected the rocket to the external fuel tank. Then Allan McDonald, an engineer for Morton Thiokol, the manufacturer of the rocket booster, appeared before the commission to state that he and his fellow engineers had told NASA the night before the shuttle launch that the mission should be scrubbed if the temperature was below 53 degrees. Under extreme pressure from NASA, the other Morton Thiokol engineers had folded, but McDonald remained adamant and declared, as Feynman recalled it, "If something goes wrong with this flight, I wouldn't want to stand up in front of a board of inquiry and say that I went ahead and told them to go ahead and fly this thing outside what it was qualified to." "The whole commission was shocked"—evidently there was gross negligence on the part of NASA management.

The moment had arrived for the showpiece scientific demonstration that would make Feynman far more famous than the Nobel Prize had. Not without difficulty, he found a hardware store where he bought screwdrivers, pliers, and the smallest C-clamp they had. From a NASA model of the joint that was being handed around during the commission's public meeting, he extracted a sample of O-ring rubber with the tools he had bought, pressed the piece of rubber tightly inside the C-clamp, and plunged it into his cup of ice water. At the climactic instant he pressed the button to activate his microphone, took the rubber out of the water, and announced the result of his experiment:

> I discovered that when you undo the clamp, the rubber doesn't spring back. In other words, for more than a few seconds, there is no resilience in this particular material when it is at a temperature of 32 degrees. I believe that has some significance for our problem.

During the lunch hour, reporters pressed Feynman with uncomprehending questions, and he feared he had failed to make his point. "But that night, all the news shows caught on to the significance of the experiment, and the next day, the newspaper articles explained everything perfectly." The crystalline logic of the demonstration impressed the multitude and his peers alike: Simple and elegant and not without a showman's touch, Feynman's experiment made him something of a media sensation. But, more importantly, it showed formidable scientific intelligence in a heroic role, sleuthing out the cause of a national tragedy that bureaucratic and political authorities might have otherwise obscured.

What it did not do, at least not right away, was to identify the specific failures of management and character that really caused the disaster. It would take some doing for Feynman to make that point clear to the public. His work was not done, and he would grill Morton Thiokol and NASA managers to reveal the bosses' willful indifference to the grave misgivings and even the protests of their engineers.

When Feynman wanted to state clearly the plain truth in the commission's final report—about the technical and managerial failures he had learned of from his investigations—some of his colleagues, and especially Rogers, favored what Feynman saw as politic euphemism and obfuscation. The extensive editing process—"wordsmithing," Feynman called it—was going to excise much of his writing, and the final report's upbeat ending about NASA's "spectacular achievements" effectively absolved it of the blame it deserved. Feynman bitingly complained that this point "reminds me of the NASA flight reviews: 'There are critical problems, but never mind—keep on flying.'" He refused to sign the report unless an addendum were included of his own determinations—unedited. It became Appendix F—the letter was seemingly a coincidence—titled "Personal Observations on the Reliability of the Shuttle."

Eviscerating NASA probability estimates, he laid bare the disparity between hopeful folly and grim reality. For instance, as Feynman recalls, one NASA manager put the chance of engine failure at one in 100,000 missions, or one lost flight in 300 years of launching once per day—by Feynman's account, an outlandishly minimized estimate cooked up to fit a preconceived number. The manager's own engineers put the figure at one in 200 or 300. The manager later disputed this account, but examples abound of NASA producing estimates of the shuttle's reliability that seemed well more than aspirational. "It would appear that, for whatever purpose, be it for internal or external consumption, the management of NASA exaggerates the reliability of its product, to the point of fantasy," Feynman wrote.

The way the immensely complicated main engines were designed made it particularly difficult to pinpoint problems and to fix them. Feynman's indictment gathered unstoppable force from the exceptional lucidity with which he mounted the evidence. Whereas engines for military or civilian aircraft were designed and tested incrementally, component by component, from the bottom up,

> The Space Shuttle Main Engine was handled in a different manner, top down, we might say. The engine was designed and put together all at once with relatively little detailed preliminary study of the material and components. Then when troubles are found in the bearings, turbine blades, coolant pipes, etc., it is more expensive and difficult to discover the causes and make changes.

Failure, Feynman seemed to say, was thus built into the shuttles, which "fly in a relatively unsafe condition, with a chance of failure of the order of a percent." Either NASA management was trying to deceive the government about the peril in order to keep the money coming or it had deceived itself by lending a deaf ear to the engineers' warnings.

Feynman offered a now famous, often echoed conclusion: "For a successful technology, reality must take precedence over public relations, for nature cannot be fooled." That signature line has a characteristic Feynman flourish: Science has one inviolable standard—everything depends on the truth, and any laxity on that score invites calamity. Feynman's sterling work on the commission was the fitting culmination of a lifetime devoted to a cherished vocational ideal.

The Energy of Life

Feynman became a figure of legend, and not just for his scientific brilliance. His reputation was abetted by the stories he loved to tell about himself, most of them amusing, some of them salty. His very public loquacity did not endear him to some colleagues, who thought he was showboating and undermining the dignity of their profession. There is no doubt that he loved his life more than most people allow themselves to, and that he expended some of his boundless vitality in activities that had nothing to do with physics: playing the bongos, cracking safes, deciphering Mayan hieroglyphics, chasing women, learning to draw with striking skill, appearing in Caltech student productions of musical comedies. The joy he took in the release of almost manic energy was his hallmark.

He lived as he chose right up until the end. He held off death for ten years from his first cancer surgery in 1978—an almost impossible feat for someone with the exceedingly rare and strange disease myxoid liposarcoma. Repeated operations to carve out abdominal tumors of the soft fat and connective tissue left him practically gutted—one surgery lasted over fourteen hours, and his aorta split while he was on the table, so that he needed seventy-eight pints of transfused blood. But he continued to work and play with glorious abandon and blazing concentration.

The productiveness and the happiness were of a piece. For all its startling variety of interests and diversions, his life was, above all, that of a born scientist. Richard Feynman was the natural successor to Albert Einstein as the epitome of the scientific hero in the mind of the public and scientists alike. The delight he took in being what he was honored both him and the calling he graced with his excellence. When the time came to die, he was intrepid, unafraid of the next step in what he called this "mysterious universe without any purpose." His only complaint, with his last words, was that he would not want to repeat the experience of dying—it bored him. It was evidently the only thing in his vibrant, vivid, heroically fruitful and joyous life that did.