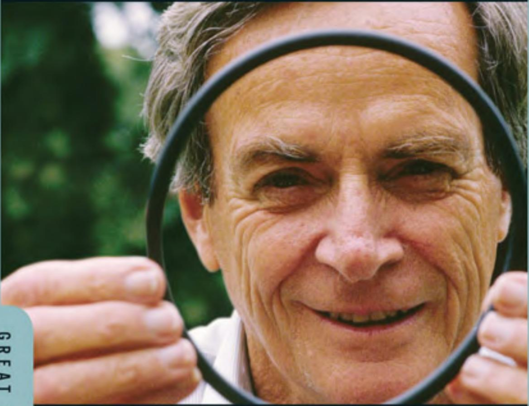
QUANTUM MAN

Richard Feynman's Life in Science



LAWRENCE M. KRAUSS

GREAT DISCOVERIES

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Richard Feynman's Life in Science

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Introduction

> I find physics is a wonderful subject. We know so very much and then subsume it into so very few equations that we can say we know very little.
>
> —Richard Feynman, 1947

It is often hard to disentangle reality from imagination when it comes to childhood memories, but I have a distinct recollection of the first time I thought that being a physicist might actually be exciting. As a child I had been fascinated with science, but the science I had studied was always removed from me by at least a half century, and thus it hovered very close to history. The fact that not all of nature's mysteries had been solved was not yet firmly planted in my mind.

The epiphany occurred while I was attending a high school summer program on science. I don't know if I appeared bored or not, but my teacher, following our regularly scheduled lesson, gave me a book titled *The Character of Physical Law* by Richard Feynman and told me to read the chapter on the distinction between past and future. It was my first contact with the notion of entropy and disorder, and like many people before me, including the great physicists Ludwig Boltzmann and Paul Ehrenfest, who killed themselves after devoting much of their careers to developing this subject, it left me befuddled and frustrated. How the world changes as one goes from considering simple problems involving two objects, like the earth and the moon, to a system involving many particles, like the gas molecules in the room in which I am typing this, is both subtle and profound—no doubt too subtle and profound for me to appreciate at the time.

But then, the next day, my teacher asked me if I had ever heard of antimatter, and he proceeded to tell me that this same guy Feynman had recently won the Nobel Prize because he explained how an antiparticle could be thought of as a particle going backward in time. Now that really fascinated me, although I didn't understand any of the details (and in retrospect I realize my teacher didn't either). But the notion that these kinds of discoveries were happening during my lifetime inspired me to think that there was a lot left to explore. (Actually while my conclusion was true, the information that led to it wasn't. Feynman had published his Nobel Prize–winning work on quantum electrodynamics almost a decade before I was born, and the ancillary idea that antiparticles could be thought of as particles going backward in time wasn't even his. Alas, by the time ideas filter down to high school teachers and texts, the physics is usually twenty-five to thirty years old, and sometimes not quite right.)

As I went on to study physics, Feynman became for me, as he did for an entire generation, a hero and a legend. I bought his *Feynman Lectures on Physics* when I entered college, as did most other aspiring young physicists, even though I never actually took a course in which these books were used. But also like most of my peers, I continued to turn to them long after I had moved on from the so-called introductory course in physics on which his books were based. It was while reading these books that I discovered how my summer experience was oddly reminiscent of a similar singular experience that Feynman had had in high school. More about that later. For now I will just say that I only wish the results in my case had been as significant.

It was probably not until graduate school that I fully began to understand the ramifications of what that science teacher had been trying to relate to me, but my fascination with the world of fundamental particles, and the world of this interesting guy Feynman, who wrote about it, began that summer morning in high school and in large part has never stopped. I just remembered, as I was writing this, that I chose to write my senior thesis on path integrals, the subject Feynman pioneered.

Through a simple twist of fate, I was fortunate enough to meet and spend time with Richard Feynman while I was still an undergraduate. At the time I was involved with an organization called the Canadian Undergraduate Physics Association, whose sole purpose was to organize a nationwide conference during which distinguished physicists gave lectures and undergraduates presented results from their summer research projects. It was in 1974, I think, that Feynman had been induced (or seduced, I don't know and shouldn't presume) by the very attractive president of the organization to be the keynote speaker at that year's conference in Vancouver. At the meeting I had the temerity to ask him a question after his lecture, and a photographer from a national magazine took a picture of the moment and used the photo, but more important, I had brought my girlfriend along with me, and one thing led to another and Feynman spent much of the weekend hanging out with the two of us in some local bars.

Later, while I was at graduate school at MIT, I heard Feynman lecture several times. Years later still, after I had received my PhD and moved to Harvard, I presented a colloquium at Caltech, and Feynman was in the audience, which was slightly unnerving. He politely asked a question or two and then came up afterward to continue the discussion. I expect he had no memory of our meeting in Vancouver, and I am forever regretful of the fact that I never found out, because while he waited patiently to talk to me, a persistent and rather annoying young assistant professor monopolized the discussion until Feynman finally walked off. I never saw him again, as he died a few years later.

RICHARD FEYNMAN WAS a legend for a whole generation of physicists long before anyone in the public knew who he was. Getting a Nobel Prize may have put him on the front page of newspapers around the world, but the next day there are new headlines, and any popular name recognition usually lasts about as long as the newspaper itself. Feynman's popular fame thus did not arise from his scientific discoveries, but began through a series of books recounting his personal reminiscences. Feynman the raconteur was every bit as creative and fascinating as Feynman the physicist. Anyone who came into personal contact with him had to be struck immediately by his wealth of charisma. His piercing eyes, impish smile, and New York accent combined to produce the very antithesis of a stereotypical scientist, and his personal fascination with such things as bongo drums and strip bars only added to his mystique.

As often happens however, the real catalyst that made Feynman a public figure arose by accident, in this case a tragic accident: the explosion shortly after liftoff of the *Challenger* space shuttle, which was carrying the first "civilian," a public school teacher who was scheduled to teach some classes from space. During the investigation that ensued, Feynman was asked to join the NASA investigatory panel, and in an uncharacteristic moment (he studiously avoided committees and anything else that kept him away from his work), he agreed.

Feynman pursued the task in his own, equally uncharacteristic way. Rather than study reports and focus on bureaucratic proposals for the future, Feynman talked directly to the engineers and scientists at NASA, and in a famous moment during the televised hearings, he performed an experiment, putting a small rubber O-ring in a glass of ice water and thus demonstrating that the O-rings used to seal the rocket could fail under temperatures as cold as those on the day of the ill-fated launch.

Since that day, books chronicling his reminiscences, compilations of his letters, audiotapes of "lost lectures," and so on, have appeared, and following his death, his legend has continued to grow. Popular Feynman biographies have also been published, with the most notable being Jim Gleick's masterful *Genius.*

Feynman the human being will always remain fascinating, but when I was approached about producing a short and accessible volume that might reflect Feynman the man as seen through his scientific contributions, I couldn't resist. The exercise motivated me because I would be reviewing all of his original papers. (Most people may not realize that it is rare for scientists to go back to the original literature in their field, especially if the work is more than a generation old. Scientific ideas get distilled and refined, and most modern presentations of the same physics often bear very little resemblance to the initial formulations.) But more important, I realized that Feynman's physics provides, in microcosm, a perspective on the key developments in physics over the second half of the twentieth century, and many of the puzzles he left unresolved remain with us today.

In what follows I have tried to do justice to both the letter and the spirit of Feynman's work in a way in which he might have approved. Perhaps for this reason, this book is first and foremost about Feynman's impact on our current understanding of nature, as reflected within the context of a personal scientific biography. I will devote little space to the many arcane blind alleys and red herrings that lure even the most successful scientists—and Feynman was no exception—as they claw their way to scientific understanding. It is hard enough, without having to sort through these false starts, for nonexperts to gain a proper perspective of what physicists have learned about the natural world. No matter how elegant or brilliant some of the false starts may be, ultimately what matters are the ideas that have survived the test of time by satisfying the test of experiment.

My modest goal therefore is to focus on Feynman's scientific legacy as it has affected the revolutionary discoveries of twentieth-century physics, and as it may impact any unraveling of the mysteries of the twenty-first century. The insight I really want to reveal to nonphysicists, if I can, is why Feynman has reached the status of a mythic hero to most physicists now alive on the planet. If I can capture that, I will have helped readers understand something central about modern physics and Feynman's role in changing our picture of the world. That, to me, is the best testimony I can give to the genius that was Richard Feynman.

PART I

The Paths to Greatness

> Science is a way to teach how something gets to be known, what is not known, to what extent things are known (for nothing is known absolutely), how to handle doubt and uncertainty, what the rules of evidence are, how to think about things so that judgments can be made, how to distinguish truth from fraud, and from show.
>
> —Richard Feynman

CHAPTER 1

Lights, Camera, Action

> Perhaps a thing is simple if you can describe it fully in several different ways without immediately knowing that you are describing the same thing.
>
> —Richard Feynman

Could one have guessed while he was still a child that Richard Feynman would become perhaps the greatest, and probably the most beloved, physicist of the last half of the twentieth century? It is not so clear, even if many of the incipient signs were there: He was undeniably smart. He had a nurturing father who entertained him with puzzles and instilled a love of learning, encouraging his innate curiosity and feeding his mind whenever possible. And he had a chemistry set and displayed a fascination with radios.

But these things were not that uncommon for bright youngsters at the time. In most fundamental respects Richard Feynman appeared to be a typical smart Jewish kid from Long Island growing up after the First World War. Perhaps it is that simple fact, as much as anything else, that colored his future place in history. His mind was extraordinary, yes, but he remained firmly grounded in reality, even as he was driven to explore the most esoteric realms of our existence. His disrespect for pomposity came from an early life in which he was not exposed to any, and his disrespect for authority came not only from a father who nurtured this independence but also from an early life in which he was remarkably free to be a child, to follow his own passions, and to make his own mistakes.

Perhaps the first signal of what was to come was Feynman's literally indefatigable ability to concentrate on a problem for hours at a time, so much so that his parents began to worry. As a teenager, Feynman made practical use of his fascination with radios: he opened a small business fixing them. But unlike conventional repairmen, Feynman would delight in solving radio problems not merely by tinkering, but by thinking!

And he would combine this remarkable ability to focus all of his energy on a problem with an innate talent as a showman. His most famous radio repair, for example, involved an episode where he paced back and forth thinking while the broken radio shrieked in front of its owner whenever it was first turned on. Finally young Feynman pulled out two tubes and exchanged them, solving the problem. My suspicion is that Feynman let the whole thing last longer than it needed to, just for effect.

In later life almost exactly the same story would be told again. But this one originated when a skeptical Feynman was asked to examine a puzzling photograph from a bubble chamber—a device where elementary particles would leave visible tracks. After thinking for a while, he placed his pencil down on a precise spot in the picture and claimed that there must be a bolt located right there, where a particle had had an unanticipated collision, producing results that otherwise had been misinterpreted. Needless to say, when the experimenters involved in the claimed discovery went back to their device and looked at it, there was the bolt!

The showmanship, while contributing to the Feynman lore, was not important to his work however. Neither was his fascination with women, which also emerged later. The ability to concentrate, combined with an almost superhuman energy that he could apply to a problem, was. But the final essential icing on the cake, when combined with the former two characteristics, ultimately ensured his greatness. It involved simply an almost unparalleled talent for mathematics.

Feynman's mathematical genius began to manifest itself by the time he was in high school. While a sophomore he taught himself trigonometry, advanced algebra, infinite series, analytical geometry, and differential and integral calculus! And in his self-learning, the other aspect of what made Feynman so unique began to materialize: he would recast all knowledge in his own way, often inventing a new language or new formalism to reflect his own understanding. In certain cases necessity was the mother of invention. When typing out a manual on complex mathematics, in 1933, at the age of fifteen, he devised "typewriter symbols" to reflect the appropriate mathematical operations, since his typewriter did not have keys to represent them, and created a new notation for a table of integrals that he had developed.

Feynman entered MIT with the intent to study mathematics, but it was a misplaced notion. Even though he loved mathematics, he forever wanted to know what he could "do" with it. He asked the chairman of the mathematics department this question and got two different answers: "Insurance estimates," and "If you have to ask that, then you don't belong in mathematics." Neither resonated with Feynman, who decided mathematics wasn't for him, so he switched to electrical engineering. Interestingly, this switch seemed too extreme. If mathematics was without purpose, engineering was too practical. Like the soup in the Goldilocks tale, however, physics was "just right," and by the end of his freshman year Feynman had become a physics major.

The choice of course was an inspired one. Feynman's innate talents allowed him to excel in physics. But he had another talent that mattered even more perhaps, and I don't know if it was innate or not. This was intuition.

Physical intuition is a fascinating, ephemeral kind of skill. How does one know which avenue of approach will be most fruitful to solve a physics problem? No doubt some aspects of intuition are acquired. This is why physics majors are required to solve so many problems. In this way, they begin to learn which approaches work and which don't, and increase their toolkit of techniques along the way. But surely some aspect of physical intuition cannot be taught, one that resonates at a certain place and time. Einstein had such intuition, and it served him well for over twenty years, from his epochal work on special relativity to his crowning achievement, general relativity. But his intuition began to fail him as he slowly drifted away from the mainstream of interest in quantum mechanics in the twentieth century.

Feynman's intuition was unique in a different way. Whereas Einstein developed completely new theories about nature, Feynman explored existing ideas from a completely new and usually more fruitful perspective. The only way he could really understand physical ideas was to derive them using his own language. But because his language was usually also self-taught, the end results sometimes differed radically from what "conventional" wisdom produced. As we shall see, Feynman created his own wisdom.

But Feynman's intuition was also earned the hard way, based on relentless labor. His systematic approach and the thoroughness with which he examined problems were already evident in high school. He recorded his progress in notebooks, with tables of sines and cosines he had calculated himself, and later on in his comprehensive calculus notebook, titled "The Calculus for the Practical Man," with extensive tables of integrals, which again he had worked out himself. In later life he would amaze people by proposing a new way to solve a problem, or by grasping immediately the heart of a complex issue. More often than not this was because at some time, in the thousands of pages of notes he kept as he worked to understand nature, Feynman had thought about that very problem and explored not just one, but a host of different ways of solving it. It was this willingness to investigate a problem from every vantage point, and to carefully organize his thinking until he had exhausted all possibilities—a product of his deep intellect and his indefatigable ability to concentrate—that set him apart.

Perhaps *willingness* is the wrong word here. *Necessity* would be a better choice. Feynman needed to fully understand every problem he encountered by starting from scratch, solving it in his own way and often in several different ways. Later on, he would try to imbue this same ethic to his students, one of whom later said, "Feynman stressed creativity—which to him meant working things out from the beginning. He urged each of us to create his or her own universe of ideas, so that our products, even if only answers to assigned classwork problems, would have their own original character—just as his own work carried the unique stamp of his personality."

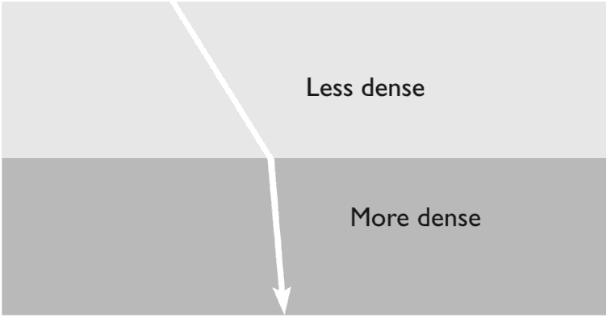
Not only was Feynman's ability to concentrate for long periods evident when he was young, but so was his ability to control and organize his thoughts. I remember having a chemistry set when I was a kid and I also remember often randomly throwing things together to see what would happen. But Feynman, as he later emphasized, "never played chaotically with scientific things." Rather he always carried out his scientific "play" in a controlled manner, always attentive to what was going on. Again, much later, after his death, it became clear from the extensive notes he took that he carefully recorded each of his explorations. He even considered at one point organizing his domestic life with his future wife along scientific lines, before a friend convinced him that he was being hopelessly unrealistic. Ultimately, his naivete in this regard disappeared, and much later he advised a student, "You cannot develop a personality with physics alone. The rest of life must be worked in." In any case, Feynman loved to play and joke, but when it came to science, starting early on and continuing for the rest of his life, Feynman could be deadly serious.

He may have waited until the end of his first year of university to declare himself a physics major, but the stars aligned when he was still in high school. In retrospect, what might have been the defining moment occurred when his high school teacher, Mr. Bader, introduced him to one of the most subtle and wonderful hidden mysteries of the observable world, a fact that had built on a discovery made three hundred years before he was born by a brilliant and reclusive lawyer-turned-mathematician, Pierre de Fermat.

Like Feynman, Fermat would achieve public recognition late in life for something that was unrelated to his most substantial accomplishments. In 1637, Fermat scrawled a brief note in the margin of his copy of *Arithmetica*, the masterpiece by the famous Greek mathematician Diophantus, indicating that he had discovered a simple proof of a remarkable fact. The equation $x^n + y^n = z^n$ has no integer solutions if $n \geq 2$ (for $n = 2$, this is familiar as the Pythagorean theorem relating lengths of the sides of a right triangle). It is doubtful that Fermat really possessed such a proof, which 350 years later required almost all of the developments of twentieth-century mathematics and several hundred pages to complete. Nevertheless, if Fermat is remembered at all today among the general public, it is not for his many key contributions to geometry, calculus, and number theory, but rather for this speculation in the margin that will forever be known as *Fermat's last theorem.*

Twenty-five years after making this dubious claim, Fermat did present a complete proof of something else, however: a remarkable and almost otherworldy principle that established an approach to physical phenomena that Feynman would use later to change the way we think about physics in the modern world. The issue to which Fermat turned his attention in 1662 involved a phenomenon the Dutch scientist Willebrord Snell had described forty years earlier. Snell discovered a mathematical regularity in the way light is bent, or refracted, when it crosses between two different media, such as air and water. Today we call this Snell's law, and it is often presented in high school physics classes as yet one additional tedious fact to be memorized, even though it played a profoundly important role in the history of science.

Snell's law pertains to the angles that a light ray makes when transmitted across the surface between two media. The exact form of the law is unimportant here; what is important is both its general character and its physical origin. In simple terms, the law states that when light goes from a less dense to a more dense medium, the trajectory of the light ray is bent closer to the perpendicular to the surface between the media (see figure).



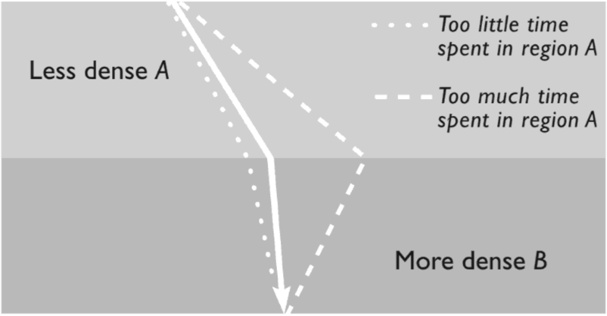
Snell's law

Now, why does the light bend? Well, if light were made up of a stream of particles, as Newton and others thought, one could understand this relationship if the particles speed up as they move from one medium to the other. They would literally be dragged forward, moving more effectively in a direction perpendicular to the surface they had just crossed. However, this explanation seemed fishy even at the time. After all, in a more dense medium any such particles would presumably encounter a greater resistance to their motion, just as cars on a road end up moving more slowly in heavy traffic.

There was another possibility, however, as the Dutch scientist Christiaan Huygens demonstrated in 1690. If light were a wave and not made of particles, then just as a sound wave bends inward when it slows down, the same would occur for light if it too slowed down in the denser medium. As anyone familiar with the history of physics knows, light does indeed slow down in denser media, so that Snell's law provides important evidence that light behaves, in this instance, like a wave.

Amost thirty years before Huygens's work, Fermat too reasoned that light should travel more slowly in dense media than in less dense media. Instead of thinking in terms of whether light was a wave or particle, however, Fermat the mathematician showed that in this case one could explain the trajectory of light in terms of a general mathematical principle, which we now call *Fermat's principle of least time.* As he demonstrated, light would follow precisely the same bending trajectory determined by Snell if "light travels between two given points along the path of shortest time."

Heuristically this can be understood as follows. If light travels more quickly in the less dense medium, then to get from *A* to *B* (see figure) in the shortest time, it would make sense to travel a longer distance in this medium, and a shorter distance in the second medium in which it travels more slowly. Now, it cannot travel for too long in the first medium, otherwise the extra distance it travels would more than overcome the gain obtained by traveling at a faster speed. One path is just right, however, and this path turns out to involve a bending trajectory that exactly reproduces the trajectory Snell observed.



Snell's law

Fermat's principle of least time is a mathematically elegant way of determining the path light takes without recourse to any mechanistic description in terms of waves or particles. The only problem is that when one thinks about the physical basis of this result, it seems to suggest *intentionality*, so that, like a commuter in Monday-morning rush-hour listening to the traffic report, light somehow considers all possible paths before embarking on its voyage, and ultimately chooses the one that will get it to its destination fastest.

But the fascinating thing is that we don't need to ascribe any intentionality to light's wanderings. Fermat's principle is a wonderful example of an even more remarkable property of physics, a property that is central to the amazing and a priori unexpected fact that nature is comprehensible via mathematics. If there is any one property that was a guiding light for Richard Feynman's approach to physics, and essential to almost all of his discoveries, it was this one, which he thought was so important that he referred to it at least two different times during his Nobel Prize address. First, he wrote,

> It always seems odd to me that the fundamental laws of physics, when discovered, can appear in so many different forms that are not apparently identical at first, but, with a little mathematical fiddling you can show the relationship. . . . it was something I learned from experience. There is always another way to say the same thing that doesn't look at all like the way you said it before. . . . I think it is somehow a representation of the simplicity of nature. I don't know what it means, that nature chooses these curious forms, but maybe that is a way of defining simplicity. Perhaps a thing is simple if you can describe it fully in several different ways without immediately knowing that you are describing the same thing.

And later (and more important for what was to come), he added,

> Theories of the known, which are described by different physical ideas, may be equivalent in all their predictions and are hence scientifically indistinguishable. However, they are not psychologically identical when trying to move from that base into the unknown. For different views suggest different kinds of modifications which might be made and hence are not equivalent in the

> hypotheses one generates from them in one's attempt to understand what is not yet understood.

Fermat's principle of least time clearly represents a striking example of this strange redundancy of physical law that so fascinated Feynman, and also of the differing "psychological utilities" of the different prescriptions. Thinking about the bending of light in terms of electric and magnetic forces at the interface between media reveals something about the properties of the media. Thinking about it in terms of the speed of light itself reveals something about light's intrinsic wavelike character. And thinking about it in terms of Fermat's principle may reveal nothing about specific forces or about the wave nature of light, but it illuminates something deep about the nature of motion. Happily, and importantly, all of these alternate descriptions result in identical predictions.

Thus we can rest easy. Light does not *know* it is taking the shortest path. It just *acts* like it does.

IT WASN'T THE principle of least time, however, but an even subtler idea that changed Feynman's life that fateful day in high school. As Feynman later described it, "When I was in high school, my physics teacher—whose name was Mr. Bader—called me down one day after physics class and said, 'You look bored; I want to tell you something interesting.' Then he told me something that I found absolutely fascinating, and have, since then, always found fascinating . . . the principle of least action." *Least action* may sound like an expression that is more appropriate to describing the behavior of a customer service representative at the phone company than a field like physics, which is, after all, centered around describing actions. But the least action principle is very similar to Fermat's principle of least time.

The principle of least time tells us that light always takes the path of shortest time. But what about baseballs and cannonballs, planets, and boomerangs? They don't necessarily behave so simply. Is there something other than *time* that is minimized whenever these objects follow the paths prescribed by the forces acting on them?

Consider any object in motion, say, a falling weight. Such an object is said to possess two different kinds of energy. One is *kinetic energy*, and it is related to the motion of objects (and derives from the Greek word for movement). The faster an object moves, the larger the kinetic energy. The other part of an object's energy is much subtler to ascertain, as reflected in its name: *potential energy*. This kind of energy may be hidden, but it is responsible for the ability of an object to do work later on. For example, a heavy weight falling off the top of a tall building will do more damage (and hence more work) smashing the roof of a car, than will a similar weight dropped from several inches above the car. Clearly the higher the object, the greater its potential to do work, and hence the greater its potential energy.

Now, what the least action principle states is that the *difference* between the kinetic energy of an object at any instant and its potential energy at the same instant, when calculated at each point along a path and then added up along the path, will be smaller for the actual path the object takes than for any other possible trajectory. An object somehow adjusts its motion so the kinetic energy and the potential energy are as closely matched, on average, as is possible.

If this seems mysterious and unintuitive, that is because it is mysterious and unintuitive. How on earth would anyone ever come up with this combination in the first place, much less apply it to the motion of everyday objects?

For this we thank the French mathematician-physicist Joseph Louis Lagrange, who is best known for his work on celestial mechanics. For example, he determined the points in the solar system where the gravitational attraction from the different planets precisely cancels the gravitational attraction from the sun. They are called Lagrange points. NASA now sends numerous satellites out to these points so that they can remain in stable orbits and study the universe.

Lagrange's greatest contribution to physics, however, may have involved his reformulation of the laws of motion. Newton's laws relate the motion of objects to the net forces acting on them. However, Lagrange managed to show that Newton's laws of motion were precisely reproduced if one used the "action," which is the sum over a path of the differences between kinetic an potential energy, now appropriately now called a Lagrangian, and then determined precisely what sorts of motion would produce those paths that minimized this quantity. The process of minimization, which required the use of calculus (also invented by Newton), gave very different mathematical descriptions of motion from Newton's laws, but, in the spirit of Feynman, they were mathematically identical, even if "psychologically" very different.

IT WAS THIS strange principle of least action, often called Lagrange's principle, that Mr. Bader introduced the teenaged Feynman to. Most teens would not have found it fascinating or even comprehensible, but Feynman did, or so he remembered when he was older.

However, if the young Feynman had any inkling at the time that this principle would return to completely color his own life story, he certainly didn't behave that way as he began to learn more about physics once he entered MIT. Quite the contrary. His best friend as an undergraduate at MIT, Ted Welton, with whom he worked through much of undergraduate and even graduate physics, later described Feynman's "maddening refusal to concede that Lagrange might have something useful to say about physics. The rest of us were appropriately impressed with the compactness, elegance and utility of Lagrange's formulation, but Dick stubbornly insisted that real physics lay in identifying all the forces and properly resolving them into components."

Nature, like life, takes all sorts of strange twists and turns, and most important, it is largely insensitive to one's likes and dislikes. As much as Feynman tried early on to focus on understanding motion in a way that meshed with his naive intuition, his own trajectory to greatness involved a very different path. There was no unseen hand guiding him. Instead, he forced his intuition to bend to the demands of the problems of the time, rather than vice versa. The challenge required endless hours and days and months of hard work training his mind to wrap around a problem that the greatest minds in twentieth-century physics had, up to that point, not been able to solve.

When he really needed it, Feynman would find himself returning once again to the very principle that had turned him on to physics in the first place.

CHAPTER 2

The Quantum Universe

> I was always worried about the physics. If the idea looked lousy, I said it looked lousy. If it looked good, I said it looked good.
>
> —Richard Feynman

Feynman was fortunate to have stumbled upon Ted Welton in his sophomore year at MIT, while both were attending, as the only two sophomores, an advanced graduate course in theoretical physics. Kindred spirits, each had been checking advanced mathematics texts out of the library, and after a brief period of trying to outdo each other, they decided to collaborate "in the struggle against a crew of aggressive-looking seniors and graduate students" in the class.

Together they pushed each other to new heights, passing back and forth a notebook in which each would contribute solutions and questions on topics ranging from general relativity to quantum mechanics, each of which they apparently had taught themselves. Not only did this encourage Feynman's seemingly relentless quest to derive all of physics on his own terms, but also it provided some object lessons that would stay with him for the rest of his life. One in particular is worth noting. Feynman and Welton tried to determine the energy levels of electrons in a hydrogen atom by generalizing the standard equation of quantum mechanics, called the *Schrödinger equation*, to incorporate the results of Einstein's special relativity. In so doing they rediscovered what was actually a well-known equation, the Klein-Gordon equation. Unfortunately, after Welton urged Feynman to apply this equation to understand the hydrogen atom, the attempt produced results that completely disagreed with experimental results. This is not surprising because the Klein-Gordon equation was known to be the wrong equation to use to describe relativistic electrons, as the brilliant theoretical physicist Paul Dirac had demonstrated only a decade earlier, in the process of earning the Nobel Prize for deriving the right equation.

Feynman described his experience as a "terrible" but very important lesson that he never forgot. He learned not to rely on the beauty of a mathematical theory or its "marvelous formality," but rather to recognize that the test of a good theory was whether one could "bring it down against the real thing"—namely, experimental data.

Feynman and Welton were not learning all of physics completely on their own. They also attended classes. During the second semester of their sophomore year they had sufficiently impressed the professor of their theoretical physics course, Philip Morse, that he invited the two of them, along with another student, to study quantum mechanics with him in a private tutorial one afternoon a week during their junior year. Later he invited them to start a "real research" program in which they calculated properties of atoms more complicated than hydrogen, and in the process they also learned how to work the first generation of so-called calculating machines, another skill that would later serve Feynman well.

By the time of his final year as an undergraduate, Feynman had essentially mastered most of the undergraduate and graduate physics curricula, and he had already become excited enough by the prospect of a research career that he made the decision to proceed on to graduate school. In fact, his progress had been so impressive that during his junior year the physics department recommended that he be granted a bachelor's degree after three years instead of four. The university denied the recommendation, so instead, during his senior year, he continued his research and wrote a paper on the quantum mechanics of molecules that was published in the prestigious *Physical Review*, as was a paper on cosmic rays. He also took some time to reinforce his fundamental interest in the applications of physics, and enrolled in metallurgy and laboratory courses—courses that would later serve him well in Los Alamos—and even built an ingenious mechanism to measure the speeds of different rotating shafts.

Not everyone was convinced that Feynman should take the next major step in his education. Neither of his parents had completed a college education, and the rationale for their son completing yet another three or four years of study beyond an undergraduate degree was unclear. Richard's father, Melville Feynman, visited MIT in the fall of 1938 to speak to Professor Morse and ask if it was worth it, if his son was good enough. Morse answered that Feynman was the brightest undergraduate student he had ever encountered, and yes, graduate school not only was worth it, but was required if Feynman wanted to continue a career in science. The die was cast.

Feynman's preference was to stay on at MIT. However, wise physics professors generally encourage their students, even their best ones, to pursue their graduate studies at a new institution. It is important for students to get a broad exposure early in their career to the different styles of doing science, and to different focuses of interest, as spending an entire academic career at one institution can be limiting for many people. And so it was that Richard Feynman's senior dissertation advisor, John Slater, insisted that he go to graduate school elsewhere, telling him, "You should find out what the rest of the world is."

Feynman was offered a scholarship to Harvard for graduate school without even applying because he had won the William Lowell Putnam Mathematical Competition in 1939. This is the most prestigious and demanding national mathematics contest open to undergraduates, and was then in its second year. I remember when I was an undergraduate the very best mathematics students would join their university's team and solve practice problems for months ahead of the examination. No one solves all the problems on the exam, and in many years a significant fraction of the entrants fail to solve a single problem. The mathematics department at MIT had asked Feynman to join MIT's team for the competition in his senior year, and the gap between Feynman's score and the scores for all of the other entrants from across the country apparently astounded those grading the exam, so he was offered the Harvard prize scholarship. Feynman would later sometimes feign ignorance of formal mathematics when speaking about physics, but his Putnam score demonstrated that as a mathematician, he could compete with the very best in the world.

But Feynman turned down Harvard. He had decided he wanted to go to Princeton, I expect for the same reason why so many young physicists wanted to go there: that was where Einstein was! Princeton had accepted him and offered him a job as future Nobel laureate Eugene Wigner's research assistant. Fortunately for Feynman, he was assigned instead to a young assistant professor, John Archibald Wheeler, a man whose imagination matched Feynman's mathematical virtuosity.

In a remembrance of Feynman after his death, Wheeler recalled a discussion among the graduate admissions committee in the spring of 1939, during which one person raved about the fact that no one else applying to the university had math and physics aptitude scores anywhere near as high as Feynman's (he scored 100 percent in physics), while another member of the committee complained at the same time that they had never let anyone in with scores so low in history and English. Happily for the future of science, physics and math prevailed.

Interestingly, Wheeler did not describe another key issue, of which he may not have been aware: the so-called Jewish question. The head of the physics department at Princeton had written to Philip Morse about Feynman, asking about his religious affiliation, adding, "We have no definite rule against Jews but have to keep their proportion in our department reasonably small because of the difficulty of placing them." Ultimately it was decided that Feynman was not sufficiently Jewish "in manner" to get in the way. The fact that

Feynman, like many scientists, was essentially uninterested in religion never arose as part of the discussion.

More important than all of these external developments, however, was the fact that Feynman had now proceeded to the stage in his education where he could begin to think about the really exciting stuff—namely, the physics that didn't make sense. Science at the forefront is always on the verge of paradox and inconsistency, and like a bloodhound, great physicists focus precisely on these elements because that is where the true quarry lies.

The problem that Feynman later said he "fell in love with" as an undergraduate had been a familiar part of the centerpiece of theoretical physics for almost a century: the classical theory of electromagnetism. Like many deep problems, it can be simply stated. The force between two like charges is repulsive, and therefore it takes work to bring them closer together. The closer they get, the more work it takes. Now imagine a single electron. Think of it as a "ball" of charge with a certain radius. To bring all the charge together at this radius to make up the electron would thus take work. The energy built up by the work bringing the charge together is commonly called the *self-energy* of the electron.

The problem is that if we were to shrink the size of the electron down to a single point, the self-energy associated with the electron would go to infinity, because it takes an infinite amount of energy to bring all the charge together at a single point. This problem had been known for some time and various schemes had been put together to solve it, but the simplest was to assume that the electron really wasn't confined to a single point, but had a finite size.

By early in the twentieth century this issue took on a different perspective, however. With the development of quantum mechanics, the picture of electrons, and electric and magnetic fields, had completely changed. So-called wave-particle duality, for example, a part of quantum theory, said that both light *and* matter, in this case electrons, sometimes behaved as if they were particles and sometimes as if they were waves. As our understanding of the quantum universe grew, while the universe also got stranger and stranger, nevertheless some of the key puzzles of classical physics disappeared. But others remained, and the self-energy of the electron was one of them. In order to put this in context, we need to explore the quantum world a little bit.

Quantum mechanics has two central characteristics, both of which completely defy all of our standard intuition about the world. First, objects that are behaving quantum mechanically are the ultimate multitaskers. They are capable of being in many different configurations at the same time. This includes being in different places and doing different things simultaneously. For example, while an electron behaves almost like a spinning top, it can also act as if it is spinning around in many different directions at the same time.

If an electron acts as if it is spinning counterclockwise around an axis pointing up from the floor, we say it has *spin up*. If it is spinning clockwise, we say it has *spin down*. At any instant the probability that an electron has spin up may be 50 percent, and the probability that it has spin down may be 50 percent. If electrons behaved as our classical intuition would suggest, the implication would be that each electron we measure has either spin up or spin down, and that 50 percent of the electrons will be found to be in one configuration and 50 percent in the other.

In one sense this is true. If we measure electrons in this way, we will find that 50 percent are spin up and 50 percent are spin down. *But*, and this is a very important *but*, it is incorrect to assume that each electron is in one configuration or another before we make the measurement. In the language of quantum mechanics, each electron is in a "superposition of states of spin up and spin down" before the measurement. Put more succinctly, it is spinning both ways!

How do we know that the assumption that electrons are in one or another configuration is "incorrect"? It turns out that we can perform experiments whose results depend on what the electron is doing when we are not measuring it, and the results would come out differently if the electron had been behaving sensibly, that is, in one or another specific configuration between measurements.

The most famous example of this involves shooting electrons at a wall with two slits cut into it. Behind the wall is a scintillating screen, much like the screen on old-fashioned vacuum-tube televisions, that lights up wherever an electron hits it. If we don't measure the electrons between the time they leave the source and when they hit the screen, so that we cannot tell which slit each electron goes through, we would see a pattern of bright and dark patches emerge on the rear screen—precisely the kind of "interference pattern" that we would see for light or sound waves that traverse a two-slit device, or perhaps more familiarly, the pattern of alternating ripples and calm that often results when two streams of water converge together. Amazingly, this pattern emerges even if we send only a single electron toward the two slits at any time. The pattern thus suggests that somehow the electron "interferes" with itself after going through both slits at the same time!

At first glance this notion seems like nonsense, so we alter the experiment slightly. We put a nondestructive electron detector by each slit and then send the electrons through. Now we find that for each electron, one and only one detector will signal that an electron has gone through at any time, allowing us to determine that indeed each electron goes through one and only one slit, and moreover we can determine which slit each electron has gone through.

So far so good, but now comes the quantum kicker. If we examine the pattern on the screen after this seemingly innocent intervention, the new pattern is completely different from the old pattern. It now resembles the pattern we would get if we were shooting bullets at such a screen through the two-slit barrier—namely, there will be a bright spot behind each slit, and the rest will be dark.

So, like it or not, electrons and other quantum objects can perform classical magic by doing several different things at the same time, at least as long as we do not observe them in the process.

The other fundamental property at the heart of quantum mechanics involves the so-called *Heisenberg uncertainty principle*. What this principle says is that there are certain combinations of physical quantities, such as the position of a particle and its momentum (or speed), that we cannot measure at the same instant with absolute accuracy. No matter how good our microscope or measuring device is, multiplying the uncertainty in position by the uncertainty in momentum never results in zero; the product is always bigger than some number, and this number is called *Planck's constant*. It is this number that also determines the scale of the spacing between energy levels in atoms. In other words, if we measure the position very accurately so that the uncertainty in position is small, that means our knowledge of the momentum or speed of the particle must be very inaccurate, so that the product of the uncertainty in position and the uncertainty in momentum exceeds Planck's constant.

There are other such "Heisenberg pairs," like energy and time. If we measure the quantum mechanical state of a particle or an atom for a very short time, then there will be a big uncertainty in the measured energy of the particle or atom. In order to measure the energy accurately, we have to measure the object over a long time interval, in which case we cannot say precisely when the energy was being measured.

If this weren't bad enough, the quantum world gets even weirder once we add Einstein's theory of special relativity into the mix, in part because relativity puts mass and energy on the same footing. If we have enough energy available, we can create something with mass!

So, if we put all of these things together—quantum multiplexing, the Heisenberg uncertainty principle, and relativity—what do we get? We get a picture of electrons that is literally infinitely more confusing than the one presented by the classical theory, which already led to an infinite self-energy for the electron.

For example, whenever we try to picture an electron, it doesn't have to be just an electron! To understand this, let's return back to classical electromagnetism. One of the key features at the heart of this theory is the fact that if we shake an electron, it will emit elecromagnetic radiation, like light, or radio waves. This great discovery resulted from the groundbreaking nineteenth-century experiments of Michael Faraday, Hans Christian Oersted, and others, and the groundbreaking theoretical work of James Clerk Maxwell. Quantum mechanically, this observed phenomenon must still be predicted because if quantum mechanics is to properly describe the world, its predictions had better agree with observations. But the key new feature here is that quantum mechanics tells us to think of the radiation as being made up of individual *quanta*, or packets of energy, called photons.

Now let's return to the electron. The Heisenberg principle tells us that if we measure the electron for some finite time, there remains some finite uncertainty in knowing its exact energy. But if there is some uncertainty, how do we know we are measuring only the electron? For example, if the electron emits a photon carrying very little energy, the total energy of the system will change, albeit very slightly. But if we don't know the exact energy of the system, then we cannot say whether it has or hasn't emitted a low-energy photon. So what we are measuring really could be the energy of the electron plus a photon that it has emitted.

But why stop there? Perhaps the electron has emitted an infinite number of very-low-energy photons? If we watch the electron for long enough, we can both measure its energy very accurately and put a photon counter nearby to see if there are any photons around. In this case, what will have happened to all the photons that were traveling along with the electron in the interim? Simple: the electron can absorb all those photons before we get a chance to measure them!

The kind of photons that an electron can emit and reabsorb on a timescale so short that we cannot measure them are called *virtual particles*, and as I will describe later, Feynman recognized that when we include the effects of both relativity and quantum mechanics, there is no getting away from the existence of these particles. So when we think of an electron moving around, we now have to think of it as a pretty complicated object, with a cloud of virtual particles surrounding it.

Virtual particles play another important role in the quantum theory of electromagnetism. They change the way we think of electric and magnetic fields and the forces between particles. For example, say an electron emits a photon. This photon can then in turn interact with another particle, which can absorb it. Depending on the energy of the photon, this will result in a transfer of energy and momentum from one electron to another. But that is what we normally describe as the manifestation of the electromagnetic force between these two charged particles.

Indeed, as we will see, in the quantum world both electric and magnetic forces can be thought of as being caused by the exchange of virtual photons. Because the photon is massless, an emitted photon can carry an arbitrarily small amount of energy. Therefore, as the Heisenberg uncertainty principle tells us, the photon can travel an arbitrarily long distance (taking an arbitrarily long time) between particles before it must be reabsorbed in order that the energy it is carrying is returned back to the electron. It is precisely for this reason that the electromagnetic force between particles can act over long distances. If the photon had a mass, then it would always carry away a minimum energy, $E = mc^2$,