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Rosalind Elsie Franklin

July 25, 1920–April 16, 1958

X-RAY CRYSTALLOGRAPHER

With a glass wand, Rosalind Franklin gently coaxed apart the lintlike fibers of DNA. Pulling them as thin as spider silk, she bunched them in tiny packets of parallel strands. Then, delicately controlling the humidity, she beamed X rays at the little bundles and photographed the thread of life.

Quick, fierce, and fun-loving, Rosalind Franklin was a commanding leader, an idealist about science, and in her time the supreme experimentalist analyzing the molecules of heredity.

Fascinated by matter, what the world is made of, and how it formed, Franklin liked facts—indisputable, provable, hardcore facts—not high-flown theories or insubstantial speculation. As she declared, "Facts are facts." While still in her early twenties, she had uncovered data about coal that established her reputation as an expert experimentalist. The evidence she later revealed about viruses helped lay the foundation for structural biology.

In the early 1950s, Franklin almost discovered—by herself—enough information about the structure of DNA to explain the molecular basis of heredity. DNA, a molecule found in all living cells, is the coded blueprint for transmitting inherited characteristics from one generation to another. The facts she did uncover about the molecule helped James Watson and Francis Crick beat her to the Nobel Prize—data they used without her knowledge and without fully crediting her.

Once the structure of DNA was understood, the field of molecular biology exploded; it became the most significant scientific development of the late twentieth century. The most important technology of the twenty-first century is expected to be bioengineering or recombinant DNA, in which programmed DNA is injected into simple organisms like bacteria to produce a desired characteris-

Rosalind Franklin at Ciba Foundation conference in London on the nature of viruses. March 26–28, 1956.

Rosalind Franklin.

April 2, 1956. Rosalind Franklin in Madrid with (left to right) Ann Cullis, Francis Crick, Donald Caspar, Aaron Klug, Odile Crick, and John Kendrew.

tic in future generations. Insulin, growth hormone, and the clotting factor missing from the blood of hemophiliacs are already manufactured commercially with recombinant DNA technology.

Today, as the facts about Franklin's life and scientific prowess have emerged, they have cast a shadow on Watson's and Crick's achievement and reestablished Franklin's place in the sun.

Rosalind Franklin was born in London on July 25, 1920, the second of five children in a wealthy Jewish banking family. Her ancestors had lived in England since 1763, and her grandparents lived in upper-class English style. They had a large house in a comfortable section of London and a country home and, when they wintered in the Mediterranean, a retinue of English servants accompanied them.

Rosalind's father, Ellis Franklin, and her mother, Muriel Waley, were raised in a tradition of public service and philanthropy. Her banker father taught science as a volunteer at the Working Men's College and helped numerous Jews escape from Nazi Germany. Among her aunts were socialists and activists in women's causes and trade unionism. An uncle was such a strong supporter of women's rights that he served six weeks in prison in 1910 for taking a dog whip to Winston Churchill, then a prominent antisuffragist. Another relative was elected to Parliament three times before the government ruled that Jews could serve without taking an oath of office on a New Testament Bible.

As a child, Rosalind felt discriminated against because she was a girl. She thought her family did not understand her and remembered her childhood as a tense struggle for recognition. Because she did not like "let's pretend" games and detested dolls, her parents found her "practical and unsentimental.... literal-minded and not imaginative." She preferred making things—sewing, carpentry, and Meccano building sets. While her mother praised Rosalind's "exquisitely neat" embroidery and a "beautifully planed" coin cabinet, her analytical mind was harder to recognize.

But Rosalind needed reasons, proofs, and facts. She read through the Bible to find a reason for believing in God and concluded, "Well, anyhow, how do you know He isn't a She?" Quick, logical, and precise herself, she was impatient with slipshod, vague, and woolly arguments.

When Rosalind was eight years old, she caught a string of colds and flus, and the family doctor recommended a convalescent boarding school near the coast. With the best of intentions, her parents agreed. Somewhat hopefully, her mother regarded Rosalind's year away from home as "a neutral experience." As far as she could tell, Rosalind was "a little homesick . . . . but never actively unhappy." Asked how she was getting on, the little girl replied laconically, "All right." In truth, Rosalind hated the school and always resented that year away from home.

Rosalind absorbed an unfortunate lesson from her boarding school convalescence. She decided that it was safer to ignore illness and pain than to seek help. When a needle became stuck deep in her knee joint, she walked for blocks to a hospital alone and in excruciating pain. When in her thirties she suffered the first pains of cancer, she ignored them until it was too late.

In London, she attended St. Paul's Girls' School, an academically rigorous day school for the daughters of well-to-do families. During part of one semester, she stayed in a Parisian pension to improve her French. She returned home an ardent Francophile with a zest for French dressmaking, cooking, and travel. From then on, she made her own clothes and raised and lowered her hemlines with each changing fashion.

Thanks to the excellent physics and chemistry classes offered by St. Paul's, Rosalind decided by age fifteen to become a scientist. An avid amateur astronomer, she followed star maps in the *London Times* and searched night skies for constellations. Hoping to study physical chemistry at Cambridge University, she took—and passed—the entrance examinations. She was in for a bitter disappointment.

Her father, who strongly disapproved of university education for women, refused to pay for her to attend Cambridge. He had once planned a science career for himself and would have been delighted if a son had pursued the same course. But women should do good works as volunteers; they should not be professionals. His refusal touched off the only crisis in her parents' happy marriage. Rosalind's favorite aunt, Alice Franklin, stormed over to inform her brother that she would personally send Rosalind to Cambridge. In the ensuing row, Rosalind's mother announced that she, Muriel, would pay for Rosalind's education out of her own family money.

Faced with three irate women in the family, Ellis Franklin backed down and agreed to pay for Rosalind's university education. His approval was grudgingly given and resentfully received. Rosalind loved her mother deeply, but she never entirely forgave her father, even though her virus work eventually made him quite proud. As she frequently told friends, daughters have special disadvantages.

In 1938, a year before the outbreak of World War II, Rosalind Franklin entered Newnham College, a women's college in Cambridge University. For a woman, Cambridge was much like a girls' boarding school. Before a Newnham woman could entertain a man in her room, she had to move her bed out into a public corridor. Women faculty members, most of them unmarried, seemed extraordinarily serious and formidable. Franklin decided that she never wanted to be like them. Years later, she almost turned down a job offer from Cambridge, rather than become a Cambridge woman don.

The outbreak of World War II in September 1939 precipitated another disagreement with her father. Ellis Franklin wanted Rosalind to quit the university and do volunteer defense work. Rosalind, on the other hand, was determined to continue her studies. Luckily, the government made it clear that all science students should complete their education.

One of the few blessings of the war was Rosalind's friendship with Adrienne Weill, a distinguished French woman physicist who had worked with Marie Curie and Irène Joliot-Curie at the Curie Institute. After Weill's escape to England, she worked in Cambridge where Franklin became her friend and for one year her boarder. It was Weill who found Franklin a job and a room in Paris after the war.

After graduating from Cambridge in 1941, Franklin spent a year doing research in physical chemistry with the future Nobel Prize–winning chemist Ronald Norrish. Then she took an unpromising job that established her reputation as a research scientist. As her contribution to the war effort, she began to study the physical structure of coals and carbon for the British Coal Utilization Research Association. Rooming with a cousin, she bicycled furiously through air raids across the exposed Putney Common each day to her job in South London. She never complained, but she was terrified. (During her last illness, she suffered delirious nightmares about cycling across the common and wondering if the war would ever end.)

In her laboratory, Franklin focused on a large and important wartime problem: how to use England's coals and charcoals more efficiently. In a series of elegantly executed experiments, she discovered the structural changes that occur when coal and carbons are heated and showed why some heated carbons turn into graphite as their molecules form parallel layers that slip and slide apart. She did the laboratory work herself, producing masses of experimental data. When the laboratory banned uncertified personnel from its machine shops, she simply turned its warning signs around and kept on working.

Between the ages of twenty-two and twenty-six, she published five papers on coals and carbons that are still quoted extensively today. Her research helped found the science of high-strength carbon fibers. It proved vitally important for both the old charcoal industry and for nuclear power, which uses graphite to slow the rate of fission. The work earned her a Ph.D. from Cambridge University in physical chemistry in 1945 and made her, at age twenty-six, a recognized authority in industrial chemistry. By today's standards, she was almost unbelievably young to have produced such important research.

Franklin soon realized that she needed to master the developing field of X-ray crystallography in order to understand matter—the material that the universe is made of. Crystallography, a branch of physics, is a powerful technique used to reveal the position of atoms within matter. Traditionally, crystallographers aim X rays at crystalline solids composed of atoms arranged in a regular and repeated pattern. The X rays enter the crystal; many of the rays pass completely through, but others are reflected inside the crystal and exit in different directions to strike photographic film or other types of detectors. (See figures 10.1 and 10.2, on pages 232 and 233.) By studying the intensity and angle of the spots on the film, researchers could figure out the positions of the atoms within a crystal. Crystallography was a British invention and specialty, and many women, like the Nobel Prize–winner Dorothy Hodgkin, achieved early prominence in it.

Franklin was never a traditional crystallographer, however. She never worked with regular, single crystals. Instead, she pioneered the use of X-ray diffraction to study disordered matter like carbons and complicated matter like large biological molecules.

When the war ended in 1945, Franklin wrote Adrienne Weill to ask if she knew any jobs in France for someone who knew a little about physical chemistry and a lot about the holes between carbon molecules. Through Weill, she found a job in Paris at the Laboratoire Central des Services Chimiques de l'État, beginning in 1947.

When Franklin arrived in Paris at the age of twenty-seven, she began the happiest three years of her life. A strikingly good-looking woman, she had clear olive skin, raven black hair, and brilliant eyes that could sparkle with amusement or flash with rage. Slim and quick-moving, she dressed fashionably in an understated European style. Her coworkers were young, many of them Communists from the wartime French Resistance. Together, they lunched in bistros, invited one another for dinners, spent weekends picnicking, and took group vacations climbing mountains, skiing, and camping. At first, she was shocked at such closeness; Cambridge women were not used to males and females sharing hotel rooms.

Speaking French, Franklin seemed to shed her British reserve. "She was a great deal of fun, not a heavy person at all," said Anne Sayre, her biographer and friend in Paris. "I thought she was very young for her age, slightly prankish, teasing. She was older than I

was, but I felt like her aunt." Off work, Franklin could sparkle gaily with a slightly teasing, mischievous wit. Although "formal occasions" like banquets made her glum, she loved small dinners. She became an expert on the latest French slang and played elaborate French word games at top speed. She liked gossiping about friends' tangled love affairs and shopping in flea markets, street fairs, and department stores. Her conversation was light, quick, observant, and often amusing. "Gaiety was her note," crystallographer David Sayre remarked.

After the war years cooped up in England, Franklin gloried in being able to travel freely around the Continent. She plotted itineraries with minute precision, correlating maps, guide books, and international timetables to locate the most economical routes through the most mountainous scenery. She loved mountains and outdoor life, strenuous twenty-mile-a-day hikes, and bike tours—no matter what the weather. She could react in surprising ways to travel incidents, though. A friend, Vittorio Luzzati, complained sharply about their hiking in foul weather one day, and her eyes filled with tears. On another hike, Luzzati found an artillery shell from the war and showed it around; Franklin blanched, stiffened, and turned away. Something had happened during the war, he thought, that she could not discuss.

She could be happily married, but she did not want children, she confided to Luzzati's wife, Denise. Franklin loved children too much to hand them over to nannies, and her commitment to science prevented her from being a full-time mother. Nor did she like her parents' upper-class lifestyle. Her flat was simple, and although her family was well-to-do, she was a Socialist.

She worked in a nineteenth-century French army explosives laboratory that was flooded with light, coated with dust, and stuffed with old brassworks. While working, Franklin was intense, reserved, and private—even austere. She took science seriously and hated to waste time. Although she hated idle chitchat at work, she loved a good science argument, and she and David Sayre argued crystallography hammer and tongs. As far as she was concerned, passionate debates were part of the fun of being a scientist. She could be pitiless and make seminar speakers feel like fools. Coworkers who left the darkroom a shambles made her angry. She was unmarried in her late twenties, though, and the French in the 1950s dismissed her foibles as spinsterish.

By 1950, after three years in France, Franklin realized she had to get down to business. If she wanted a career in England, it was time to go home.

Her timing was excellent. Crystallographers already knew how to determine atomic positions in small, simple, and highly regular crystals. Now they were turning to extremely large and complex arrangements in biological matter. Borrowing techniques from physics, biologists and biochemists were solving one major problem after another.

Physicist John Randall, who invented the key to radar in World War II, formed an interdisciplinary team of physicists, chemists, and biologists to study living cells at King's College in the University of London. The team knew that DNA (deoxyribonucleic acid, to be precise) carries genetic information from one generation to another. It was also known that atoms of many proteins are shaped like a helix, that is, like a spiral staircase or an extended coil of springs. But no one understood DNA's structure or dreamed that it would explain heredity.

At King's, a graduate student named Raymond Gosling was taking X-ray photographs of DNA molecules. His photos were the best yet taken, but Randall decided an expert should analyze them. Randall went headhunting, heard about Rosalind Franklin, found her a fellowship, and hired her. Writing to Franklin to explain her new job, Randall made it clear that she would be working alone on a new topic, not the subject they had discussed earlier: "After very careful consideration and discussion with the senior people concerned, it now seems that it would be a good deal more important for you to investigate the structure of certain biological fibres in which we are interested.... This means that as far as the experimental X-ray effort is concerned, there will be at the moment only yourself and [the graduate student] Gosling, together with the temporary assistance of a graduate from Syracuse, Mrs. Heller."

Franklin arrived for her first day of work at King's College in 1951 and walked straight into a meeting fraught with consequences for her future. Randall's second in command, Maurice Wilkins, was away for a short holiday. Wilkins had been Randall's graduate student before World War II, had worked on the atomic bomb during the war, and was to play a crucial and controversial role in Franklin's life at the laboratory. In Wilkins's absence, Randall attended the meeting. And Randall turned DNA and Gosling over to Franklin "lock, stock, and barrel." No one in the lab had worked on DNA for several months, and Franklin assumed she was in charge. When Wilkins returned, on the other hand, he supposed she had been hired as a high-class technical assistant to supply the team with experimental data for it to analyze.

Gosling was caught in the middle. "I don't think Wilkins ever imagined that giving a problem to Rosalind meant that nobody else was going to work on it. The lab wasn't built like that, but Rosalind

was built like that." Later, Gosling wondered if anyone had bothered to explain to Franklin the department's hierarchical command structure, Wilkins's position as its linchpin, or the fact that team members worked and published together. Certainly, King's was the only place where Franklin had much difficulty working with colleagues.

Although Gosling had been handed from one thesis advisor to another like a bale of hay, he quickly decided that Franklin was "terrific." She had a strong personality that people either loved or hated. She had strong opinions and high principles and did not compromise; if something was worth discussing, it was worth defending. She was dedicated, but she had a good sense of humor. As she told a friend, "What's the point of doing all this work, if you don't get some fun out of it?" Once, while trying to understand how radiation penetrates the skin of a sphere, she and Gosling peeled oranges. Giving up in frustration, they had a glorious orange fight, hurling fruit at each other across the lab.

Franklin needed a research partner so she could toss ideas around instead of oranges. As Francis Crick pointed out later, "It is one of the requirements for collaboration of this sort that you must be perfectly candid, one might almost say rude, to the person you are working with. It is useless working with somebody who is either much too junior than yourself, or much too senior, because then politeness creeps in and this is the end of all good collaboration in science." Gosling was too young and inexperienced to be the counterpoint Franklin needed. Unfortunately, there were few other prospects in sight.

Wilkins was the obvious candidate. He was interested in DNA, and he and Franklin got along at first. But Wilkins was "meditative, speculative, markedly indecisive," wrote the historian Horace Judson. He was "shy, passive, indirect...he could respond to vigorous disagreement only by turning aside." Wilkins thought carefully before speaking; Franklin was quick, decisive, and impulsive, and could snap at people. "She scared the wits out of me," Wilkins told colleague Aaron Klug. Between Wilkins's shyness and Franklin's lack of small talk, their meetings consisted mostly of staring at each other. Only later did their relationship deteriorate into antipathy and what Judson called "one of the great personal quarrels in the history of science."

At lunch, Franklin discovered that King's College was considerably more formal than Paris. A number of women scientists worked on the staff, but they were not allowed to eat with the men in the men's common room; women ate outside the lab or in the students' cafeteria. After work, the men visited a male-only bar for beer and shoptalk; the women were not invited. As a result, the men talked science casually among friends while the women operated in a more formal office atmosphere. Later, Franklin concluded that King's was also cool to foreigners and Jews.

Shut off from casual friendships at King's, Franklin developed a social life that was almost completely independent from the laboratory. She reserved her evenings and weekends for the theater and films, volunteer work for the Labour party, friends from St. Paul's School and Cambridge, weekly visits with her family, and trips to the countryside. At home, she gave small dinner parties where she introduced British friends to French delicacies like artichokes, new potatoes cooked in butter, and good wine. On holidays she snorkeled in Corsica, climbed mountains in the Alps and Yugoslavia, and toured Israel and Europe, snapping pictures wherever she went.

At the lab, Franklin and Gosling worked alone, collecting enough data about DNA to write five papers. Between her articles, reports, and the lab notes she kept in little red exercise books—all of which passed at her death to her friend and colleague Aaron Klug —it is possible to follow her work over the next few years.

First, she adjusted her X-ray camera to get a needle-fine beam. Then she worked on her DNA sample. Purified DNA looks like the fibrous lint from an old handkerchief, but no one had ever deciphered the molecular structure of such complex fibrous matter. Previous experimenters had tried, using thick DNA fibers. Franklin, who had already worked with amorphous coals and clay structures, knew how to deal with materials that were not fully crystalline. So she was able to invent a new and better method of aligning DNA's lintlike fibers.

With a glass rod, she pulled thinner fibers than had ever been made before and laid them parallel. Since a single fiber was too fine to scatter an X-ray beam, she bundled the gossamer threads together for bulk. Then she matched the optics of the X-ray beam to the diameter of the fibers to get a clearer picture. Finally, she studied how the fibers behaved in a humid atmosphere. Standing them over a closed container of saltwater, she measured the moisture concentration in the air and correlated it to the behavior of the fibers. As a physical chemist, she realized that humidity control was one of the keys to getting a clear picture. Water molecules, filling the spaces between the atoms of a crystal, hold the crystal erect and stable.

Soon, she could show that DNA molecules exist in two forms, A and B, depending on how much water they absorb. When the air surrounding the fibers reached a relative humidity of 75 percent, her X-ray photographs resembled the best pictures that Gosling had taken before her arrival. She called these photographs the dry, A-form of DNA. When the humidity rose to around 95 percent, the

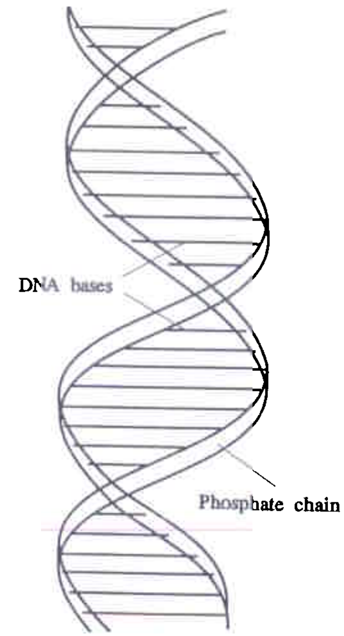


Figure 13.1. DNA.
The DNA molecule is shaped like a helix with base steps and outside phosphate chains going up and down.

molecules stretched 25 percent longer and actually popped off their stand. X rays scattered by these wet fibers produced fewer details on the photographic film. Instead, they made a simple cross shape, the characteristic sign of a helix, as Franklin knew. The cross indicated that a wet DNA molecule was shaped like a helix. She referred to the cross as the wet, B-form of DNA.

Franklin could actually make the DNA molecule shift from one form to another by changing the moisture of the air around the fibers. In only one year at King's College, Franklin had transformed the study of DNA. Her discovery that DNA existed in two forms gave her a big advantage. Other researchers worked with samples that were, unknown to them, mixtures of the two structures.

Because the molecule could absorb and give off water from the surrounding air so easily, she also deduced the location of the phosphate sugars known to be in DNA. In a stroke of intuition, she concluded that they are located on the outside of the molecule close to the surrounding water. The bases, tucked inside the helix away from the water, march up the helix like so many steps in a staircase. She was right in both respects.

She had discovered the first of four crucial points about the arrangement of the DNA molecule. Three more pieces of the puzzle had to be deciphered. She still had to learn that the molecule is shaped like a helix composed of two phosphate strands wound together; that the two strands are oriented in opposite directions so that one marches up and the other down; and that each base step is composed of a pair of two particular bases. Whoever grasped all four points about DNA could explain heredity. But neither Franklin nor anyone else knew that.

As Franklin began producing data, Wilkins became anxious to interpret it. "How dare you interpret my data for me?" she snapped. She thought Randall's and Wilkins's attitude toward her was, "Thank you for the pretty pictures. We'll analyze them." Wilkins told her that the simpler, crosslike B-picture indicated a helical structure, but she objected to his jumping to conclusions. Although she was proceeding on the assumption that both forms of DNA were helical, she wanted hard evidence to prove the point, not supposition. During the fall of 1951, she had a terrific argument with Wilkins that nearly resulted in her return to Paris. Afterward, they agreed to differ.

In November of 1951, Franklin gave a colloquium talk at King's College on her work to date. Staring at her from the rear of the room was a strange, skinny broomstick of a fellow with pop-eyes and wild hair. It was a young Midwestern geneticist, James Watson, who was working on DNA at Cambridge University with an English graduate student, Francis Crick. At this point, Franklin knew far more about the structure of DNA than either Watson or Crick. Watson could have learned a good deal from her talk, but he prided himself on not taking notes at lectures and he was so busy analyzing Franklin's physical appearance that he remembered her data incorrectly.

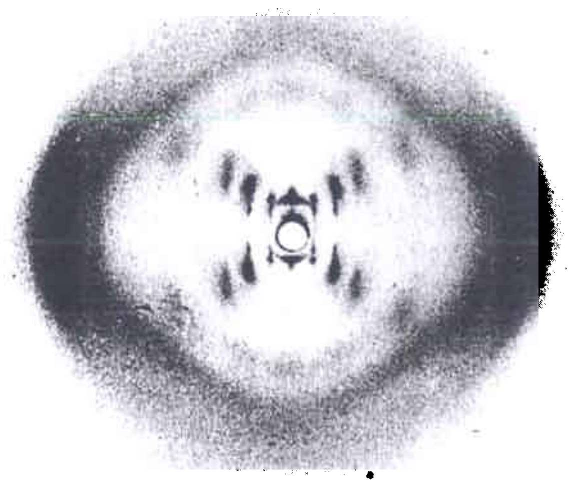
Later, in a bestseller that ridiculed Franklin's personality and scientific talent, Watson critiqued her lecture like a beauty contest. "There was not a trace of warmth or frivolity in her words," he complained. Franklin never wore glasses, but in his imagination, he put them on her and wondered "how she would look if she took off her glasses and did something novel with her hair." Watson thought the audience was afraid of "Rosy... Maurice's assistant," as he called her. "To be told by a woman to refrain from venturing an opinion about a subject for which you were not trained... was a sure way of bringing back unpleasant memories of lower school." Although Franklin's career was largely free of the legal and bureaucratic discrimination that hampered many other women scientists, more subtle problems did impede her progress. Watson's condescension, for example, immediately excluded him as a possible collaborator.

Thanks to his garbled version of Franklin's data, Watson and Crick produced a model of the DNA molecule and called in their friends to admire it. When Franklin saw it, she instantly spotted their mistakes and told them so. "Most annoyingly, her objections were not mere perversity," Watson admitted. "At this stage the embarrassing

fact came out that my recollections of the water content of Rosy's DNA samples could not be right." Sir Lawrence Bragg called the model "the biggest fiasco" he had ever been associated with and forbade Watson and Crick from working on DNA. Horning in on a King's College project was not good sportsmanship—especially when you were wrong. So far, Franklin was still ahead of Crick and Watson. The next time they built a model based on her experiments, though, they might get her facts right.

By spring of 1952, Franklin was the only person working on DNA full time. During the previous eighteen months, she had also made the only significant progress toward solving the problem. That May, Franklin left her X-ray beam focused on extra-wet DNA fibers for an extra long time. After sixty-two hours of exposure, she had a magnificently vivid photograph of DNA, the simple cross reproduced in so many biology textbooks. Its cruciform pattern clearly originated from a helix-shaped molecule. The picture is regarded as one of the most beautiful X-ray photographs ever taken. But Franklin put it away in a drawer. She continued analyzing the A-picture of dry fibers. It had more details and promised to deliver more facts.

That spring, the United States State Department refused to issue a passport to the eminent American chemist Linus Pauling. He had been invited to speak at a protein conference in London in May 1952,



Rosalind Franklin's X-ray photograph of DNA.

but a congressional witness had accused him of being a Communist. Pauling denied the charge, but in the anti-Communist hysteria of the postwar era, he lost his chance to attend the conference. As Pauling realized later, the government's travel ban had prevented him from seeing Franklin's data and her X-ray photographs. Had he done so, Franklin and Pauling might have discovered the structure of DNA together, before Watson and Crick. If so, Pauling might have won three Nobel Prizes instead of two. This was the second time that Franklin had lost an opportunity to acquire a collaborator. She was still analyzing her data alone. As the historian Judson observed, "The situation [in Cambridge] was exactly the reverse: volatile collaborative enthusiasm and no data."

Meanwhile, at King's College, the split between Wilkins and Franklin was widening rapidly. Although both discussed their work with others in the lab, they rarely spoke to each other. Wilkins had begun duplicating Franklin's data as best he could, but her DNA sample and her technique may have been superior; for whatever reason, his photographs produced much less information than hers. He wrote Crick, "Franklin barks often but doesn't succeed in biting me. Since I reorganized my time so that I can concentrate on the job, she no longer gets under my skin."

Wilkins had been confiding his problems to Watson and Crick but rejecting their suggestions to build toylike models based on what he knew and could guess about the structure of DNA. Franklin, like the rest of the researchers of King's College, thought model building was pointless. "We all felt that you could build models 'till the cows came home,' but how could you tell which one was right? And why bother when you had the [X-ray] spots? It was a down-to-earth attitude," Gosling remembered.

On the advice of her friend Luzzati, Franklin began the complex mathematical calculations that crystallographers use to solve simple crystals. No one had ever used these so-called Patterson calculations to solve a fiber structure, however. The job was immensely complicated—much too complicated, as it turned out. She had begun to doubt whether the dry, A-form of DNA was helical. Ironically, Wilkins shared her doubts and actually published them in an agency report. Franklin did not publish her doubts; she had to be sure of her data before she committed herself.

Franklin joked about her hesitation that summer. She and Gosling hand-lettered a black-bordered funeral announcement for the dry, crystalline A-form of DNA: "It is with great regret that we have to announce the death on Friday 18th July 1952 of D.N.A. Helix (crystalline). Death followed a protracted illness." The "Death of the A-Helix" was a joke—but it had some steel in it.

Franklin was bogged down in mathematical calculations through the winter of 1952–1953. She still wanted to know whether the A-form, like the wet B-form, was helical. The question was quite legitimate at the time. "It's one of the quirks of perception in science that helical symmetry is now very obvious for any structure that is periodic and fibrous. But the idea was really very novel in the early 1950s," emphasized her friend, Donald L. D. Caspar, now a physics professor at Brandeis University. Then she misread another piece of data, and her doubts about the helix-shape of her dry A-form were reinforced. So she lavished time and energy on the A-form, when she could have been reaping the fruits of the wet B-form.

If she had asked Crick's advice, the two of them might have solved the structure together in a few months. At one point, Franklin and Crick actually met in line for tea, and Crick tried to give her some off-the-cuff advice. But Crick had a reputation as an eccentric, a flashy theoretician, and Franklin ignored him. Crick admitted, "I'm afraid we always used to adopt—let's say, a patronizing attitude towards her." Once again, Franklin had missed a chance to acquire a research partner.

Suddenly, early in 1953, the balance of power shifted from Franklin to Crick and Watson. In two fell swoops, facts that Franklin had painstakingly developed were given—without her knowledge or permission—to Watson and Crick in Cambridge. For the first time in two years, they would know more about DNA than she did. The race was quickening without Franklin's even knowing it.

Linus Pauling precipitated the race by writing a draft article about DNA and sending it to his son in Cambridge to critique. Peter Pauling promptly gave it to Watson, who took it down to King's College to show Franklin on January 30, 1953. She coolly pointed out that there was not a shred of evidence to prove that DNA was a helix. And she was right—she had the evidence and was not finished analyzing it. She must have been annoyed: Franklin, the woman with no time at work for idle chitchat, interrupted by Watson, the brash American who had no facts but who considered small talk "the essence of getting along with people." She had written Pauling's lab for information and received no reply, yet here was Watson waving a copy of Pauling's manuscript. She could tell at a glance that it was wrong; it was based on five-year-old photographs of DNA made long before she discovered its two different forms.

Watson transformed this scene into the dramatic climax of his bestseller, *The Double Helix*. In the book, Watson lectured her on helical theory and "implied that she was incompetent in interpreting X-ray pictures." When Franklin moved toward him, he became "fearful that in her hot anger she might strike me." Those who know

Franklin believe she must have been annoyed. But they also regard Watson's scene as a clever dramatic device bearing little relationship to reality. Watson was twenty-five years old and well over six feet tall; Franklin, at thirty-two, was five feet six inches tall. The idea of Franklin's physically attacking Watson seems more farce than fact.

Racing out of Franklin's lab, Watson met Wilkins in the hall. Commiserating, Wilkins went into the next room and grabbed a copy of Franklin's spectacular B-form cross. Without asking Franklin's permission or telling her what he was doing, he showed it to Watson. "Look, there's the helix, and that damned woman just won't see it," Wilkins complained.

The instant Watson saw the picture, his mouth fell open and his pulse began to race. He and Crick had been working with five-year-old photos of DNA and had had no inkling of its two forms, wet and dry. The picture told him the basic dimensions of the helix.

As Wilkins complained later, "They could not have gone on to their model, their correct model, without the data developed here. They had that—I blame myself. I was naive—and they moved ahead.... We were scooped, I don't think quite fairly." Defending himself in 1992, Watson countered, "I didn't feel guilt. The picture was old. I'm sure Maurice wouldn't have shown it to me if it had been only two weeks old."

With the race heating up, Sir Lawrence Bragg lifted his injunction against Cambridge DNA work. If the American Pauling was working on DNA, Cambridge owed it to Britain to enter the fray. As a result, Watson and Crick were hard at work. Watson was coordinating information from friends and colleagues, weaving their data together as surely as if they were all part of an interdisciplinary team.

Once Watson had won the Nobel Prize, he stopped doing research and became an administrator and textbook writer. As he explained his role in DNA, he said, "Except for my writing, all my work has been getting other people to help me. If I have to use someone else to get the answer, I'll do it.... The most important thing in science is getting the answer, not showing that you've done it yourself.... It helps you doing science if you're very social." Thanks to Watson's attitude, Franklin was competing against Watson and Crick *and* all the experts Watson queried.

The second transfer of data from Franklin to Watson and Crick involved a government report. In it, Franklin had summarized the data that she had reviewed in her November 1951 colloquium talk—the lecture that Watson had remembered incorrectly. Her report was distributed to members of the agency's review committee in December. Max Perutz, a young crystallographer who headed a research unit at Cambridge, passed the report to Watson and Crick in early February. Whether or not the report was intended to be confidential, normal etiquette would have been to ask her permission before handing her data around. Perutz apologized later, saying "I realized later that, as a matter of courtesy, I should have asked Randall for permission to show it to Watson and Crick, but in 1953 I was inexperienced and casual in administrative matters and, since the report was not confidential, I saw no reason for withholding it."

Thanks to the agency report, Crick and Watson finally had Franklin's colloquium facts accurately. They knew the water content of the fibers and the placement of the phosphate sugars on the outside of the helix. Even more important, however, Crick's reading of Franklin's report told him something that neither Franklin nor Watson knew. Elements in Franklin's data resembled horse hemoglobin crystals, which Crick had studied while writing his Ph.D. thesis. Thanks to his traditional crystallographic training and the equine connection, Crick realized that one of the outside chains of the DNA molecule must go up and the other down. That way, the molecule looks the same when it is turned upside down. Franklin was still struggling to grasp that point as she moved back and forth between the A and B forms. At this juncture, Watson and Crick finally had more data than Franklin.

Franklin brought her beautiful photograph of the wet B-form out of her drawer that same week. Starting on February 10, she began analyzing it and building models to help visualize her mathematical calculations. Sketching the A-model first, she almost figured out the key concept that Crick had already discovered: that the outside chains march up and down the outside of the molecule. In her lab book, she drew the dry A-form as a figure eight: one chain up and the other chain down. At this point she was not thinking in terms of a helix for the A-form, although the spiral S shape virtually assumes a helix, Klug noted.

Looking through the little red exercise books after her death, Klug broke away again. "Oh, it's awful. I can't bear to look at it. She's finally making the right connections between A and B. She's shuttling back and forth between the two things.... It's awful to see it." As Franklin confided later, "I could have kicked myself for not noticing it."

Franklin was still in the running, though. In fact, regarding the most important concept of all about DNA, both groups were on an equal footing. Neither Franklin nor Watson and Crick had yet discovered base pairing. The helix is visually elegant, but biologically the important point about DNA is the base pairing. It is the code that passes individual characteristics on to succeeding generations.

Crick's memory is that he suggested base-pairing on February 27.

But Watson's book claims that he, and no one else, figured that part out the next day. Using evidence uncovered by biochemist Erwin Chargaff, Watson knew that pairs of bases form the steps of the helical staircase. Building models of the molecule showed him that each step consists of a *particular pair* of bases: adenine with thymine or guanine with cytosine.

To reproduce itself, DNA simply divides in half longitudinally, leaving one outside chain attached to one of the bases; the complementary base is attached to the opposite chain. Finally, each chain makes its complement and recombines. This incredibly simple mechanism explains how genetic information can pass from generation to generation for thousands of years without change. Triumphantly, Watson and Crick showed their model to colleagues and wrote their friends. Strangely, neither told Franklin or Wilkins about it, despite the help they had received from Franklin's data.

Working on the B-form photograph in February, Franklin broke through the impasse that had blocked her for nine months. By February 23, she knew for sure that the wet B-form is helical and that its helix is made of two, not three, chains. Counting her deduction about the location of the phosphate chains on the outside of the helix, she now had two of the four vital points about DNA. She had not yet recognized the remaining two concepts: the one side down/other side up chains and the base pairing. Nevertheless, at the beginning of March, she and Gosling wrote a paper summarizing what they knew about the beautiful B-form photograph.

By the time Franklin got her manuscript typed, it was March 17, 1953. The next day, a *Nature* magazine editor called. Watson and Crick had solved the structure of DNA. They had submitted an article on March 6. The editor thought Wilkins and Franklin might like to contribute articles to accompany theirs. Hastily, Franklin revised her manuscript slightly to support Watson and Crick's hypothesis. They had won the race—even before Franklin knew they were competing.

Nature rushed the Watson and Crick article into print faster than it had published anything before. The article is scarcely one thousand words long, a mere one page. It offers a hypothesis without proofs. It cites no authorities or historical record. Nor does it credit the scientists on whose shoulders it was built. Crick and Watson could have published their theory jointly with Franklin. Instead, they merely thanked physical chemist Jerry Donohue for "constant advice and criticism." Then, in the next-to-last sentence they add ambiguously, "We have also been stimulated by a knowledge of the general nature of the unpublished experimental results and ideas of Dr. M. H. F. Wilkins, Dr. R. E. Franklin, and their co-workers at King's College, London."

Could Franklin have solved the structure of DNA on her own? Her friends and supporters have debated that ever since. Franklin has become a patron saint of feminists, and for them the answer is clear. "Had Franklin not had her work secretly taken from her and had she thus been allowed enough time to use her data to solve her puzzle, there is hardly any doubt that she would have unraveled the helix—perhaps even before Crick and Watson. For, after all, Watson and Crick would then have had to have made their own unequivocal photographs of the DNA helix. This they had not succeeded in doing," charged G. Kass-Simon in *Women of Science: Righting the Record*.

Franklin's colleague Aaron Klug thinks she was only one and a half steps away from solving DNA on her own and that she would have done so eventually: one-half step for the opposite direction of the chains and a whole step for the base pairs. Klug's opinion is not to be dismissed lightly. He was Franklin's closest collaborator and friend for four years at Birkbeck. He won a Nobel Prize for chemistry in 1982 and directs one of the world's leading molecular biology centers, the Medical Research Council Laboratory of Molecular Biology in Cambridge. Moreover, he has studied her papers and notebooks extensively, more closely than anyone else alive.

"It is rather heartbreaking to look at these notebooks and to see how close she had come to the solution by herself," Klug observed. "Crick and I argue whether she was one and a half or two steps behind. She had two things to do: She didn't know that the chains ran in opposite directions; I maintain she was almost at the point of spotting that."

"The other thing was, how do you put the bases in? She knew they had to be on the inside; and she had talked about base interchangeability. The step from base interchangeability to base pairing is a quite long one but she was poised to make it," Klug asserted. "If you steep yourself in the notebooks as I have, you get the pace.... She didn't need intuition. She had facts. She wasn't highly imaginative like Crick or Pauling, but she was a superb experimentalist, a good analyst, and she'd have done it her own way."

Watson cites a curious reason for Franklin's failure to win the DNA race. In Watson's view, Franklin lost because she was interested in the steps more than the goal, she wanted to analyze the material herself without help, and she had "no patron, no one who cared for her." According to Watson, Lord Victor Rothschild, who then chaired the Agricultural Research Council, should have helped her. Why

Rothschild? Because he was a Rothschild and she was a Franklin related to the Samuels, an important Jewish family in England. "She came from one of the most prominent Jewish families in Great Britain. We had no idea who Rosalind was," Watson protested. "She just made life difficult for Wilkins."

By that time, Franklin was so disenchanted with King's College that she had decided to leave. She asked John Desmond Bernal if she could join his group at Birkbeck College, the graduate night school of the University of London. Bernal agreed, provided that Randall let her bring her fellowship. Randall and Bernal made a gentlemanly deal: Franklin could leave and become head of her own, larger research group—a considerable promotion—but she could not work on nucleic acids. Prohibiting a scientist to think about a problem she had been working on for years is unimaginable today. But at the time, British scientists were accustomed to dividing up the research world and allocating different projects to particular laboratories. Randall was clearing the decks for Wilkins to pick up his work on DNA, free of any competition from Franklin. She was not even supposed to help Gosling finish his Ph.D. thesis. Moving to Birkbeck in mid-March, Franklin ignored Randall and quietly helped Gosling get his degree.

At Birkbeck College, Franklin settled into part of two ramshackle townhouses at 21 and 22 Torrington Square. The buildings on either side had been bombed out during the war, and the 120-year-old remains needed major repairs. Her first office, under the roof, was artfully decorated with pots and pans to catch the leaks when it rained. Each evening, she opened an umbrella and placed it carefully over her desk to protect her papers overnight. Later, she moved to a downstairs office.

Despite the raindrops, Franklin finished her coal and DNA studies there. She produced two papers crammed with DNA information that, in some respects, scientists are just catching up with. By forcing Franklin's move to Birkbeck, Randall had actually done her a favor. Over the next five years, she published seventeen articles on viruses. She established a reputation as the world's finest experimentalist for dealing with helical structures. Bernal considered her one of the "major founders of biomolecular science." Sir Lawrence Bragg said he had not believed it was possible to discover as much about viruses as she did.

Franklin led a four-person research team at Birkbeck. Besides Klug, she had two graduate students: Kenneth C. Holmes, now professor at the Max Planck Institute for Medical Research in Heidelberg, and John T. Finch, now at the MRC Laboratory of Molecular Biology at Cambridge. Klug joined the group after he met Franklin on the stairs, heard about her work, and switched research topics. He became her first and only collaborator. Known as an extraordinary theoretician, he enjoyed debating with Franklin. Together they developed "marvelously delicate techniques for securing new and beautiful X-ray data," recalled crystallographer Dorothy Hodgkin.

Franklin proved to be a commanding leader with presence and even an aura of authority about her, recalled Finch. "She knew what she wanted to do scientifically, and she knew experimentally how to get there."

She was also deeply devoted to scientific research at a very high level of performance and could be single-minded and fierce. "She could be very pleasant, and she had a sense of fun. But in the lab, she was actually quite tough. She could snap at people," Aaron Klug recalled. "It would have gone quite unremarked if she had been a man. But she stood up for things. She was rather persistent. She wasn't the saintly, nunnish figure portrayed in the BBC film *Road to the Double Helix*."

Brandeis University professor Donald Caspar, who also worked with Franklin on viruses, remembers, "The most negative things I can think about her are still admirable qualities.... She wouldn't put up with nonsense. She was a very vital human being who didn't indulge in speculation."

Reminiscing years later, Holmes said, "She had charisma. She was a fascinating, very attractive woman, and she affected all of us in a very deep way. Her friends and students have great difficulty thinking about her because it's so painful."

Had Franklin been a man in charge of the research team, she might have been called the "strong silent type." She did not suffer fools graciously. She was not soft and gentle like Hodgkin, and she did not approve of her research assistants getting distracted by romance or hobbies. At this stage in her career, she strove for results.

And as always, she resented boring social functions. At dinner in Birkbeck's common room one evening, she sat silent all through the meal as others chatted. Franklin was a bit choosy about where she put her effort and, if she did not think the occasion was important or interesting, she did not try. But late in the dinner, she decided to make a contribution. Thus, when there was a lull in the small talk, she pronounced loudly: "It's a good year for mushrooms." And that was all she said. Unaccustomed to seeing her socially, her students decided that her only flaw was an incapacity for small talk.

Otherwise, she was a good mentor. "Go on, you do the first draft," she told Holmes when they wrote their first paper. Then she turned his totally inadequate draft into a good paper. "That was one of the nicest aspects about her," Holmes recalled. "She didn't control you on a day-to-day basis."

Having studied DNA at King's College, Franklin began working on RNA (ribonucleic acid) at Birkbeck. She decided to work on viruses that are composed of both RNA and protein, RNA being the infective part of the viruses. By understanding RNA's structure, she hoped to explain how a virus particle, which is not in the full sense alive, can grow and reproduce in other cells. In Franklin's five years at Birkbeck, her group outlined the general molecular structure of several RNA-containing viruses and helped lay the foundation of structural virology. At the time, her group was the world's leader in using X-ray diffraction to uncover the molecular structure of viruses.

Like other virus researchers, she concentrated on tobacco mosaic virus (TMV). TMV was to viruses what corn and fruit flies were to genetics—the model used to establish basic scientific principles. TMV is stable, easy to handle, and abundant. She particularly liked the way TMV's long, rod-shaped particles produced detailed X-ray diffraction patterns with a wealth of information about molecular structure. She was intrigued with TMV for two other reasons too. She was convinced—correctly—that structural studies of TMV would help scientists understand the organization of other regular virus particles, including the polio virus and the common cold virus. Second, TMV's fibrous structure was even more technically challenging than DNA. Franklin's DNA research had made her the world's expert in fiber diffraction, so she was intrigued by all the difficulties involved.

Watson had hypothesized that TMV is constructed in a helix, but a different type of helix than DNA. Franklin swiftly confirmed his conclusion. But when she measured the helix, she discovered that he had underestimated the number of small protein subunits that form each turn of the helix. She also located the long single strand of RNA—the carrier of the virus's genetic information and hence the source of its infectivity. She showed that it exists—not in the helix's central cavity—but buried deep between the subunits of the virus's protein coat. For the first time, it was possible to understand the structural relationship between protein and a nucleic acid and how they fit together.

Watson and Crick actually met occasionally and exchanged information with Franklin and Klug on the virus structure project. Seeing them, Franklin was cheerful and ebullient and there was no sign of animosity among them. Franklin had great respect for Crick's ability. She became close friends with Crick and his French wife, Odile, and together they traveled through southern Spain one

summer. She was more reserved about Watson, referring to him as "the horrible American."

Franklin had a rousing argument with the director of her funding agency in 1956. Storming back from the meeting, her eyes filling with tears of rage, she complained angrily that "the ARC refuses to support any project that has a woman directing it." Fortunately, friends helped arrange for a three-year grant from the U.S. Public Health Service to continue her work at Birkbeck.

During 1956, Franklin reported on her results at conferences in London, Madrid, and New England, and visited labs in Berkeley, Los Angeles, Pasadena, St. Louis, and New Haven. At Berkeley, where Franklin worked for a month with the Nobel Prize–winner Wendell Stanley, she had trouble getting a ride to a lab picnic. Watson's stories about "Rosy," the temperamental bluestocking, had preceded her. Afraid to tangle with her, the young people in the lab wiggled out of giving her a ride. So Stanley himself drove her. At the picnic, the students discovered that Franklin was actually lively and fun, and they were forced to revise their opinions of her. Later that summer, when she climbed in the Rocky Mountains with other Americans, she befriended them as well. Nevertheless, Franklin was still an outsider in the scientific establishment.

Several episodes of terrifying pain that summer sent her to an American physician, who told her to see a specialist as soon as she got home. The diagnosis was ovarian cancer. Over the next two years, Franklin had three operations and experimental chemotherapy. She was irritated by doctors, nurses, and surgeons who refused to answer her questions. On the other hand, she refused to talk about the illness with her friends or relatives. Only her close family and research group knew much about it.

After her first bout of illness, the cancer went into remission for almost ten months and she resumed tennis and mountain climbing, theater going, and work. At one point, she convalesced with the Cricks; they did not know what her operation had been for or how serious it was, but she felt easier with friends who knew nothing. When Crick suggested that Franklin and her group move to what became the MRC Laboratory of Molecular Biology in Cambridge, her main fear was that she might become a spinster professor like those she had hated as a student. Nevertheless, she decided to move with her group.

By accident, Frederick L. Schaffer's laboratory at the University of California at Berkeley had crystallized some polio virus, the first crystals ever formed from an animal virus. Schaffer's wife agreed to try to take a thermos of the crystals to Franklin for analysis. British customs officers questioned Mrs. Schaffer about the contents of the thermos. Polio caused as much fear and hysteria in the mid-twentieth century as AIDS does today, and the tiny crystals in the thermos were fully infectious. But she replied jauntily, "It's polio virus. But it's all right. It's crystalline." She sounded so trustworthy that customs let her through.

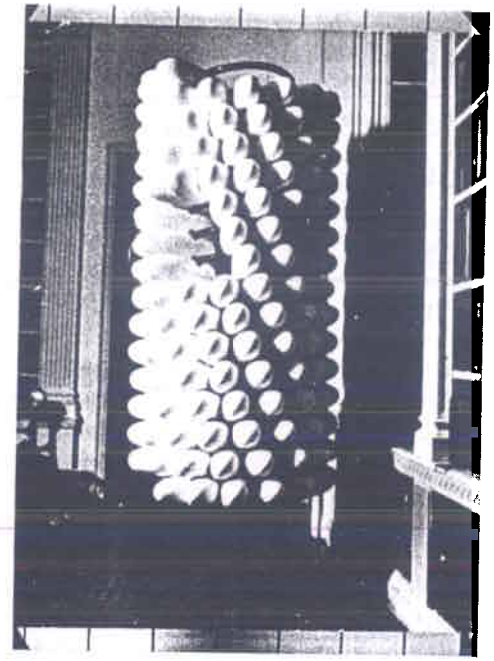
When Franklin got the thermos, she waved it at her mother. "You'll never guess what's in here," she teased. "Live polio!" Then she opened the family refrigerator and slipped the virus in.

Working with an infectious virus in a dilapidated, dirty laboratory without proper safety equipment was dangerous. The Salk vaccine had been available for only three years, and many people had not yet been vaccinated against the disease. Franklin, on the other hand, knew by now that she was dying. Watching the work, Bernal's secretary thought Franklin was a modern Marie Curie. Soon after Franklin's death, the polio work was halted because of the risks.

Franklin's work on small plant viruses attracted such widespread interest that both the august Royal Society of London and the Royal Institution of Great Britain requested material to exhibit. In 1957, the Brussels World's Fair committee asked her to build two models of virus molecules. The request was a great honor. During the 1950s before jet travel and television, world's fairs were glamorous and exciting events. She was the first scientist to know enough about the structure of a virus to build a realistic model. A revolution in biology was just beginning. For fair visitors, her model would be their first glimpse of biology in terms of the molecules that make up all living organisms.

A small plastics company produced dozens of white plastic, shoe-shaped pieces for a six-foot-tall model of TMV. Each shoe represented one molecule of the protein coat surrounding the virus. When they arrived, however, they were all slightly too big. So Franklin, Klug, Finch, and Holmes spent a day filing them down by hand. When they assembled the model, they omitted a few shoes in order to show the single strand of RNA winding around like a bracelet near the hollow section of the molecule.

Watson had thought that TMV would "self-assemble" by replicating protein subunits over and over again at the end of the growing helix. But when Franklin and Klug started putting the model together, they discovered that getting the assembly process started was actually quite difficult. Some kind of special mechanism must be involved, they concluded. Unraveling that process occupied the next decade. Scientists were so interested in the models that the Royal Institution of Great Britain displayed them before they were shipped to Brussels.



Rosalind Franklin's model of the TMV virus molecule which she built for the 1958 World's Fair, on exhibit at the Royal Institution in London before transport to Brussels.

During the last year of her life, Franklin seemed softer and easier to approach. Aware that she was dying, she worked on TMV until a few weeks before her death, putting her data in order. The day after organizing a supper party for her parents' fortieth wedding anniversary, she checked into a hospital for the last time. By her bedside, she kept an invitation from a Venezuelan laboratory to spend a year in Caracas.

On April 16, 1958, within a few minutes of the time that her last scientific paper was due to be read at the Faraday Society, Rosalind Franklin died. She was thirty-seven years old. She had made crucial contributions to one of the most important discoveries of the twentieth century. Her work on two other major biological problems and the techniques for solving them helped lay the foundations of structural molecular biology. And that summer, her virus models went on view before 42 million visitors to the Brussels World's Fair.

* * *

In 1962, four years after Franklin's death, the Nobel Prize for medicine was awarded to Francis Crick, James Watson, and Maurice Wilkins. On the basis of what the three winners said in their Nobel Prize lectures, no one would have known that Franklin had contributed to their triumph. Their three Nobel lectures cite ninety-eight references, none of them Franklin's. Only Wilkins included her in his acknowledgments.

If Franklin had lived, would she have won the Nobel Prize? Most scientists today believe that she deserved it. Nobels are given only to living persons, however, and each prize can have no more than three winners. Would the committee have known about her contributions? And if it had, would the committee have been willing to give a third of the prize to her and not to Wilkins? Or would the committee have awarded two prizes, one in medicine and the other in chemistry, and split them among four winners?

"The Nobel committees have sometimes made quirky awards, omissions and downright mistakes, but we cannot doubt that the value of her work was known," the historian Judson concluded. Everyone in Randall's unit at King's College knew her work; so did Crick. Bragg, a crystallographer, would have understood the importance of her published articles. It was he who insisted that King's College in the person of Wilkins share the Nobel Prize. Furthermore, when the Nobel Committee studied the publications of the four scientists, they would have realized that Franklin's papers contained by far the most hard data. Had she lived, she might well have shared the Nobel Prize for one of the twentieth century's greatest scientific achievements.

Six years after Watson got a Nobel Prize, he wrote *The Double Helix,* a breezy account of his DNA experiences. He catalogued everyone's foibles and idiosyncrasies, from his first sentence ("I have never seen Francis Crick in a modest mood") to Sir Lawrence Bragg ("I quietly concluded that the white-mustached figure of Bragg now spent most of its days sitting in London clubs like the Athenaeum"). The manuscript raised a storm. As drafts were passed around and subjects complained about their treatment, Watson softened and modified some of his portraits—except Rosalind Franklin's. She was dead and could not argue.

In Watson's book, Franklin plays the role of "Rosy," the wicked stepmother. She is both Watson's central rival and the stereotypical old maid who keeps the plot line moving. Besides denigrating her personality, Watson attacked her scientific abilities, accusing her of being categorically "anti-helical" and opposed to model-building. Fortunately, Watson could not let a good story go to waste, so he also related how he and Crick used her data from the funding agency report and her X-ray diffraction photograph of DNA.

In response to complaints from Franklin's friends, Watson added an epilogue to the book. It stated that his "initial impressions of her, both scientific and personal…were often wrong." But he did not change his portrayal of her in the book. His fictionalized stereotype of a woman who has abandoned her femininity for science made the book more readable and exciting.

Some scientists praised its lighthearted rendition of scientific research. Others were outraged. "He has carelessly robbed Rosalind of her personality," Anne Sayre protested. Dismissing Watson as a case of retarded emotional development, the Nobel Prize–winner André Lwoff charged that "his portrait of Rosalind Franklin is cruel.…At the very least, the fact that all the work of Watson and Crick starts with Rosalind Franklin's X-ray pictures and that Jim has exploited Rosalind's results should have inclined him to indulgence." Robert L. Sinsheimer complained that the book is "unbelievably mean in spirit, filled with the distorted and cruel perceptions of childish insecurity." "It was a mean, mean book," observed Nobel Prize–winner Barbara McClintock. Watson is an excellent writer but arrogant and a well-known antifeminist, commented Nobel Prize–winner Rita Levi-Montalcini. David Sayre believed that Watson's book lowered the moral tone of scientific research by glorifying "the big grab for credit." To restore Franklin's scientific reputation, Klug wrote two papers outlining her DNA contributions for *Nature* magazine in 1968 and 1974.

The controversy continues to this day. As late as 1989, Anthony Serafini's biography of Linus Pauling stated, "There are so many actual and possible degrees of unethical behavior that it is difficult to draw the line. Sometimes, of course, the case is clear, as when James Watson made use of Rosalind Franklin's data without crediting her in the famed DNA race.…Certainly Watson and Crick would not have gotten the Nobel Prize had they not stolen her data."

Despite such criticism, Watson asserted early in 1992 that if he were writing the book again today, he would write it the same way. "Because that was the way it happened. I told it like it was. But you get into trouble when you tell it like it happened."

In the short run, the book enhanced Watson's reputation as a brash and brilliant young scientist on the move. In the long run, it contained a time bomb. His admission that he had used Franklin's data without her knowledge has tarnished not only his brilliant achievement but Crick's as well. And his fictionalized portrayal of her personality and scientific achievements has made her the martyred saint of feminists and women scientists. The oddest element of the entire story is that it was Watson himself who brought the facts of her contributions to light. He cast a shadow on his own achievement and shone the sun on hers.

EPILOGUE

In January 1992 the English Heritage society placed a historical marker outside Franklin's apartment at 22 Donovan Court, Drayton Gardens, in the Kensington neighborhood of London. The plaque is inscribed: "Rosalind Franklin, 1920–1958, pioneer of the study of molecular structures including DNA, lived here 1951–1958."

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14

Rosalyn Sussman Yalow

July 19, 1921–

MEDICAL PHYSICIST

Nobel Prize 1977

When Rosalyn Sussman Yalow's brother was a first-grader, his teacher smacked his hand with a ruler. He promptly burst into tears and threw up. Five years later, when Rosalyn entered first grade, the same teacher hit Rosalyn with a ruler. Rosalyn struck back. Marched to the principal's office for questioning, Rosalyn explained that she had been waiting for years to avenge her older brother.

Amused and proud, her parents encouraged Yalow's combative spirit. They staged a triumphant photograph in the park: Rosalyn, a tiny five-year-old wearing enormous man-sized boxing gloves, looms over her brother. He lies sprawled on his back, looking as if she had knocked him out in a ferocious fight. The snapshot has become crinkled and faded with time, but Yalow keeps it handy in her desk. Smoothing the photo, she says, "That's the attitude that made it possible for me to go into physics."

This is the Yalow—part protective Earth Mother, part Aggressive Warrior—who helped invent a technique so sensitive that it can detect a teaspoonful of sugar in a body of water sixty-two miles long, sixty-two miles wide, and thirty feet deep. Thanks to their daring, she and her scientific partner, Solomon A. Berson, developed the radioimmunoassay (RIA) procedure. Thanks to their determination, they convinced the scientific community of its value. In 1977, after Berson's death, Yalow won the Nobel Prize for their discovery. She was the first American-born woman to win a Nobel Prize in science.

RIA revolutionized endocrinology—the study of ductless glands and hormones—and the treatment of hormonal disorders like diabetes. For the first time, doctors could diagnose conditions caused by minute changes in hormones. Thanks to Yalow and Berson, dwarfed children can be treated with human growth hormones; newborns are