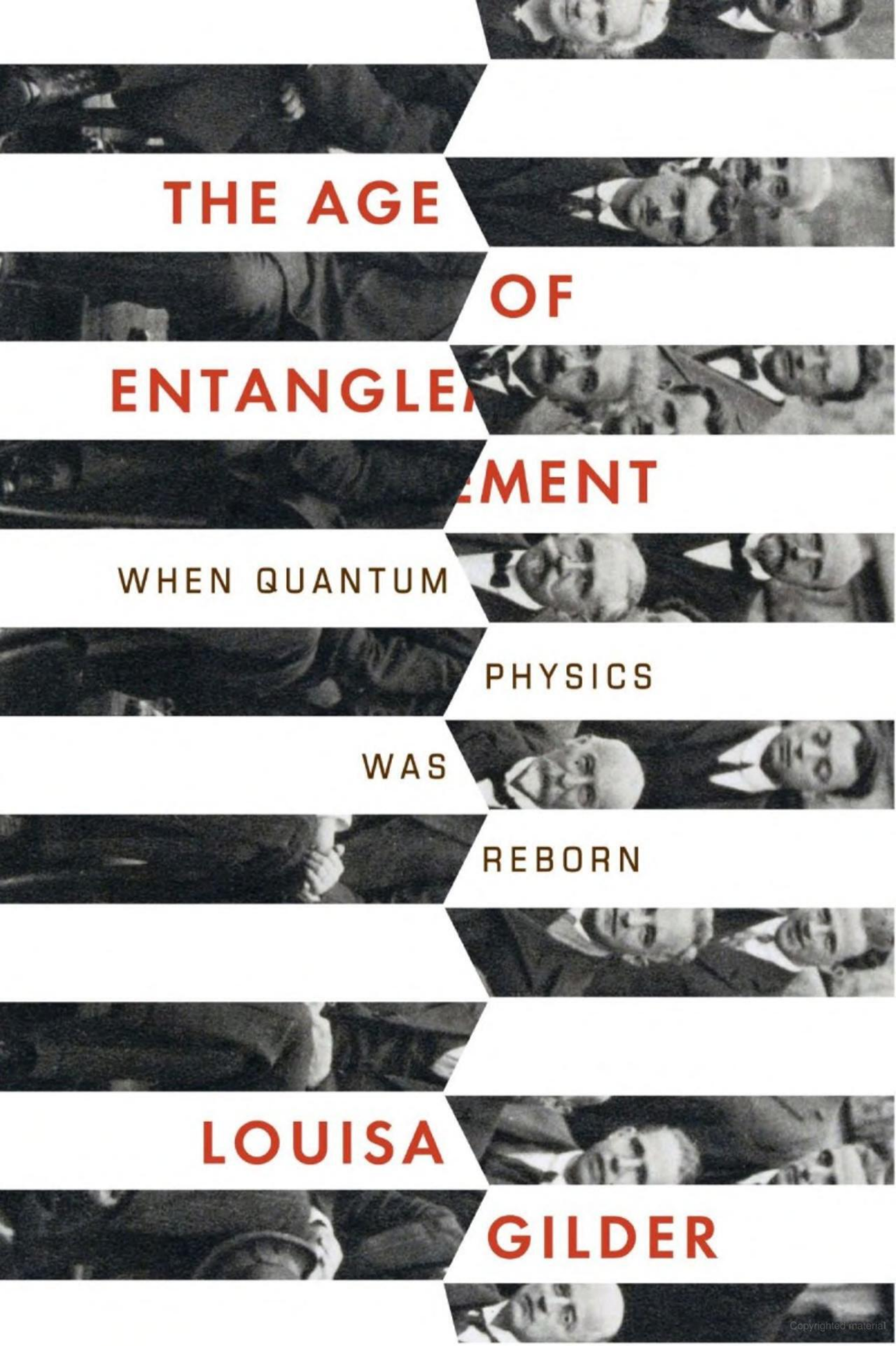

THE AGE OF ENTANGLEMENT

WHEN QUANTUM PHYSICS WAS REBORN

LOUISA GILDER

The Age of Entanglement

WHEN QUANTUM PHYSICS WAS REBORN

Louisa Gilder

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A NOTE TO THE READER

Werner Heisenberg, the pioneer who first laid down the laws of the fundamental behavior of matter and light, was an old man when he sat down to write about his life. The book he wrote is not an autobiography of the man but an autobiography of his intellect, entirely a series of reconstructed conversations. His two most famous papers are solo affairs—one introducing quantum mechanics (the laws of the fundamental behavior of matter and light) and the other on the uncertainty principle (which declares that at any given time, the more specific a particle's position, the more vague its speed and direction, and vice versa). But the roots of each solitary paper reach deep into months of heated and careful conversation with most of the great names of quantum physics. "Science rests on experiments," wrote Heisenberg, but "science is rooted in conversations."

Nothing could be further from the impression physics textbooks give to students. There, physics seems to be a perfect sculpture sitting in a vacuum-sealed case, as if brains, only tenuously connected to bodies, had given birth to insights fully formed. These Athena-like theories and Zeus-like theorists seem shiny, glassy, smooth—sometimes, if the light is right, you can see through them into the mysteries and beauties of the physical universe; but there is hardly a trace of humanity, or any sense of questions still to be answered.

Physics, in actuality, is a never-ending search made by human beings. Gods and angels do not come bearing perfectly formed theories to disembodied prophets who instantly write textbooks. The schoolbook simplifications obscure the crooked, strange, and fascinating paths that stretch out from each idea, not only back into the past but also onward into the future. While we aspire to universality and perfection, we are lying if we write as if we have achieved it.

Conversations are essential to science. But the off-the-cuff nature of conversation poses a difficulty. It is rare, even in these digital times, to have a complete transcript of every word spoken between two people on a given day, even if that conversation someday leads to a new understanding of the world. The result is that history books rarely have much of the to-and-fro of human interaction. Heisenberg's statement suggests that something is therefore lost.

When I first started poring through the memoirs and biographies of the quantum physicists of the twentieth century, I felt as if I were watching a movie—the cast of characters was so vivid and the plot twists so unexpected. While the strength of science is its ability to slough off the contingencies of history and reach toward pure knowledge, this knowledge is built, one puzzle piece at a time, by people living their lives in specific times and places with specific passions. Science unfolds in some directions rather than in others because of circumstances. Characters (not disembodied brains) and plot twists (not the relentless forward march of truth) almost guarantee that this is true.

As Tom Wolfe wrote at the beginning of *The Electric Kool-Aid Acid Test:* "I have tried not only to tell what the Pranksters did but to re-create the mental atmosphere or subjective reality of it. I don't think their adventure can be understood without that." Wolfe was recounting a very different kind of mental history, but his point, I find, is even more true about the portentous history of science and intellect that unfolded as the age of entanglement.

This is a book of conversations, a book about how the give-and-take between physicists repeatedly changed the direction in which quantum physics developed, just as conversations, subtly or dramatically, change the world we live in and experience every day. All the conversations in this book occurred in some form, on the date specified in the text, and I have fully documented the substance of every one. (The endnotes detailing the source of each quote speak for themselves.) Most are composed of direct quotes (or close paraphrases) from the trove of letters, papers, and memoirs that these physicists left behind. When occasional connective tissue (e.g., "Nice to see you," or "I agree") was necessary, I tried to keep it both innocuous and also sensitive to the character, beliefs, and history of the people involved. A glance at the notes will separate quote from filler.

Here is a sample from the text, from a conversation that took place in the summer of 1923 on a streetcar in Copenhagen between two of the founders of the quantum theory, Albert Einstein and Niels Bohr, and its first great teacher, Arnold Sommerfeld.

> "It's good to see you doing so well," says Einstein.
>
> Bohr shakes his head, smiling: "My life from the scientific point of view passes off in periods of over-happiness and despair . . . as I know that both of you understand . . . of feeling vigorous and overworked, of starting papers and not getting them published"—his face is earnest—"because all the time I am gradually changing my views about this terrible riddle which the quantum theory is."
>
> "I know," says Sommerfeld, "I know."
>
> Einstein's eyes almost close; he is nodding. "That is a wall before which I am stopped. The difficulties *are* terrible." His eyes open. "The theory of relativity was only a sort of respite which I gave myself during my struggles with the quanta."

We know that the conversation (of which this interchange represents a tiny piece) happened, because Bohr mentioned it in an interview late in his life with his son and one of his closest colleagues. The content of the conversation is easy to gather from a look at what the three men were working on and writing friends about around the same time. Here Bohr, in the interview, describes that day in 1923:

> Sommerfeld was not impractical, not quite impractical; but Einstein was not more practical than I and, when he came to Copenhagen, I naturally fetched him from the railway station. . . .
>
> We took the streetcar from the station and talked so animatedly about things that we went much too far past our destination. So we got off and went back. Thereafter we again went too far, I can't remember how many stops, but we rode back and forth in the streetcar because Einstein was really interested at that time; we don't know whether his interest was more or less skeptical—but in any case we went back and forth many times in the streetcar and what people thought of us, that is something else.

Here is the first quote on which this particular short section of the conversation is based. It comes from a letter Bohr wrote to a British colleague in August of 1918:

> I know that you understand . . . how my life from the scientific point of view passes off in periods of over-happiness and despair, of feeling vigorous and overworked, of starting papers and not getting them published, because all the time I am gradually

> changing my views about this terrible riddle which the quantum theory is.

How can a passage written five years earlier be relevant? Some things had changed for Bohr in the intervening years, but what he touches on in the letter had remained the same—the excitement, dejection, and overwork (during this whole period he was building his institute of physics in Copenhagen); the long, arduous papers only partially published; and, most of all, his struggle to understand the quantum theory, which until Heisenberg's breakthrough in 1925 stood on shifting sand.

Here is the second quote, from a journey by train taken a year before. The astronomer of the Paris Observatory rode with Einstein from Belgium to Paris and asked him about the quantum problem. "That is a wall before which one is stopped," Einstein replied. "The difficulties are terrible; for me, the theory of relativity was only a sort of respite which I gave myself during their examination." His opinions on the subject were the same at the time of our scene in the summer of 1923; by the following summer, an unexpected letter from India would help him chip a crack in this quantum wall.

As for the filler: Bohr was the kind of person whose happiness was infectious—he would indeed have been looking well when he picked up Einstein to show him his newly completed institute, no matter how overworked and secretly despairing he might actually be. And Sommerfeld, always intellectually engaged with Bohr during those early years of the quantum theory, would have known intimately what Bohr meant by "this terrible riddle."

I believe the risks of telling the story in this way are outweighed by the reward: a sense of how, through minds meeting minds, the quantum theory unfolded. Please check the notes (found on page 351) if ever it seems that someone "couldn't have said that!," and the glossary on page 337 for any unfamiliar physical terms. I am hopeful of earning your trust, and of honoring Heisenberg's sense of how science is really done.

—L. G., October 2007

The Age of Entanglement

John Stewart Bell

INTRODUCTION

Entanglement

ANY TIME TWO ENTITIES INTERACT, they entangle. It doesn't matter if they are photons (bits of light), atoms (bits of matter), or bigger things made of atoms like dust motes, microscopes, cats, or people. The entanglement persists no matter how far these entities separate, as long as they don't subsequently interact with anything else—an almost impossibly tall order for a cat or a person, which is why we don't notice the effect.

But the motions of subatomic particles are dominated by entanglement. It starts when they interact; in doing so, they lose their separate existence. No matter how far they move apart, if one is tweaked, measured, observed, the other seems to instantly respond, even if the whole world now lies between them. And no one knows how.

Strange as it seems, this kind of correlation is happening all the time—and we know it happens because of the work of John Bell. Raised in the chaos of Ireland during the Second World War, he spent his working years in peaceful Switzerland and died just after his sixty-second birthday, the year (unbeknownst to him) that he was nominated for the Nobel Prize. He called the work for which he is now most famous his hobby: probing into the logical foundations of quantum mechanics. His second paper on this subject, in 1964, briefly, beautifully, and conclusively demonstrates the existence of entanglement, this magical correlation of two particles. Bell had extended and deepened a hitherto sneered-at paper of Einstein's on the subject, written in 1935 with two little-known colleagues (Boris Podolsky and Nathan Rosen). Forty years after its rehabilitation by John Bell, the paper is, by a massive margin, the most cited of *all* Einstein's roster of glittering, earthshaking work,* and

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*A paper is considered famous if it has been cited in more than a hundred subsequent papers; Einstein's monumental papers on special relativity (1905) and the quantum theory (1917) have each been cited more than seven hundred times; his 1905 Ph.D. dissertation on the size of an atom, more than fifteen hundred times. By contrast, twenty-five hundred the most cited paper of the dominant physics journal of the second half of the twentieth century, *Physical Review.*

Hints of entanglement's spooky presence go all the way back to the springtime of the quantum theory, in the first third of the twentieth century. But it was Bell, with his simple algebra and deep thinking, who laid open the central paradox.

The mysteries embedded in quantum mechanics provoked four major reactions from its founders: orthodoxy, heresy, agnosticism, and simple misunderstanding. Three of the theory's founders (Bohr, Heisenberg, and Wolfgang Pauli) gave it its orthodox exegesis, which came to be known as the Copenhagen interpretation. Three more founders (including Einstein) were heretics, believing that something was rotten in the quantum theory they had played such a role in developing. Finally, pragmatic people said, The time is not yet ripe for understanding these things, and confused people dismissed the mysteries with simplistic explanations.

This riot of different reactions had a huge impact on the future of quantum mechanics, because the theory needed interpretation the way a fish needs water. This fact alone was a drastic break with the past history of science. A classical (i.e., pre-quantum) equation, after its terms were defined, essentially explained itself. With the quantum revolution, the equations fell silent. Only an interpretation allowed them to speak about the natural world.

Take this analogy. A Bhutanese artist, flown to the Metropolitan Museum of Art and introduced to Western painting for the first time, would have no problem understanding the essentials of the gory story represented by any of the several paintings of Judith, sword in one elegant hand, the head of Holofernes swinging from the other. Before 1900, a painting could be relied on to speak about what the painter intended. Standing in the Guggenheim before a series of razor-edged swaths of browns that give an impression of motion, however, our Bhutanese artist will be pardoned for glancing quickly over to the little title card (in a now universal art-gallery ritual) to find out that this is actually a "Sad Young Man on a Train."

More scandalous than any Jewish maiden carrying a severed head, the companion painting to the sad young man—Marcel Duchamp's famous "Nude Descending a Staircase," which rocked the New York art world in

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papers in physics journals have cited Bell's 1964 paper on entanglement; the same as for the 1935 Einstein-Podolsky-Rosen paper that inspired him.

1913—graces the cover of one of Heisenberg's books; quantum mechanics represented a perfectly contemporaneous and analogous break with the past. Just as much as the paintings of Duchamp and his successors, quantum mechanics needed that little title card to connect with a reality outside its beautiful mathematics, and in the 1920s and '30s physicists argued over who would get to script it.

Here are the protagonists.

1. THE COPENHAGEN INTERPRETATION

Niels Bohr, a lifelong friend and intellectual adversary of Einstein's, who founded the Institute for Theoretical Physics in Copenhagen, tried to make sense of the mysteries with a concept he called complementarity. For Bohr, complementarity was an almost religious belief that the paradoxes of the quantum world must be accepted as fundamental, not to be "solved" or trivialized by attempts to find out "what's really going on down there." Bohr used the word in an unusual way: the "complementarity" of waves and particles, for example (or of position and momentum), meant that when one existed fully, its complement did not exist at all.

In order to take this view, Bohr emphasized, there has to be a big "classical" world, devoid of complementarity—the world of circling planets and falling apples that Isaac Newton had explained so well—which serves as a platform from which to stare into the quantum abyss. In fact, instead of thinking of classical-sized things, like apples and cats, as being made of quantum things, like atoms, Bohr put the dependence the other way. In his famous Como lecture of 1927, he emphasized that waves and particles are "abstractions, their properties being definable and observable only through their interaction with other systems"—and these other systems must be "classical," like a measuring apparatus.

Rather than urging physicists to find a way to move beyond such "abstractions" to a more accurate description, Bohr further insisted that "these abstractions are indispensable to describe experience in connection with our ordinary space-time view." That is, quantum things must be talked about in a classical language ill-suited to describe them, and the existence of any property we can recognize in a quantum object must always depend upon finding another system that will interact with it in a "classical" way. Classical systems are paradoxically necessary to describe the quantum systems of which they are made.

His enthusiastic supporter *Werner Heisenberg* and best critic, *Wolfgang Pauli,* would go so far as to say that the quantum world is in a certain way created or transformed by our observation of it, since the atom seems to have no properties before measurement.

"Those who are not shocked when they first come across quantum theory," said Bohr in conversation with Heisenberg and Pauli, "cannot possibly have understood it."

2. "SOMETHING IS ROTTEN"*

Starting in 1909, only nine years after quantum theory's tentative debut, *Albert Einstein* began to worry that it implied a world composed of non-separable pieces that were "not . . . mutually independent." When he tried to treat the individual particles as individuals, they seemed to exert "a mutual influence . . . of a quite mysterious nature" on each other, or even seemed to affect each other in what he ridiculed as "spooky action-at-a-distance," or "a sort of telepathic coupling." To him it was clear that this meant a fatal flaw in the theory.

Erwin Schrödinger showed that, on its face, the quantum theory (and in particular its foundational equation that bears his name) leads to a bizarre paradox. If we do not firmly declare with Bohr that something big, like a cat, does *not* follow the laws of quantum mechanics (though it is indubitably constructed of particles that do), we can prove the cat to be alive and dead simultaneously. Schrödinger yearned to reject the Copenhagen dualism and believe in a single world described by his equation, but could never find a way to do it.

Louis de Broglie, a young Frenchman, came up with a version of the quantum theory in which the Schrödinger equation describes a long-range force that moves faster than the speed of light, spookily guiding the particles that make up our world.

This interpretation has gone under many names; for decades, "hidden variables" was the most common. The concept to remember and link with this opaque designation is "a quantum theory without observers": a quantum theory in which the reality of particles does not depend on whether they are observed.

3. THE TIME IS NOT RIPE

Paul Dirac (always known in public life by his first initials, P.A.M.), whose equation describing electrons† was one of the most astonishingly powerful results of the quantum theory, felt that it was too soon to be wasting time worrying about entanglement. It would make sense someday.

4. DISMISSIVE INCOMPREHENSION

Max Born, like Bohr a lifelong friend of Einstein's and contributor to the Copenhagen interpretation, could never understand why the others

---

*The words of both Hamlet and John Bell.

†Electricity-carrying subatomic particles that are a crucial component of all matter.

thought the meaning of the theory was such an important and difficult issue.

After the 1930s it seemed clear that the analyses of Einstein, Schrödinger, and de Broglie were dead ends, and, in fact, most of the great and lasting triumphs of the quantum theory did come from one of the other schools of thought.

But no one following Bohr, Heisenberg, Pauli, Dirac, or Born dared grasp, measure, or even name the deepest of all the puzzles, entanglement. Then along came John Bell. An admirer of Einstein, Schrödinger, and de Broglie, he followed their minority views to their natural conclusions and came across the discovery that unleashed entanglement upon the world.

Bohr used to say, "Truth and clarity are complementary"—meaning that the more truthful you try to be, the more unclear will be your statements, and vice versa. This was certainly true of Bohr himself. But Bell wasn't buying it. As he once told one of Bohr's most famous postwar disciples, John Wheeler, "I'd rather be clear and wrong than foggy and right."

Bohr's books and papers—full of careful prohibitions about what cannot be contemplated and obscure statements about "complementarity," "indivisibility," and "irrationality"—have become holy writ to be interpreted and reinterpreted by each new generation of physicists. From the point of view of the history of entanglement, they are not worth one clear sentence from Einstein, Schrödinger, de Broglie, or John Bell, who each said, in a way that opened up a new world: "Hey, look at this."

1

The Socks

1978 and 1981

Reinhold Bertlmann

In 1978, when John Bell first met Reinhold Bertlmann, at the weekly tea party at the Organisation Européenne pour la Recherche Nucléaire, near Geneva, he could not know that the thin young Austrian, smiling at him through a short black beard, was wearing mismatched socks. And Bertlmann did not notice the characteristically logical extension of Bell's vegetarianism—plastic shoes.

Deep under the ground beneath these two pairs of maverick feet, ever-increasing magnetic fields were accelerating protons (pieces of the tiny center of the atom) around and around a doughnut-shaped track a quarter of a kilometer in diameter. Studying these particles was part of the daily work of CERN, as the organization was called (a tangled history left the acronym no longer correlated with the name). In the early 1950s, at the age of twenty-five, Bell had acted as consultant to the team that designed this subterranean accelerator, christened in scientific pseudo-Greek "the Proton Synchrotron." In 1960, the Irish physicist returned to Switzerland to live, with his Scottish wife, Mary, also a physicist and a designer of accelerators. CERN's charmless, colorless campus of box-shaped buildings with protons flying through their foundations became

Bell's intellectual home for the rest of his life, in the green pastureland between Geneva and the mountains.

At such a huge and impersonal place, Bell believed, newcomers should be welcomed. He had never seen Bertlmann before, and so he walked up to him and said, his brogue still clear despite almost two decades in Geneva: "I'm John Bell."

This was a familiar name to Bertlmann—familiar, in fact, to almost anyone who studied the high-speed crashes and collisions taking place under Bell's and Bertlmann's feet (in other words, the disciplines known as particle physics and quantum field theory). Bell had spent the last quarter of a century conducting piercing investigations into these flying, decaying, and shattering particles. Like Sherlock Holmes, he focused on details others ignored and was wont to make startlingly clear and unexpected assessments. "He did not like to take commonly held views for granted but tended to ask, 'How do you know?,' " said his professor Sir Rudolf Peierls, a great physicist of the previous generation. "John always stood out through his ability to penetrate to the bottom of any argument," an early co-worker remembered, "and to find the flaws in it by very simple reasoning." His papers—numbering over one hundred by 1978—were an inventory of such questions answered, and flaws or treasures discovered as a result.

Bertlmann already knew this, and that Bell was a theorist with an almost quaint sense of responsibility who shied away from grand speculations and rooted himself in what was directly related to experiments at CERN. Yet it was this same responsibility that would not let him ignore what he called a "rottenness" or a "dirtiness" in the foundations of quantum mechanics, the theory with which they all worked. Probing the weak points of these foundations—the places in the plumbing where the theory was, as he put it, "unprofessional"—occupied Bell's free time. Had those in the lab known of this hobby, almost none of them would have approved. But on a sabbatical in California in 1964, six thousand miles from his responsibilities at CERN, Bell had made a fascinating discovery down there in the plumbing of the theory.

Revealed in that extraordinary paper of 1964, Bell's theorem showed that the world of quantum mechanics—the base upon which the world we see is built—is composed of entities that are either, in the jargon of physics, not *locally causal,* not *fully separable,* or even not *real unless observed.*

If the entities of the quantum world are not locally causal, then an action like measuring a particle can have instantaneous "spooky" effects across the universe. As for separability: "Without such an assumption of the mutually independent existence (the 'being-thus') of spatially distant things . . . ," Einstein insisted, "physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation." The most extreme version of nonseparability is the idea that the quantum entities do not become solid until they are observed, like the proverbial tree that makes no sound when it falls unless a listener is around. Einstein found the implications ludicrous: "Do you really believe the moon is not there if nobody looks?"

Up to that point, the idea of science rested on separability, as Einstein had said. It could be summarized as humankind's long intellectual journey away from magic (not locally causal) and from anthropocentrism (not real unless observed). Perversely, and to the consternation of Bell himself, his theorem brought physics to the point where it seemingly had to choose between these absurdities.

Whatever the ramifications, it would become obvious by the beginning of this century that Bell's paper had caused a sea change in physics. But in 1978 the paper, published fourteen years before in an obscure journal, was still mostly unknown.

Bertlmann looked with interest at his new acquaintance, who was smiling affably with eyes almost shut behind big metal-rimmed glasses. Bell had red hair that came down over his ears—not flaming red, but what was known in his native country as "ginger"—and a short beard. His shirt was brighter than his hair, and he wore no tie.

In his painstaking Viennese-inflected English, Bertlmann introduced himself: "I'm Reinhold Bertlmann, a new fellow from Austria."

Bell's smile broadened. "Oh? And what are you working on?"

It turned out that they were both engaged with the same calculations dealing with quarks, the tiniest bits of matter. They found they had come up with the same results, Bell by one method on his desktop calculator, Bertlmann by the computer program he had written.

So began a happy and fruitful collaboration. And one day, Bell happened to notice Bertlmann's socks.

Three years later, in an austere room high up in one of the majestic stone buildings of the University of Vienna, Bertlmann was curled over the screen of one of the physics department's computers, deep in the world of quarks, thinking not in words but in equations. His computer—at fifteen feet by six feet by six feet one of the department's smaller ones—almost filled the room. Despite the early spring chill, the air-conditioning ran, fighting the heat produced by the sweatings and whirrings of the behemoth. Occasionally Bertlmann fed it a new punch card perforated with a line of code. He had been at his work for hours as the sunlight moved silently around the room.

He didn't look up at the sound of someone's practiced fingers poking the buttons that unlocked the door, nor when it swung open. Gerhard Ecker, from across the hall, was coming straight at him, a sheaf of papers in hand. He was the university's man in charge of receiving preprints—papers that have yet to be published, which authors send to scientists whose work is related to their own.

Ecker was laughing. "Bertlmann!" he shouted, even though he was not four feet away.

Bertlmann looked up, bemused, as Ecker thrust a preprint into his hands: "You're famous now!"

The title, as Bertlmann surveyed it, read:

Bertlmann's Socks and the Nature of Reality

J. S. Bell

CERN, Geneve, Suisse

The article was slated for publication in a French physics periodical, *Journal de Physique,* later in 1981. Its title was almost as incomprehensible to Bertlmann as it would be for a casual reader.

"But what's this about? What possibly—"

Ecker said, "Read it, read it."

He read.

> The philosopher in the street, who has not suffered a course in quantum mechanics, is quite unimpressed by Einstein-Podolsky-Rosen correlations. He can point to many examples of similar correlations in everyday life. The case of Bertlmann's socks is often cited.

My socks? What is he talking about? And EPR correlations? It's a big joke, John Bell is playing a big published joke on me.

"EPR"—short for the paper's authors, Albert Einstein, Boris Podolsky, and Nathan Rosen—was, like Bell's 1964 theorem, which it inspired thirty years later, something of an embarrassment for physics. To the question posed by their title, "Can Quantum-Mechanical Description of

Physical Reality Be Considered Complete?," Einstein and his lesser-known cohorts answered no. They brought to the attention of physicists the existence of a mystery in the quantum theory. Two particles that had once interacted could, no matter how far apart, remain "entangled"—the word Schrödinger coined in that same year—1935—to describe this mystery. A rigorous application of the laws of quantum mechanics seemed to force the conclusion that measuring one particle affected the state of the second one: acting on it at a great distance by those "spooky" means. Einstein, Podolsky, and Rosen therefore felt that quantum mechanics would be superseded by some future theory that would make sense of the case of the correlated particles.

Physicists around the world had barely looked up from their calculations. Years went by, and it became more and more obvious that despite some odd details, ignored like the eccentricities of a general who is winning a war, quantum mechanics was the most accurate theory in the history of science. But John Bell was a man who noticed details, and he noticed that the EPR paper had not been satisfactorily dealt with.

Bertlmann felt like laughing in confusion. He looked at Ecker, who was grinning: "Read on, read on."

> Dr. Bertlmann likes to wear two socks of different colors. Which color he will have on a given foot on a given day is quite unpredictable. But when you see (Fig. 1) that the first sock is pink . . .

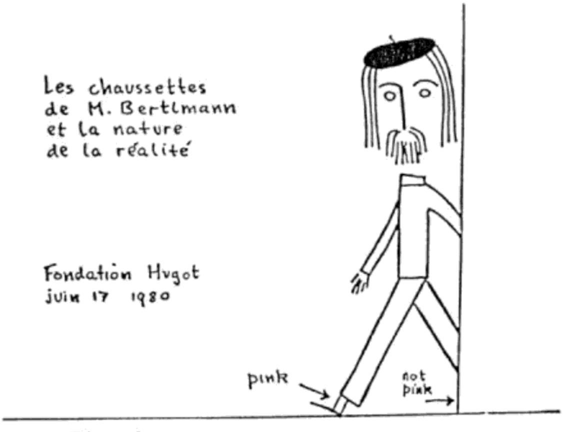

Fig. 1.

What is Fig. 1? My socks? Bertlmann ruffled through the pages and found, appended at the end, a little line sketch of the kind John Bell was fond of doing. He read on:

> But when you see that the first sock is pink you can be already sure that the second sock will not be pink. Observation of the first, and experience of Bertlmann, give immediate information about the second. There is no accounting for tastes, but apart from that there is no mystery here. And is not the EPR business just the same?

Bertlmann imagined John's voice saying this, conjured up his amused face. *For three years we worked together every day and he never said a thing.*

Ecker was laughing. "What do you think?"

Bertlmann had already dashed past him, out the door, down the hall to the phone, and with trembling fingers was calling CERN.

Bell was in his office when the phone rang, and Bertlmann came on the line, completely incoherent. "What have you done? *What have you done?*"

Bell's clear laugh alone, so familiar and matter-of-fact, was enough to bring the world into focus again. Then Bell said, enjoying the whole thing: "Now you are famous, Reinhold."

"But what is this paper about? Is this a big joke?"

"Read the paper, Reinhold, and tell me what you think."

A tigress paces before a mirror. Her image, down to the last stripe, mimics her every motion, every sliding muscle, the smallest twitch of her tail. How are she and her reflection correlated? The light shining down on her narrow slinky shoulders bounces off them in all directions. Some of this light ends up in the eye of the beholder: either straight from her fur, or by a longer route, from tiger to mirror to eye. The beholder sees two tigers moving in perfectly opposite synchrony.

Look closer. Look past the smoothness of that coat to see its hairs; past its hairs to see the elaborate architectural arrangements of molecules that compose them, and then the atoms of which the molecules are made. Roughly a billionth of a meter wide, each atom is (to speak very loosely) its own solar system, with a dense center circled by distant electrons. At these levels—molecular, atomic, electronic—we are in the native land of quantum mechanics.

The tigress, though large and vividly colored, must be near the mirror for a watcher to see two correlated cats. If she is in the jungle, a few yards' separation would leave the mirror showing only undergrowth and swinging vines. Even out in the open, at a certain distance the curvature of the earth would rise up to obscure mirror from tigress and decouple their synchrony. But the entangled particles Bell was talking about in his paper can act in unison with the whole universe in between.

Quantum entanglement, as Bell would go on to explain in his paper, is not really like Bertlmann's socks. No one puzzles over how he always manages to pick different-colored socks, or how he pulls the socks onto his feet. But in quantum mechanics there is no idiosyncratic brain "choosing" to coordinate distant particles, and it is hard not to compare how they do it to magic.

In the "real world," correlations are the result of local influences, unbroken chains of contact. One sheep butts another—there's a local influence. A lamb comes running to his mother's bleat after waves of air molecules hit each other in an entirely local domino effect, starting from her vocal cords and ending when they beat the tiny drum in the baby's ear in a pattern his brain recognizes as *Mom.* Sheep scatter at the arrival of a coyote: the moving air has carried bits of coyote musk and dandruff into their nostrils, or the electromagnetic waves of light from the moon have bounced off the coyote's pelt and into the retinas of their eyes. Either way, it's all local, including the nerves firing in each sheep's brain to say *danger,* and carrying the message to her muscles.

Grown up, sold, and separated on different farms, twin lambs both still chew their cud after eating, and produce lambs that look eerily similar. These correlations are still local. No matter how far the lambs ultimately separate, their genetic material was laid down when they were a single egg inside their mother's womb.

Bell liked to talk about twins. He would show a photograph of the pair of Ohio identical twins (both named "Jim") separated at birth and then reunited at age forty, just as Bell was writing "Bertlmann's Socks." Their similarities were so striking that an institute for the study of twins was founded, appropriately enough at the University of Minnesota in the Twin Cities. Both Jims were nail-biters who smoked the same brand of cigarettes and drove the same model and color of car. Their dogs were named "Toy," their ex-wives "Linda," and current wives "Betty." They were married on the same day. One Jim named his son James Alan; his twin named his son James Allen. They both liked carpentry—one made miniature picnic tables and the other miniature rocking chairs.

The correlations that Bell's theorem discusses are so obviously twin-like, so blatantly correlated, that the natural thing would be to imagine that they, like these lambs and Jims, have something approximating DNA. And that is where their mystery lies: for what the theorem shows is just how strange and nonlocal—"spooky"—those "genes" would have to be.

The person who most clearly presented the intellectual puzzle of Bell's theorem to nonphysicists was a low-temperature physicist at Cornell named David Mermin, and he first became aware of it in 1979, from a *Scientific American* article by Bell's friend Bernard d'Espagnat. Mermin hailed from an opposite corner of the physics world from Bell, studying slow atoms chilled to a few degrees above absolute zero. But soon Bell's hobby became his hobby, too. He boiled Bell's theorem down "to something so simple that I could convey the argument using no mathematics beyond simple arithmetic and no quantum mechanics at all."

From these musings arose "something between a parable and a lecture demonstration," centering around a cartoon version of a three-part machine like the one that Bell described in "Bertlmann's Socks." This machine can be viewed in two ways. It is a reified, more visual way to talk about the equations of quantum mechanics and their predictions and results. It is also an abstraction of an apparatus that, these days, may be found in any quantum optics lab. In the center is a box that, at the push of a button, emits a pair of particles, sending them in opposite directions. On either side of the box, and far from it, sit two detectors. Each has a lever or crank on one side that allows a person to realign its internal apparatus so that it measures the particle along a different axis. We can turn the crank from the "normal setting" (which measures the particle head-on) to the "vertical setting" to the "horizontal setting." Each detector also has a light on top that, upon receipt of a particle, flashes either red or green.

Mermin invites us to imagine that we have just come upon this machine with no further information. Tinkering, we press START, and shortly thereafter each detector flashes red or green. Garnering as much information as possible, we crank the detectors between the three settings, all the while pressing the button and noting which lights come on.

Over several hours, we accumulate thousands and thousands of apparently random results. But the results are not random. They are precisely what quantum mechanics predicts for certain two-particle situations.

This is what a sample of our results would look like (where H is horizontal, V is vertical, and * is normal):

LEFT DETECTOR SETTING	RIGHT DETECTOR SETTING	LEFT DETECTOR RESULT	RIGHT DETECTOR RESULT
H	*	**GREEN**	**RED**
H	**V**	**GREEN**	**RED**
*	**V**	**RED**	**GREEN**
*	*	RED	RED
*	**V**	**GREEN**	**RED**
H	H	GREEN	GREEN
V	V	RED	RED
*	*	RED	RED
V	V	RED	RED
V	*	**GREEN**	**RED**
*	**H**	**RED**	**RED**
*	**H**	**RED**	**GREEN**

Looking the results over, we can divide the data into two cases:

Case (1): When both detectors are on the same setting, they always flash the same color.

Case (2) (in bold type): When the detectors are on different settings, they flash the same color not more than 25 percent of the time.

"These statistics," Mermin remarks, "may seem harmless enough, but some scrutiny reveals them to be as surprising as anything seen in a magic show, and leads to similar suspicions of hidden wires, mirrors, or confederates under the floor."

Consider the case when the detectors are on the same setting. The same lights always flash. "Given the unconnectedness of the detectors, there is one (and, I would think, only one) extremely simple way to explain" this behavior, Mermin writes. "We need only suppose that some property of each particle (such as its speed, size, or shape) determines the color its detector will flash for each of the three switch positions." They share some kind of gene. Twin particles make twin lights flash.

This is such a reasonable explanation that it is disheartening to realize that the very same data prove it to be dead wrong.

If the hypothesis of genes is true then we can write out a prediction for further results. Here is an example of such a prediction, showing all the possible permutations for a series of pairs of particles all bearing "flash red for normal, flash green for horizontal or vertical" genes:

LEFT DETECTOR SETTING	RIGHT DETECTOR SETTING	LEFT DETECTOR RESULT	RIGHT DETECTOR RESULT
*	*	RED	RED
*	**H**	**RED**	**GREEN**
*	**V**	**RED**	**GREEN**
H	*	**GREEN**	**RED**
H	H	GREEN	GREEN
H	**V**	**GREEN**	**GREEN**
V	*	**GREEN**	**RED**
V	**H**	**GREEN**	**GREEN**
V	V	GREEN	GREEN

But particles such as these could never produce the results we actually got. Notice the cases where the settings are different (in bold type). The same lights flashed twice out of these six times: 33.3 percent of the time, not 25 percent.

This is the kind of result known as "Bell's inequality." It lay hidden for so long partly because no one, until Bell, thought to solve the equations of quantum mechanics for the situations in which the detectors were not aligned, and compare these with the predictions for particles with predetermined attributes. More than forty years after Bell's discovery, the completely mystifying unanswered question remains: if there are no connections between the detectors, and no coordination of the particles at the source, what in the world causes identical lights to flash when the detectors are on identical settings?

In a sense Bell's argument in his theorem is really simple—to Bell it was, certainly—but there's something about it, as he said, that nobody follows originally. Because of this, Bell himself restated it in many ways, from his original five-line mathematical proof in 1964 to several formulations that rely on analogy—more than one of which are contained in "Bertlmann's Socks."

His friend Bernard d'Espagnat, for example, humorously gave this analogy to Bell's inequality:

> The number of young nonsmokers
> plus the number of women smokers of all ages
> is greater than or equal to
> the total number of young women, smokers and otherwise.

It is a logical statement this trivial—a tautology!—that quantum theory violates. Instead, in quantum theory, the whole seems to be greater than the sum of its parts.

The recoil of one ram from the head-butt of another; the lamb trotting up to the call of his mother; the arrival of the coyote and departure of the sheep: for all these correlations there is a cause and an effect; they all take place in time.

The ram's hard head moves as fast as the ram's muscles and hooves can carry him, covering perhaps ten meters in a second (roughly twenty miles per hour). The call of the mother sheep travels both faster and farther: about a kilometer in three seconds (nearly seven hundred fifty miles per hour) on a chilly spring day. The speed of the diffusion of the telltale smell of the coyote is slower and more arbitrary. And, even more than the ewe's call, the diffusion of this musk is at the mercy of the air: local contingencies of temperature, pressure, and any changes of these that form a wind all speed or slow its arrival in the quivering nostrils of a sheep.

The signal to the eye is the fastest one, since it occurs near the speed of light, almost three hundred thousand kilometers per second (compare this to the speed of sound, one-third of a kilometer per second). This speed is almost inconceivably fast—a ray of light could circle the earth seven times in a second—but it is, like the other local influences, a speed. It is not instantaneous.

With the possibility ruled out that Bell's strangely connected particles start with their instructions, like quantum DNA or a shared history, we might wonder if instead there is some kind of signaling going on. Upon reaching the detector with the green and red lights, one particle might somehow communicate with the other so they can coordinate the results.

On a visit to Paris in 1979, John Bell explained the problem with this idea by telling a whimsical story about French TV.

"It has been feared that television is responsible for the disturbing decline of birth rate in France." He was speaking to a group of physicists at the University of Paris-South in Orsay, who must have wondered what this had to do with quantum physics. "It is quite unclear which of the two main programs"—Bell used the word in its old-fashioned sense as "channel"—"(France 1 and 2, both originating in Paris) is more to blame. It has been advocated that deliberate experiments be done, say in Lille and Lyon, to investigate the matter. The local mayors might decide, by tossing coins each morning, which one of the two programs would be locally relayed during the day." Bell noted that after enough time, one could get a pretty good sense for the number of conceptions in Lille and Lyon, respectively, after exposure to one or the other channels (a joint distribution of probability, involving both towns).

"You might at first think it pointless to consider such a *joint* distribution, expecting it to separate trivially into independent factors," Bell continued. "But a moment of reflection will convince that this will not be so. For example, the weather in the two towns is correlated, although imperfectly. On fine evenings, people do not watch television. They walk in the parks, and are moved by the beauty of the trees, the monuments, and of one another. This is especially so on Sundays." The investigators must recognize such extraneous factors affecting both towns, and remove their effects from the analysis.

It would be remarkable if the towns were still correlated after the investigators had dealt with these extraneous causal factors. It would be even more remarkable "if the choice of program in Lille proved to be a causal factor in Lyon, or if the choice of program in Lyon proved to be a causal factor in Lille"—if the result of showing France 1 in Lyon produced a spike in pregnancies in Lille. "But according to quantum mechanics, situations presenting just such a dilemma can be contrived. Moreover"—he came to the center of the problem—"the peculiar long-range influence in question seems to go faster than light."

And that is impossible, as the theory of relativity shows. Space and time are not constant realities unaffected by anything. Space, Einstein said, is merely what we measure with a ruler; time is what we measure with a clock. And as it turns out, the faster an object goes, the more it compresses and the slower ticks any clock it might carry (for example, its heartbeat). In fact, it compresses just enough, and its clock slows down just enough, that it can never reach the speed of light. Every day, accelerators like the ones that John and Mary Bell helped design—full of particles moving close to the speed of light—bear out in precise detail Einstein's amazing predictions: 299,800 kilometers per second is the universe's absolute speed limit.

Two years after the Orsay talk, as Bell was publishing "Bertlmann's Socks," a young experimental physicist there named Alain Aspect (with an auspiciously Hercule Poirotesque mustache) was about to test if such a long-range influence really must be faster than the speed of light. Rigging up something very much like the Bell-Mermin machine, he found that the mysterious correlations remained, unfazed no matter how fast he switched the settings on the detectors. Physical signals traveling at mere light speed could not explain the results.

So, there are no genes and there is no signaling. The world is entangled in a beautiful and mysterious way. At the beginning of the twenty-first century, after three-quarters of a century of coexistence with the idea, there is still no clear explanation of its magic. But a change is in the air.

One of the first people to think of trying to build something out of entanglement was an early reader of Mermin's entertaining elaboration of Bell's thought-experiment. This paper gave many nonphysicists their first peek into the mysteries of the quantum world, but this reader was someone who did not require any simplification: Richard Feynman. The greatest and most famous physicist alive (and not someone known for reading and appreciating other people's papers), Feynman wrote to Mermin: "One of the most beautiful papers in physics that I know of is yours in the *American Journal of Physics*. . . . All my mature life I have been trying to distill the strangeness of quantum mechanics into simpler and simpler circumstances," he explained, which had led him to craft a similar but twice as complicated gedanken demonstration "when your ideally pristine presentation appeared."

Feynman had computers on his mind, and he had instantly seen that Bell's theorem prohibited them from simulating nature on the quantum level. Characteristically he viewed this as an opportunity rather than a problem. At the Massachusetts Institute of Technology that same year, as Aspect tweaked his machinery, Feynman brought Bell's inequality before a meeting of the best computer scientists in the world. He challenged them to produce a new kind of computer. This might hardly be recognizable to us as a computer (in fact, the first one made, at the end of the twentieth century, was a liquid of specially engineered molecules in a tiny vial), but in whatever form it takes, the person using it to compute will do so by manipulating the states of quantum particles. Most important to

Feynman, a quantum computer would use the magic of entanglement, and bring us to an understanding of it in the process.

Not long after Feynman gave this speech, a few brilliant minds proved some of the things such a computer might be able to do. Most significant to nonphysicists, a quantum computer could crack all the codes that the security of our banks, government, and the Internet is based on.

As experimental quantum physics groups, in physics departments all over the world, turn their attention to the building of a quantum computer, entanglement remains a mystery. But it is a mystery that gets better known all the time. Physicists are beginning to look at the magical correlations as something as fundamental—and worth fathoming—as energy or information. Famously, it was through machine-building that scientists began to understand both these fundamental ideas. In the nineteenth century, advances in understanding energy were inseparable from the building and running of steam engines; in the twentieth century, the rise of computers was inextricably intertwined with the rise of information theory; in the twenty-first century, hands-on work on the quantum computer and quantum cryptography—another entanglement-based miracle—will make us both more comfortable and more awed at entanglement.

But it was the twentieth century that first encountered entanglement, and to tell the story of entanglement is to tell much of the story of quantum physics itself. The story of entanglement begins near the start of the century with a suspicion of the spookiness of the quantum theory. For centuries, physics had seemed to be on a relentless march to total understanding of the world. The dawn of the twentieth century brought the news that the deeper we delved into both matter and light, the more mysteries we would find.

The Arguments

1909–1935

Albert Einstein and Paul Ehrenfest, ca. 1920

2

Quantized Light

September 1909–June 1913

During the autumn in Salzburg, a hot, dry wind called the *Föhn* sweeps down the slopes of the Alps and through the chilly air of the city. It evaporates all haze and fog so that faraway things appear suddenly clear. But the atmosphere is heavy and unpleasantly unseasonal; people blame the *Föhn* for their headaches and irritability.

Albert Einstein, a rumpled and large-eyed thirty-year-old in a straw hat, about to change his official career from patent clerk to professor, came to Salzburg in late September of 1909 for his first physics conference. With its pale stucco facades and copper-roofed towers, the city is known for its particularly beautiful light, and light was what was on Einstein's mind.

Rooster tail feathers and hummingbirds; the pearly inner chambers of shells and the wing cases of beetles; soap bubbles and oil slicks; thick glass and dappled sunlight through gaps between leaves—all these, examined closely, show light as a wave. It does not rain down on us like the *Schnürlregen,* or "straight-string-rain" downpours of Salzburg. It ripples and interferes.

While the actual interference is invisible, its calling card is striking: precise bands of darkness in places that a "string-rain" of light would illuminate, and precise bands of light in places that the imagined downpour of light drops would leave in shadow. Color, moreover, is purely a wave phenomenon—it is the number of times a light wave rises and falls per second—and each color bends differently when it strikes liquid or striated surfaces, producing the iridescence of the soap bubble or beetle. The understanding of all these phenomena was the climax of centuries of study of electromagnetic radiation (light is merely the visible stretch of the electromagnetic spectrum—ranging from radio waves bigger than a house to X-rays and gamma rays smaller than an atom).

Then Einstein, in 1905, came across the beginning of a great mystery: sometimes light, so clearly a wave, seemed to behave like drops or particles. This mystery was as strange as the discovery of unicorn horns on Arctic beaches. Such a discovery encourages some to dismiss it entirely while others proclaim the existence of magic horned horses; only a few will search for the narwhal, the Arctic whale to whom the horn belongs. Einstein was going to Salzburg to tell his fellow physicists, whom he had never met, that light was made of neither waves nor particles, but some currently incomprehensible fusion of the two.

But the real narwhal is a strange beast—stranger than the mythical unicorn. Einstein was embarking on a quest to understand each particle of light (and matter) as possessing its own independence, disentangled from all the others; its own local reality; its own unique, separable state. This fifty-year search for separability led him again and again to its nemesis, entanglement. And the clarity with which he reported his unwanted results made this unsuccessful quest one of the most fruitful investigations of the twentieth century.

The year before the conference, Einstein's focus on light had reached an intense pitch. "I am incessantly busy with the question of the constitution of radiation," he wrote in 1908, engaging in arguments by letter with H. A. Lorentz of Leiden, Holland, and Max Planck of Berlin—the two preeminent theoretical physicists in the world, both more than two decades older than Einstein.

He found Planck "an utterly honest man who thinks of others rather than himself" (and because of this, he would show Planck more steadfast loyalty than he gave either of his own wives). "He has, however," Einstein decided in 1908, "one fault: he is clumsy in finding his way about foreign trains of thought." Lorentz, on the other hand, seemed to Einstein in 1908 "astonishingly profound," and by 1909 he was writing, "I admire this man as no other, I would say I love him."

Einstein and Lorentz believed that Planck, in the last month of the nineteenth century, had turned physics on its head. It had all started with light in a box (an image to which Einstein would return repeatedly). In 1900, after years of work, Planck had come up with a formula that predicted, for any given temperature, the energy carried by each color of light inside a box. (The "box" could be any size or shape, as long as it was empty and could hold heat.)

In order to get the correct formula, Planck had to count energy in "quanta" of a certain size, symbolized by $h\nu$. *Quantum* was nothing mysterious yet—in German, it just means "amount"—while ν stood for the color (i.e., frequency) of the light, and h was a new, tiny, constant number.

Then came Einstein's discovery in 1905 that the data for bluer, high-frequency light showed that Planck's discovery was not just a counting device. Ultraviolet light, X-rays, and gamma rays behaved, in or out of the box, as if actually built from "mutually independent energy quanta"—atoms of light.

The man whose mathematical analysis they were all using to attack this problem was Ludwig Boltzmann of Vienna, who had done more than anyone to demonstrate logically that *matter* was built of atoms. But he lost himself in his ever-present depression and committed suicide in 1906 at the age of sixty-two. As that tragedy unfolded, his student, a twenty-five-year-old named Paul Ehrenfest, showed that Planck's new formula had introduced something completely new that could not be derived from, or even harmonized with, any physics that had gone before. A pure wave theory led to wildly wrong predictions for high-energy, high-frequency light. Ehrenfest dubbed the situation "the ultraviolet catastrophe."

"This quantum question is so uncommonly important and difficult," Einstein wrote in 1908, "that it should concern everyone." At the time, it hardly concerned anyone aside from himself, Planck, Lorentz, and Ehrenfest.

Early in May of 1909, Lorentz wrote Einstein a long and thoughtful letter criticizing Einstein's particles of light. "I must have expressed myself unclearly in regard to the light quanta," Einstein replied late that month. "That is to say, I am not at all of the opinion that one should think of light as being composed of mutually independent quanta localized in relatively small spaces." What strange things would mutually dependent or nonlocal quanta be? Einstein very much hoped that the truth, with further digging, would set him free of such chimeras.

On the way to Salzburg from his home in Switzerland, he had stopped in Munich to see the only schoolteacher who had really inspired him, a Dr. Ruess, who taught fourth- and fifth-grade languages and history. The perpetually amused, stubborn-as-a-mule patent officer standing before his old teacher had already accomplished much of what would later make him the most famous man in the world. He had already shown that though motion is relative to a reference point, the speed of light and the laws of physics are not. He had already shown that energy and matter were transmutable ($E = mc^2$). But Dr. Ruess saw only Einstein's frayed clothes, thought he must be there to ask for money, and sent him on his way, an inauspicious prelude to his first conference.

"It is my opinion," Einstein explained, looking out at the assembled physicists in Salzburg, "that the next phase of the development of theoretical physics will bring us a theory of light that can be interpreted as a kind of fusion of the wave and particle theories." The purpose of his speech, he explained, would be "to justify this opinion and to show that a deep change in our conception about the nature and the constitution of light is *indispensable.*" He showed an increasingly skeptical and bewildered audience that Planck's formula actually required light to be a particle as well as a wave.

Planck immediately stood up after the mystified clapping died down. He had come from a family of theologians on both sides, and he himself, with his serious eyes, dignified mustache, and thin frame, was in many ways the pastor of German physicists. "I will restrict myself naturally to the points where I have a different opinion from that of the speaker," he said. He felt that Einstein had made "a step that is in my opinion not yet necessary. . . . In any case, I think that we should first try to transfer the problem of quantum theory into the area of *interaction* between matter and radiating energy."

The belligerent Johannes Stark stood up, in pince-nez and a sweeping mustache that dwarfed his handsome face. He was a thirty-five-year-old Bavarian experimentalist, and, along with Planck, he had merited one of the few footnotes in Einstein's light-quantum paper of 1905. Einstein, who was not sensitive enough to be bothered by difficult people, seemed to have made a friend of Stark (who usually made only enemies). For a decade he would be Einstein's only light-quantum follower. But as Einstein's fame grew, Stark's jealousy became a mania. When Hitler rose to power, Stark would lead the cry for Einstein's blood, and for the removal of "Jewish physics" from Germany.

In 1909, Stark recognized Einstein's valid point. "Originally, I too was of the same opinion," he said to Planck. "However, there is one phenomenon which forces us to think of electromagnetic radiation as *separated* from matter and concentrated in space." Röntgen rays, as X-rays were then called, "can still act *concentratedly* [with their full force] on a single atom, even at up to ten meters": the opposite of a wave diffusing out into the world in ever-widening circles.

"There is something unique to Röntgen rays," Planck agreed. "Stark has mentioned something in favor of the quantum theory; I wish to add a remark against it," he continued. Most light behavior—most strikingly, interference—can hardly be explained by particles. "If a quantum interferes with itself," Planck said, "it must have a spatial extension of hundreds of thousands of wavelengths." How could a string-rain of particles produce those neat bands of light and shadow? Interference demands a wave explanation.

Stark responded confidently: "The interference phenomena would probably be different with very low radiation density." It would be three-quarters of a century before this reasonable statement could be shown to

Ehrenfest was now describing his struggles with the quantum theory to Einstein, who nodded sympathetically: "The more success the quantum theory has, the sillier it looks."

Ehrenfest turned to von Laue: "Did he tell you about the park in Prague?"

Von Laue shook his head.

"Well, when I came to visit Einstein in Prague a year ago—Einstein, you tell it."

"My office had a really quite nice view of a park with trees and gardens," said Einstein. "And people would walk in it, some deep in thought, others gesticulating intensely at each other in groups." Einstein grinned. "The strange thing was, it was only women in the morning and only men in the evening. And when I asked what was this place, they told me, 'It's the Bohemian Insane Asylum!' "

Ehrenfest turned to von Laue: "And he said, 'Those are the madmen who do not occupy themselves with the quantum theory.' "

3

The Quantized Atom

November 1913

Niels Bohr

THE LATE NOVEMBER FOG accompanied Max von Laue and Otto Stern most of the way up the Uetliberg. It was five months after Ehrenfest's visit. They were hiking the little mountain on this gloomy day because they knew that its peak was above the clouds, in the sun. That morning in the fog-bound streets, Stern and von Laue had seen yellow placards reading "UETLIBERG HELL"—Mt. Uetli light.

Laue and Stern had only recently become locals, Laue a professor at the University of Zurich and Stern a lecturer at the E.T.H. (the letters stand for Eidgenössische Technische Hochschule—the Swiss Federal Institute of Technology—but it is always known by its initials, the "*A. tay hah*"). Like the Alsatian Laue, Stern had grown up on the much disputed fringes of Bismarck's booming German empire, in Silesia (the as-yet unknown and ordinary town of Auschwitz sat on its border).

Stern was a decade younger than von Laue—chunky, long-chinned, radiating good humor. He would brilliantly occupy the border between theory and experiment, but he was so clumsy that he would do anything to avoid handling the more breakable equipment once he became a professor with assistants to do it for him. Even if it was toppling over, "you do less damage if you let the thing fall than if you try to catch it," he would explain, gesturing with his cigar. Spending his own money to join Einstein in Prague in 1911, he had been Einstein's sole confidant there; the memories of those "beautiful days" would bring tears to his eyes when Stern was an old man exiled by the Nazis on the other side of the world.

On the top of the Uetliberg, taking deep breaths of the cold air while sweat chilled between their shoulder blades, they looked out across the white sea of fog. The city behind them had vanished. Instead they saw the thunderous Alps: the snowy trinity of the Eiger, the Monk, and the Virgin, and the precipitous dark steeple of the Finsteraarhorn. The two men made a funny silhouette against this view: the short and semispherical Stern beside the tall and angular von Laue.

They were talking about the atom, as everyone they knew seemed to be. Ever since it became clear in 1911 that the atom was something like a tiny solar system (its sun the positively charged nucleus, exerting a constant electrical pull on its planets, the negatively charged electrons), there were problems. A charged object like an electron is inseparable from the electric field it emanates; if it moves, it generates a magnetic field, too; and if it changes its speed (speeding up, slowing down, or turning), that change makes a wave in the electric and magnetic fields surrounding it. This electromagnetic wave is what we call light. The electrons, charged and orbiting the heart of the atom, should be making constant light-wave ripples in their electromagnetic fields, leaking energy with each wave until every atom in the universe goes flat like a punctured tire. This, of course, does not happen.

In 1913, a few weeks before Stern and von Laue climbed the Uetliberg, the theoretical problem of the inexplicably stable atom had been declared solved by an unknown twenty-eight-year-old Danish physicist, Niels Bohr, just returned home to Copenhagen after a year in Manchester, England. It had taken him seventy-one dense pages, and his explanation was illogical. Rather than radiating light all the time, Bohr said, the electrons would emit light only when they made a kind of ineffable transition (the famous "quantum jump"). These jumps or leaps were nothing like the smooth bounding of a cat. They were a baffling, quantized, all-or-nothing disappearance in one orbit and emergence in another—like Earth suddenly materializing in the orbit of Mars.

The quantum leaps alone were like nothing that had ever happened in a physical theory before, but just as unsettling was the *frequency* of the light that the leaping electron emitted. We perceive the frequency of light as color, but the concept of frequency applies to anything that cycles, from literally round objects like wheels to things like the seasons that recur in a cyclical way. The frequency of a carousel, for example, is the number of times per minute the spotted pony with your little sister on it passes while you stand and wave. Inside the carousel a record player cranks out a tinkly band-organ tune. The frequency of the record is its number of rotations per minute (rpm), which is directly related to the frequency of the sound produced. If the operator happens to set the turntable at a slow 33⅓ rpm to play a 45-rpm record, the tinkling sound will deepen into a tired pizzicato, while the opposite mistake will produce a manic speed jingle. But in Bohr's atom, the frequency of the electron's orbit is not the same as the frequency of the light it emits. Incredibly, it is a single, pure frequency halfway between the orbit where the electron started and the orbit in which it would land, as if the electron, radiating the light, already knew where it was going to stop.

"It's just absurd. I don't think it's physics at all," said von Laue finally, turning from the view. "He has simply stabilized the atom by fiat—"

Stern grinned: "The dictator!"

Von Laue laughed a little in his frustration.

They sat staring again at the peaks in the distance. Then they both turned to each other and said, "Have you talked to Einstein?"

"At this last colloquium when they presented Bohr's theory," von Laue said, "I stood up at the end and said"—he looked at Stern with a practical expression on his face—" 'but this is nonsense! If an electron is going in a circular orbit it has to radiate light.' "

Stern nodded.

"But *Einstein*—he said, 'Very curious. There must be something to it.' " Von Laue gave Stern a quick glance. "He said that he didn't believe it was pure chance that the Rydberg constant could be predicted so accurately in terms of basic constants."

The Rydberg constant had been for thirty years an unexplained number in the equation predicting the colors of light each element of the periodic table might emit. Bohr's preposterous theory had accidentally and effortlessly yielded this heretofore arbitrary number, producing meaning where before there had only been mandate.

"Well," von Laue finally said, "when he really thinks about it, he won't like the Bohr theory."

"I agree," said Stern. "This dictatorial decision, laying out flight paths and ordering inexplicable jumps for the electrons—it might seem successful right now, but it's not *physics.*"

With a sardonic expression, von Laue commented: "*Someone* should stand up and stop this nonsense."

Stern, with a mock-elegiac tone in his voice, harked back to the fabled fourteenth-century birth of Swiss democracy: "The lone man with two arrows . . . where is Wilhelm Tell? Where are the men of the Ruetli Oath?"

Getting into the spirit of Schiller's famous play, von Laue quoted from it: " 'No, there is a limit to the tyrant's power.' " He and Stern were unwilling to accept a dictator, no matter how benevolent.

They both were laughing now. "Do you solemnly swear, Max Laue"—Stern grinned and corrected himself—"Max *von* Laue, to give up physics if Bohr turns out to be right?" (Max's father had been bestowed with hereditary nobility that year, hence the "von.")

Von Laue grinned widely. "Absolutely. I wouldn't be able to stand it. And you, Otto Stern, do you so swear?"

"How does the Ruetli Oath go?" asked Stern. "Something about the 'inalienable and indestructible stars . . .' "

"No," said von Laue, stretching out his hand: they were on the Uetliberg, after all. "We need new words," he said, beginning to grin.

Stern caught on: "For the *Uetli* Oath!"

"Swear by the atom," said von Laue.

The atom, ever since Greek philosophers in the fifth century B.C. first postulated it, has been one of the great mysteries. Is all matter—you, the chair you're sitting in, the air you're breathing—ultimately composed of the same building blocks? What would such an ultimate building block be like? People fumbled through philosophy trying to find an answer. Then, in the mid–eighteenth century, an inquisitive Scotsman, Thomas Melvill, burned table salt and looked through a prism at the light produced, as Isaac Newton had once looked through a prism at white light and seen the rainbow spectrum. Melvill did not see a rainbow spectrum: he saw only a pair of yellow-orange stripes, surrounded by darkness.

Sixty-two years later, Joseph von Fraunhofer looked through a prism at the sun while calibrating surveying lenses for a military supply company. He noticed for the first time that there were dark lines across Newton's rainbow spectrum. The rainbow was, in fact, missing two chunks of warm yellow—as if it were the salt spectrum turned inside out.

This coincidence went unexplored for almost half a century until Gustav Kirchhoff, a dapper little physicist who walked about the medieval halls of the University of Heidelberg on crutches, deduced why that

Stern vowed to give up physics if he was right, Einstein was visiting Vienna. There he chanced upon Georg von Hevesy, a Hungarian experimentalist who was a good friend of Bohr's.

"I asked him about his view of your theorie," Hevesy wrote Bohr in his characteristically erratic English. "He told me it is a very interesting one if it is right and so on" ("faint praise," remarks Einstein's friend and biographer Abraham Pais, "as I know from having heard him make that comment on other occasions").

Hevesy then told Einstein that Bohr had been able to explain a mysterious series of spectral lines in starlight as belonging to helium. Bohr's theory had produced a result "in exact agreement with the experimental value"—an unheard-of feat in the field of spectroscopy. "The big eyes of Einstein looked still bigger," Hevesy reported to Rutherford. "He was extremely astonished and told me"—with his excitement, Hevesy's spelling grows even more scattershot—" 'Than the frequency of the light does not depand at all on the frequency of the electron . . . and this is an *enormous achiewment.* The theory of Bohr must be then wright.' "

He confided to Rutherford, "I felt very happy hearing Einstein saying so."

But the reaction of von Laue and Stern was far more common than the reaction of Einstein. "Bohr's work on the quantum theory . . . (in the *Phil. Mag.*) has driven me to despair," wrote Ehrenfest to Lorentz. "If this is the way to reach the goal," he continued, "I must give up doing physics." He liked to congratulate students with, "And now you've pulled the whole rat out of the soup!" Bohr, he felt, had left a lot of rat in the soup. He proceeded to ignore what he referred to as the "completely monstrous" Bohr model.

Before most physicists had absorbed the abstractions of the Bohr atom, and in the midst of the shortages and hardships of the First World War, in 1915 Einstein produced general relativity, science's greatest work of art. The earth turns about the sun; but according to general relativity, the sun also turns about the earth. There is no reference frame that is the correct one from which all the spinning of the worlds might be viewed; no "fixed stars," no stationary observer. General relativity is necessary to explain not only galaxies in their courses, but also the tiniest subatomic particle hurtling down from the sky. It is famously not amenable to quantization, and if Einstein had to pick between the two, he would choose relativity.

Ehrenfest wrote in 1917 that he only wanted "a general point of view which may trace the boundary between the 'classical region' " (which covered nonquantized physics, including relativity) "and the 'region of the quanta' "—a yearning that in the ensuing years Bohr would be glad to satisfy. Einstein, on the other hand, wanted a single unified physics, and would not be happy with such a truce.

In 1919, Bohr came to Ehrenfest's Leiden University. Speaking earnestly, with a "soft voice, indistinct pronunciation, and involved sentences, carefully qualified as to exclude possibilities which it was often unduly flattering to suppose one had considered" (as J. J. Thomson's son, G. P., described it in classic British understatement), Bohr lectured on his atom.

Accompanying his elliptical explanations were intricate, hypnotizing drawings of electron orbits crisscrossing about a central dot: "the Bohr atom." It was to be both the first and last quantum icon, before all such images vanished into clouds of abstraction. Bohr explained that these orbits were not to be taken exactly literally; but few could hear, while everyone could see the beautiful planetary drawings. Everyone could also see the successes of the Bohr theory, even if they couldn't understand it.

Ehrenfest was won over by the theory and the man himself. "Ehrenfest writes enthusiastically about Bohr's theory of atoms; he is visiting him," Einstein wrote in 1921 to his lifelong friend and colleague Max Born, whom he had met at that speech in Salzburg. "If Ehrenfest is convinced, there must be something in it, for he is a skeptical fellow."

4

The Unpicturable Quantum World

Summer 1921

Werner Heisenberg

"Do you honestly believe," asked Werner Heisenberg, sitting in the grass beside his bike one late summer afternoon, "that such things as electron orbits really exist inside the atom?" He took a bite of cheese and looked over at Wolfgang Pauli, who was lying in the grass like the dead. Otto Laporte was drinking the sweet drafts of the really thirsty, holding his canteen above his head.

"Pass the cheese," said Pauli, without moving.

Heisenberg was nineteen. Pauli was only a year and a half older but had just completed his Ph.D. in Munich under Max von Laue's friend and former colleague Arnold Sommerfeld, with whom Heisenberg was also studying. Laporte was about to turn nineteen, and had come to Munich only a semester earlier, from Frankfurt am Main, where his family had lived until the German army took over their house.

Laporte and Pauli had met as "fellow sufferers" in the eight-hour-long old-fashioned experimental physics class of the dignified Nobel laureate

Wilhelm Wien. The three boys had escaped on a bicycle trip, in a whir of enthusiasm: "probably the only time Wolfgang dared enter my world," the outdoorsman Heisenberg wrote of his urban friend.

He passed the cheese, and squinted at the dusty road that led to the top of the Kesselberg. A noise came up from the grass.

Pauli, refortified, but still lying down, said, "I know, the whole thing seems a myth." He sat up with a huge effort, his heavy-lidded eyes almost closed in the midday sun—*he has a secretive face,* thought Heisenberg when he first met Pauli, the year before. Pauli and Heisenberg on first meeting could hardly have seemed more different. Heisenberg was blond, thin, "like a simple farm boy" (as his professor Max Born thought when he first met him). Pauli, dark-haired, already a little overweight, constantly oscillating and rocking, spent his extracurricular time in coffeehouses and nightclubs.

The physics brought them together. They were already the rising stars of their profession. In 1920, Pauli had written a monumental two-hundred-page review explaining all of general relativity—mathematically forbidding even to experts—which had impressed Einstein himself. And in the confused infant field of quantum theory, both of them were starting to produce original ideas, under the inspired (and unusually laissez-faire) guidance of Sommerfeld in Munich.

Laporte managed not to be overawed. Heisenberg liked his directness, the matter-of-fact expression behind his big, clunky, dark-rimmed glasses, his easy smile, and his interest in everything.*

"The talks we began during that tour and continued in Munich," Heisenberg remembered later, "were to have a lasting effect." The difficulty of picturing the quantum world as made of either waves or particles would lead Heisenberg and Pauli to deny the usefulness of striving for pictures at all, while Bohr would advocate holding two contradictory pictures in mind. For pictures are always simpler than what they describe, and oversimplicity can mislead. But just as deceptive is a repudiation of pictures: nothing is better than language for drawing an intricately vague veil over truth. It would turn out that what was obscured by an image-free description of quantum mechanics—or by Bohr's cubist description that welcomed contradictory pictures—was entanglement.

"You know," Pauli continued, "Bohr has succeeded in associating the strange stability of atoms with Planck's quantum hypothesis—which has

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*A decade down the road, as a guest lecturer at the University of Tokyo, he would become fluent in Japanese, winning a prize for a haiku, and as a sideline to physics, he would specialize in the botany of cacti.

not yet been properly interpreted either—but I can't for the life of me see *how*, since he is unable to get rid of the contradictions."

"Well," said Laporte, "we should only use such words and concepts as can be directly related to sense perception."

Pauli's eyes almost closed. "Ahh, Mach. He always sounds so plausible, just like the devil." Ernst Mach was one of the main influences on nineteenth-century German physics, famous for his belief in positivism, according to which only observables had any meaning. Pauli's eyes opened. "He's my godfather, actually."

"What!" said Heisenberg.

"He's my godfather," said Pauli, nodding rhythmically. "Evidently he was a stronger personality than the priest and the result seems to be that . . . I am baptized antimetaphysical instead of Catholic. His apartment was chock-full of prisms, spectroscopes, stroboscopes, electrifying machines. When I visited him he always showed me a nice experiment . . . for the purpose of correcting thought processes, which are always untrustworthy and cause delusions and errors." Pauli grinned. "He always presumed his *own* psychology to be generally valid. But his positivistic doctrine is a waste of time."

Laporte, annoyed, said, "Didn't Einstein arrive at his theory of relativity by sticking to Mach's doctrine?"

Heisenberg nodded.

"I think," said Pauli, gesturing with his wedge of cheese, "that that is a crude oversimplification."

"What's wrong with sticking to observables?" asked Laporte.

"Mach did not believe in atoms because he could not observe them," said Pauli, with a firm sideways look at Laporte. "He was led astray by the very principle you're defending, and, as far as I am concerned, this was not by chance."

Heisenberg's brow furrowed.

Laporte said, "Mistakes are no excuse for making things more complicated than they are."

"Well, you're right about that, and my opinion is, these orbits should be the first thing to go. But Sommerfeld loves them. He relies on experimental results and atomysticism," Pauli continued. For an instant he raised his eyebrows.

"Atomysticism?" said Laporte.

Pauli laughed, rocking a little more. This was a word Sommerfeld's students had coined to describe what was, by 1921, called the Bohr-Sommerfeld model of the atom in acknowledgment of all the improvements Sommerfeld had made to it. With each improvement, the results because we were near Einstein." Einstein declared prophetically in 1920, when Born was trying to decide whether or not to move to Frankfurt, "Theoretical physics will flourish wherever *you* happen to be—there is no other Born to be found in Germany today."

With a knife-shaped magnet designed by the young experimentalist Walther Gerlach—an unofficial member of Born's lively, cutting-edge theoretical department—and financing, in those grim, money-starved days, from an American philanthropist and from Born's sold-out lectures on relativity, Stern was observing one of his trademark molecular beams. This was a ray of hot, gaseous silver atoms that passed through the magnetic field created by Gerlach's magnet to strike a screen on the other side.

Classical (pre-quantum) physics would predict a single smeared clump of silver on this screen as the result. Each atom on its flight approaches the magnetic field tilted at a slightly different angle, which affects its response to the big magnet, and thus each would land on the screen in a slightly different place, not too far from the middle. But Sommerfeld, trusting his quantized calculations, said that the silver atoms should hit the collecting screen in three neat piles, and he could predict the distance separating them.

But what Stern and Gerlach found, no one had predicted. No silver atoms ended up in the center. The atomic beam split neatly into *two* discrete beams (exactly as far apart as Sommerfeld had predicted, though). The response of the atoms to the field was even more quantized and less classical than Bohr and Sommerfeld had expected. The atoms had made a yes-or-no, up-or-down, either-or response to the field.

The Stern-Gerlach experiment was a sensation among physicists when it was published in 1922, and it was such an extreme result that many who had doubted the quantum ideas were converted. Bohr saw "the apparent contradictions inherent in quantum theory" emerging more strongly. A paper by Einstein and Ehrenfest, in which they had tried to understand what Stern's silver atoms did as they passed through the two halves of Gerlach's magnet, rang an alarm bell for him. As they "exposed so clearly, [the Stern-Gerlach experiment] presented with unsurmountable difficulties any attempt at forming a picture of the behavior of atoms in a magnetic field."

Einstein and Bohr would draw different morals from this difficulty of forming a picture of atomic behavior. Bohr would soon say it couldn't be done. The behavior of atoms, and their insides, were irreducibly unvisualizable.

Einstein would say there was something wrong with a physics that would come to this conclusion.

One thing was sure: quantization occurred; there was no real explanation beyond that fact, much as Sommerfeld might decorate it with musings on atomic harmony. As Heisenberg remembered, "This peculiar mixture of incomprehensible mumbo jumbo and empirical success quite naturally exerted a great fascination on us young students."

It would take three years for a solution to emerge—started, as soon as they got back to Munich, in a fit of inexplicable inspiration by Heisenberg, and clarified, corrected, and tied to reality by Pauli (a pattern that the friends would repeat many times). Heisenberg made the math work by introducing a half-quantum into Sommerfeld's equation, horrifying his professor's mystical leanings: "That is absolutely impossible! The only fact we know about quantum theory is that we have *integral* numbers, and not half numbers." Drily, Pauli suggested that his friend would next introduce quarter-quanta, then one-eighth-quanta, and in no time "the whole quantum theory will crumble to dust in your capable hands."

But eventually Pauli found that the half-quanta described something real about the electron. Real, but impossible to visualize: the electron seems to be spinning, but this is no spin anyone has ever seen; what should be a complete rotation is only halfway around to an electron. It must "spin" two full times to reach its starting point again. No one understands what this means. But the electrons that "spin" in one direction are attracted to one pole of the Stern-Gerlach magnet, and electrons that "spin" in the opposite direction are drawn the other way: two piles.* (Because 360 degrees is only halfway around for electrons, they are called by the ungainly name of "spin–½ particles.")

These deeper mysteries were still in the future when Heisenberg, on his bike, reached the saddle of the steep mountain road, where it prepared to plunge precipitously down to the Walchensee, a cup of blue among the mountains. He was light-headed from the exertion and the view. Laporte, with the sound of tires braking on the dirt, joined him in silence.

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*A technical footnote: Sommerfeld was wrong only because neither he nor anyone else yet knew about spin. He based his calculation on the atom's quantized angular momentum, which indeed is a factor. But silver, like hydrogen, has a single unpaired electron in its outermost (valence) energy level. That electron's spin (up or down) is what causes the binary response to the magnetic field. If Stern and Gerlach had done the experiment with, for example, magnesium (which has a pair of electrons in its valence energy level), Sommerfeld would have been perfectly correct: the beam would have split into three. Magnesium's valence pair of electrons (one spins up, and one spins down) cancel out each other's influence, so that spin is no longer an issue, and the three quantized valences of angular momentum create the three piles.

"This was Goethe's first view of the Alps," said Heisenberg finally.

After a while, Pauli appeared, muttering to himself. Then the breeze, like a brook running through the still day, met him, and he saw the view. He stood, rocking gently, gazing with those mysterious eyes out over the Walchensee.

Finally he broke the spell: "Now I am going to teach you two some physics. Today's lesson is on momentum: speed times mass." And he took off down the mountain road.

Laporte and Heisenberg, laughing, leaped on their bikes, trying to catch him, but soon their wheels were turning faster than they could pedal. They swerved down switchbacks, wide grins spread across their faces. The whirring of the tires, the air thrumming through the hair on their arms and tearing tears from their eyes, the flash of a sail on the lake in the sun—everything became an ecstatic blur, each boy inside his own blurry bubble, quivering to his own heartbeat.

Pauli's greater mass and hence greater momentum had carried him farther than the other two—the giddy descent done, he was still coasting while they pedaled again to catch him. The lakeshore beneath the Alps was striped with the gray-skinned trunks of knobby beeches leaning out over the water.

Heisenberg was still exhilarated. He loved the medieval towns, the little bucks that leaped about on cloven hooves up the cliffs, and these valleys, these lakes, these ever-present mountains: *How could anyone live anywhere else but Bavaria?*

He looked at his two companions and knew that they did not feel the same. Not Pauli, the child of the Viennese coffee shops, the cobblestone streets, the electric light; nor Laporte with his dreams of America.

But for Heisenberg the beauty had sometimes been the only thing keeping him going, through the years of the Great War (nearly starving in the turnip winter, and then the catastrophic, unexpected defeat) and the civil war afterward (the Red Terror, the White Terror). Like many others all over Germany, he had driven oxen, carried guns, and sneaked through enemy lines in the dark to get food for his family. There were five years of horror and upheaval, while his elders repeatedly, frighteningly proved that they had no idea how to live or run a country. A generation of intellectual German boys, Heisenberg among them, decided to ignore politics, with its commonness and militarism, to find a higher order. And many of them did and said nothing when Hitler gained power.

In a decade, these three boys' lives would be completely changed. In Ann Arbor, Michigan, Laporte would be an American citizen; the half-

Jewish Pauli would flee because of the racial laws—first to Zurich, and finally to Princeton; and Heisenberg would remain, trying to save German science and his own skin from the barbarians.

"A saying occurs to me that ends thus—*but if it sinks in shining splendor, still it shines a long way back,*" Heisenberg wrote to his mother in the waning months of 1930. "I believe as long as we ourselves are in this world, we must be satisfied with feeling this shining-back. . . . About ten years ago," he told his mother, "that was the most beautiful time of my life."

5

On the Streetcar

Summer 1923

NIELS BOHR is riding the streetcar to pick up the world-traveling (and, after the astronomical confirmation of general relativity in November 1919, suddenly world-famous) Einstein at the port of Copenhagen. With him is Arnold Sommerfeld, visiting from Munich. Einstein has just given a speech in Sweden, making up for his nonattendance at his Nobel Prize ceremony in December 1922.

Von Laue, hearing that Einstein was planning a trip to Asia that year, had written him in barely cryptic fashion the September before the prize was awarded: "According to information I received yesterday and which is certain, events may occur in November which might make it desirable for you to be present in Europe in December. Consider whether you will nevertheless go to Japan."

The year after von Laue's oath with Stern on top of the Uetliberg, he himself had become a Nobel laureate for his beautiful interference experiment, showing X-rays to be waves. Seven years later, the Nobel committee was recognizing Einstein for suggesting that they were particles.

Einstein's fame had soured somewhat. On June 24, 1922, his friend Walther Rathenau, the German foreign minister, was assassinated, the latest of more than three hundred prominent Jews assassinated in the postwar search for scapegoats. Einstein knew he might well be next. "It is no art to be an idealist if one lives in cloud-cuckoo-land," he wrote in a eulogy for Rathenau. "He, however, was an idealist even though he lived on earth, and knew its smell better than almost anyone else."

Einstein himself only barely lived on earth, but enough so that he saw it was time for him to disappear for a while. The faithful von Laue took his place at a lecture overrun with antirelativity and anti-Semitic demonstrators (including Stark, who had received his own Nobel Prize in December 1919, but almost no recognition for it, as all eyes were on Einstein). Von Laue understood when, in December 1922, despite the forthcoming Nobel Prize, Einstein sailed as far from Europe as he could.

bearing Einstein's suitcase and heavy bag of books and papers, while Einstein carries his violin.

"Einstein! It is so good to see you," says Bohr as they sit at the tram stop near the half-timbered clock tower of the ferry building.

"Tell us about Japan," says Sommerfeld.

"Probably much more interesting than the Nobel ceremonies, at any rate," says Bohr.

As Einstein was officially informed via telegram a hemisphere away, he had received the deferred 1921 prize,* and Bohr the 1922 prize that year. Bohr wrote him on November 11, 1922, the same day he found out: "For me it was the greatest honor and joy . . . that I should be considered for the award at the same time as you. I know how little I have deserved it, but I should like to say that I consider it a good fortune that your fundamental contribution in the special area in which I work as well as contributions by Rutherford and Planck should be recognized before I was considered for such an honor."

A month later, when the Nobel ceremonies occurred in Stockholm, Bohr threw down the gauntlet to the absent Einstein and his "fundamental contribution." "The hypothesis of light-quanta," Bohr had punned in his Nobel speech, ". . . is not able to throw light on the nature of [electromagnetic] radiation." He was serious, and he would be ready to say so to Einstein's face the next time he saw him.

Einstein, sitting on his deck chair sailing to Singapore, wrote back on the ship's stationery in January 1923:

> Dear or rather beloved Bohr!
> Your cordial letter reached me shortly before my departure from Japan. I can say without exaggeration that it pleased me as much as the Nobel Prize. I find especially charming your fear that you might have received the award before me—that is typically Bohr-ish. Your new investigations on the atom have accompanied me on the trip and they have made my fondness for your mind even greater.

As for Einstein's own mind, he continued conversationally, "I believe that I have finally understood the connection between electricity and gravitation"—a heroic, perhaps impossible, quest for unification that he would unsuccessfully pursue for the rest of his life. At that moment, the

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*It seems that the prize was deferred, at least in part, because of a stalemate resulting from the Academy's skepticism over relativity, on one hand, and the growing pressure from theoretical physicists for Einstein to receive the prize, on the other.

bread-hungry and bloodthirsty madness of Berlin seemed very far away. "A sea voyage . . . is like a cloister. Warm rain drips lazily down from the sky, engendering peace and a plant-like state of semi-consciousness—this little letter attests to it. . . . Yours in admiration, A. Einstein."

"Look—here is the streetcar," says Einstein, standing to greet it. "Where are we going?"

"To the institute! Number 15 on the Blegdamsvej!" says Bohr over his shoulder as he climbs on, paying the three fares. Blegdamsvej (pronounced *Bly-dams-vai*) is the wide boulevard running past what will become the long green lawn of Bohr's newborn institute, only three kilometers from the ferry terminal. Five young physicists from five different countries, temporarily reposing in the future library and laboratory, have already come to work with Bohr. The first paper with the byline "The Institute for Theoretical Physics, Copenhagen," came out months before the building was completed, from two of Bohr's students too excited to wait.

The streetcar lurches to a start, its wheels shrill against the tracks. The three physicists, making their way down the aisle, are the only people speaking German, which emerges from the mouth of Bohr with a generous sprinkling of English and Danish for good measure.

"So, my dear Bohr," says Einstein, "I hear that you have predicted an element."

"Oh, yes, *that,*" says Bohr.

Sommerfeld raises his eyebrows at this uncharacteristically brief statement. Einstein catches his glance and looks ironic. It was a new triumph for the Bohr atom that it was able to make sense, in terms of number of electrons, of the beautiful and hitherto inexplicable periodic patterns of the famous table of the elements.* Bohr had even described the properties of the (missing) element with seventy-two electrons.

"And then Hevesy, working right there in your new institute, *found* it,"

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*The periodic table, first laid out in the 1860s and 1870s by the visionary Dimitri Mendeleev, is a way of organizing the elements into rows (roughly) from lightest to heaviest: each column holds a group of elements with similar properties. Bohr's solar-system atomic model explained these properties internally—for instance, through the number of electrons in an atom's outermost orbit. For example, neon (with ten electrons) is totally inert, while sodium (with eleven) is extremely reactive. Ten electrons completely fill neon's two atomic orbits, giving the atom a "smooth" outer surface—a full orbit leaves nothing for another atom to grab. It is the opposite case with sodium; its eleventh electron is alone in the atom's otherwise empty third orbital ring.

prompts Sommerfeld. Hevesy, though a Catholic nobleman, had been fired from his position in Hungary at the end of the Great War because of his Jewish ancestry; as a result, the friends Bohr and Hevesy were reunited in Copenhagen. In Hevesy's charming broken English, he wrote Rutherford in 1922, while he was searching for the new element: "Bohr reads the language of spectra like other people goes through a magazine."

The story begins to pour out from Bohr: "We quite innocently dropped into the most terrible muddle of postwar nationalism; we had never dreamt of any competition with the chemists in the hunt for new elements, but wished only to prove the correctness of the theory. There was Alexandre Dauvillier at the de Broglie lab" (Maurice de Broglie was a well-known experimentalist working on X-rays in his mansion in Paris) "trying to claim priority for it as 'celtium' for France—with de Broglie's younger brother Louis backing him up—and then a Brit emerged, saying he'd found it before anyone else and it should be 'oceanum' for the British navy . . . no one paying any regard to the important scientific discussion of the properties of the element."

Einstein can't resist: "You did not quite avoid nationalism, yourself, did you?"

"Right," says Bohr, beginning to laugh, "and when we couldn't decide whether to call it 'hafnium'—for the Latin name of Copenhagen—or 'danium,' we got a letter from the editor of *Raw Materials Review* in Britain saying the papers claimed we'd discovered *two* elements, was it true? And someone in Canada suggested 'jargonium.' " Einstein roared with laughter, so that people on the streetcar turned around, wondering what the joke in German could be, and Sommerfeld chuckled heartily into his big mustache.

"Oh, it's good to see you doing so well," says Einstein.

Bohr shakes his head, smiling: "My life from the scientific point of view passes off in periods of over-happiness and despair . . . as I know that both of you understand . . . of feeling vigorous and overworked, of starting papers and not getting them published"—his face is earnest—"because all the time I am gradually changing my views about this terrible riddle which the quantum theory is."

"I know," says Sommerfeld, "I know."

Einstein's eyes almost close; he is nodding. "That is a wall before which I am stopped. The difficulties *are* terrible." His eyes open. "The theory of relativity was only a sort of respite which I gave myself during my struggles with the quanta."

"But, you know, everything is so exciting," says Sommerfeld. "This crazy model my young Heisenberg has thought up—"