THE AGE OF UNCERTAINTY:
How Physics Changed the Way We See the World

by

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Sample translation by Marshall Yarbrough

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The First Cracks

Paris. A summer evening in 1903. A garden on Boulevard Kellerman in the Thirteenth Arrondissement. Light falls onto the lawn from the surrounding windows, a door opens, joyful voices ring out in the night air. A small group of revelers spills out onto the gravel paths, among them a woman in a black dress: the physicist Marie Curie, thirty-nine years old. Her often-tense face is relaxed and cheerful. She has just received her doctorate and is throwing a party to celebrate.

Marie is at a high point in her career. She is the first woman in France to receive a Ph.D. in a scientific field, awarded with the distinction “très honorable.” And she is the first woman ever to be nominated for the Nobel Prize.

At Marie’s side, her husband Pierre is beaming with pride. With Marie tonight are her older sister Bronia, her doctoral adviser Gabriel Lippmann, her colleagues Jean Perrin and Paul Langevin, and several of her students. The physicist Ernest Rutherford from New Zealand has also joined the party. He and his wife Mary are on their honeymoon—finally: their wedding was three years ago. Rutherford and Marie Curie are rivals; both are investigating the structure of the atom, a subject on which there is vehement disagreement between them. But for tonight this feud has been laid aside. Tonight is a time for celebration.

The path that will lead Marie to this happy evening on Boulevard Kellermann begins far from the French metropolis, in Warsaw in the 1860s. Poland has been divided up between the three great powers of Prussia, Russia, and Austria. Warsaw lies under the tyranny of the Russian tsar. On November 7, 1867, Maria Skłodowska is born, the youngest of five children. Maria's parents are teachers. The family's views are opposed to the occupation. When Mania, as Maria is known in the family, is four years old, her mother, sick with tuberculosis, is forced to avoid contact with her and her siblings. She doesn't want to infect any of her children and dies after a long battle with the then-incurable disease.

It is more than ten years before Mania is able to find joy in life again. First she uses learning as a means of escape, burying herself in her books; thanks to her relentless hard work she finishes top of her class at the imperial high school. At fifteen, she suffers a nervous breakdown, collapsing under the pressure she puts on herself. Her father, now raising her and her siblings on his own, sends her to the country to recover. There she manages to put her books aside. She discovers music, attends parties, flirts and dances the whole night through. She begins to study at a Polish underground university that accepts women. Again she surpasses all her classmates.

In order to provide financial support to her older sister Bronia, who goes to Paris to study medicine, Mania takes a position as governess to the children of a Warsaw sugar beet magnate—and falls in love with the son of the family, Casimir, a twenty-three-year-old mathematics student. When Casimir's father learns of this liaison, he is horrified. Casimir offers only meek resistance, and after years of vacillating finally falls in line with his father's wishes. Mania is left alone, her heart deeply wounded and full of rage towards men: "If they don't want to marry any poor young girls then they can all go to hell!"

In 1891, Mania follows her sister to Paris. Bronia has since gotten married, as chance would have it to a man named Casimir. They are both doctors and brimming with communist ideals; they practice medicine out of their apartment and treat patients in need for free. Too much commotion for

Mania, who now calls herself Marie. She finds a garret to move into and holes up there, literally burying herself underneath all her clothes on cold winter nights. To save money she rarely buys coal, which at least spares her the effort of hauling it up the stairs one bucket at a time. She subsists on tea, fruit, dry bread, and chocolate—who cares! She's free. Granted, in Paris at the turn of the century, women are considered anything but equal. The word for female student, *étudiante*, can refer either to a woman studying at a university or to the lover of a male student. But still, if nothing else they are free to attend university, and this Marie does with passion. She spends her days in lecture halls, laboratories, and libraries, her nights with her books; she soaks up the arguments of the legendary Henri Poincaré. Again she overdoes it, collapsing in the library. Her sister Bronia takes her in and feeds her meat and potatoes, nursing the exhausted and undernourished Marie back to health. As soon as Marie has recovered her strength, she rushes back to her books. Her performance on the final exams places her at the top of her class yet again.

But what now? Women are allowed to go to university, but not many men are prepared to tolerate women scientists working alongside them. Marie can count herself lucky when she receives a grant to conduct research into the magnetic qualities of different types of steel. When she has trouble with the instruments in the laboratory, an acquaintance recommends an expert on magnetism for her to seek out for help: Pierre Curie, thirty-five years old, though he looks younger; a shy and thoughtful man. Marie gives up her vow never to fall in love again after the misery she experienced with Casimir. Pierre and Marie become a couple.

But the magnetism of steel isn't Marie's calling—there are more exciting things to research. In Würzburg, Wilhelm Conrad Röntgen has just accidentally discovered the mysterious x-rays after placing his hand near a vacuum tube and seeing it lit up from within. For New Year's in 1896 he sends photos around to his colleagues showing the bones of his wife's hand, wedding ring and all. No one has ever seen anything like it before. Roentgenograms—x-ray images—cause a scientific and societal sensation.

That same year Henri Becquerel in Paris discovers, also accidentally, a kind of radiation that he calls *rayons uraniques*, uranium rays, because they are emitted by uranium that he leaves in a desk drawer along with a photographic plate. This however is the only thing that Becquerel manages to find out about these rays. He can't explain what causes them. His suspicion—and his hope—is that they have something to do with phosphorescence, a phenomenon that he and his predecessors have been investigating for generations. His rays don't cause nearly as much of a stir as Röntgen's. Becquerel's blurry images pale in comparison to x-ray images, which are printed on magazine covers and showcased at fairs.

Marie Curie, however, is fascinated by Becquerel's discovery. It's apparent to her that the few experiments conducted by Becquerel—who isn't exactly known for his work ethic—have by no means closed the book on the phenomenon, and so she develops a new method for measuring the uranium rays which relies on Pierre's electrometers. And she dares to disagree with the powerful Becquerel. She calls the rays "*radioactif*" instead of "*uranique*"—she's convinced that uranium isn't the only element that produces them. To prove this, she sets out to find evidence of other radioactive elements. In the next few years, she'll find two: polonium and radium.

But that's not all. Marie Curie claims "that the incomprehensible uranium radiation is a property of the atom," as she writes in 1898—a provocative statement, given the level of scientific knowledge at the time. Scientists just can't get a grip on the atom. They've simply got too many of them to deal with. There are the atoms talked about by chemists, indivisible and immutable building blocks of matter that break free of their bonds in chemical reactions and bind together in new ways. And of late there are also the atoms talked about by physicists, shooting through the vacuum like billiard balls and colliding to produce pressure and heat in gases. Finally there are the atoms of the philosophers, which since the days of Democritus have been considered the forever abiding, fundamental elements of which the world is formed. But there is no theoretical link connecting these different kinds of atoms—only the fact that they're all called "atoms." And now Marie Curie is claiming that, inside these atoms, there's something going on.

How can that be possible? By what mechanism do atoms become radioactive—and how does that mechanism function? Apparently, as the experiments demonstrate, it is not affected by chemical processes, by light and temperature, by electric and magnetic fields. So what causes it? Marie Curie has an unheard-of suspicion: nothing. The process in which radiation is emitted begins on its own—spontaneously. In a treatise submitted to the International Congress of Physicists, held on the occasion of the Paris Exposition in 1900, she writes these portentous words: "The spontaneity of radiation is a mystery, a matter of profound wonder." Radioactive emission happens on its own, without cause. Curie is rocking the very foundation of physics, the principle of causality. What's more, she is even considering throwing out the law of the conservation of energy, the iron law of physics, which says that energy is never created and never destroyed. The man who sheds light on Curie's mystery is the physicist Ernest Rutherford of New Zealand. He develops the "transmutational theory" of radioactivity: when an atom becomes radioactive, it transforms from one chemical element into another. With this, another scientific dogma is toppled. Transmutation of this sort is considered impossible, a delusion of alchemists and charlatans. For a long time even Marie Curie is reluctant to accept Rutherford's theory. In the end they're both right, Curie about spontaneity, Rutherford about transmutation. It is the old physics that must give way.

The Curies set up their laboratory at the *École supérieure de physique et de chimie industrielles*, one of many prestigious universities located in Paris's Latin Quarter. The lab itself is housed in an old shed in the interior courtyard. The wind whistles through the cracks in the walls. The floor is never completely dry. Earlier in the school's history the students used to dissect cadavers here—until it got too uncomfortable for them. Now the autopsy slabs have had to make way for strange instruments: glass flasks; electrical wires and vacuum pumps; scales, prisms, and batteries; gas burners and crucibles. A "mix between a barn and a root cellar"—this is how the Baltic-German chemist Wilhelm Ostwald describes the Curies' shanty-laboratory after his "urgent request" to tour it is granted. "If I hadn't seen the chemical instruments on the work bench, I'd have thought the whole thing was a joke." Here, in the atmosphere of an alchemist's kitchen, the Curies make some of the most important discoveries of the dawning twentieth century. They don't yet suspect that in their drafty shed they are helping to lay the foundation for a new physical conception of the world.

In this shed of theirs the Curies intend to produce a substance which just a short time ago many of their fellow scientists considered hocus pocus: pure radium. But of course they're not magicians; the radium has to come from somewhere. What they need is raw material. After a protracted series of experiments, Marie hits upon a radioactive material called pitchblende. They need tons of it, but it's not to be had in Paris, and the Curies don't have any money. Pierre asks around all over Europe and finds out that at the Joachimsthal ore mine, deep in the Bohemian forest, where the metal for Thaler coins comes from, substantial quantities of pitchblende are extracted and left over as a waste product of the mining process. He's able to convince the director of the mine to let him have ten tons of it.

Transport of the material is financed by Baron Edmond James de Rothschild, whom his father's banking business has left enormously wealthy but who is himself more interested in art, science, and horses than in high finance.

When a mountain of pitchblende is delivered to the courtyard and dumped outside the shed in the spring of 1899, Marie lifts a handful of the "brown dust mixed with pine needles" to her face. They're in business.

The work is backbreaking. Marie hauls heavy buckets, transfers liquids from one vessel to another, wields iron rods to stir the material in seething crucibles. The pitchblende has to be washed with acid, alkaline salts, and thousands of liters of water. In order to extract the material they need, the Curies have developed a technique called fractionation. They bring the material to a boil again and again, letting it cool down and crystallize each time before boiling it again. Lighter elements crystallize more quickly than heavier ones, thus using this method, little by little, they can enrich radium. The process demands precise measurements and lots of patience. Despite the murderous drudgework, the Curies are happy. Walking home from the laboratory at night, they fantasize together about what pure radium might look like. Meanwhile their radium mixture is becoming ever purer; the glow seeping out of the glass flasks into the laboratory grows ever stronger. By the summer of 1902, they've reached their goal. They hold in their hands a few decigrams of radium. Marie determines the atomic weight of the element and assigns it the number eighty-eight on the periodic table.

That evening in June on Boulevard Kellermann, Marie Curie doesn't yet have any inkling of the misfortune that is soon to befall her family. She has had a new dress made especially for the occasion—of black cloth, so the stains from the laboratory don't show as much. Nor the swelling of her stomach—Marie is three months pregnant. A few weeks after the party she and Pierre go on a cycling tour. They love pedaling through the countryside; they travelled by bike on their honeymoon. But now Marie is five months pregnant. Her body can't handle the jostling of the bicycle on the bumpy gravel roads. She has a miscarriage. Trying to escape her grief, she throws herself ever deeper into her work, until she has another breakdown. She can't travel to Stockholm to accept the Nobel Prize that she and Pierre have been awarded, along with Henri Becquerel, for the discovery of radioactivity. The stage in Stockholm belongs solely to the vain Becquerel. He accepts his prize wearing a green brocade jacket with gold embroidery, medals on his chest and a saber on his hip.

That evening in June, when Marie steps out the salon door and into the summer night, arm in arm with Pierre, the guests raise their glasses to her. The couple walk a few steps away from the light, for a second it's just the two of them. Standing beneath the starry sky, Pierre reaches into his vest pocket and takes out a glass vial of radium bromide. The glow illuminates their faces, cheerful and flush with alcohol, and the skin on Pierre's fingers, burnt and cracked all over—an early sign of the radiation sickness that Marie will die of, and the first hint of the full force of the knowledge they are seeking.

A Different Era

At the beginning of the twentieth century, the world seemed to be in order. Physics seemed to have reached its terminus, as if all there was left for physicists to do was to measure a few more values after the decimal point. Then the first cracks started to show in this neat picture of the world. Small, unremarkable contradictions and inconsistencies that would soon be cleared up. Nothing to worry about.

But then things got turbulent. The cracks grew larger and deeper, until finally physicists could no longer ignore them. Their conception of the world teetered and then collapsed; the theories of Isaac Newton and James Clerk Maxwell, seemingly written in stone, proved untenable. It was a profound crisis for physics, but also a historic, once-in-a-lifetime opportunity for young scientists who were hungry for action. Albert Einstein brought about a new understanding of space and time with his theory of relativity. Werner Heisenberg, at the age of just twenty-three, cast doubt on the principle of causality, the iron law dictating that for every effect there is a cause. The young revolutionaries were able to show the older, established physicists that their method of scientific inquiry wasn't the only valid one. All of a sudden, physics was an adventure, an odyssey; even today, no one can say where the journey will end.

This brief span of time a century ago was probably the most exciting in the history of physics. It was a time in which a single savant alone in his study could unleash a scientific revolution; in which Albert Einstein, brooding in solitude, was able to develop his theory of relativity. But this era came to an end. Quantum mechanics was the first theory in physics that was too big for a single mind. The best physicists of the age had to work together to develop it. Physics became a collaborative endeavor.

All this happened in an age of massive political and social changes. After all the wars, revolutions, technological breakthroughs, and social upheavals, Europe was unrecognizable. Monarchies became democracies. The Spanish flu raged throughout the world from 1918 to 1920. People elected their political representatives instead of being subjects of emperors and kings. They listened to the radio, drove cars, flew airplanes, fought for women's rights, doubted the existence of God, went to the psychoanalyst. It's no coincidence that in this of all eras, physics too reinvented itself. Physicists are not purely creatures of intellect. They are human beings, mothers and fathers, Christians, Jews, and atheists. They too sought freedom in those years, fought in wars, fled regimes, lost friends and family members. They too doubted what was once taken for granted and searched for new certainties. In Germany, some resisted the Nazis. Others made their accommodations with them, still others became Nazis. For many, the stance they took towards the regime would leave its mark on their thinking.

As this era came to a close, physicists were horrified at the power that they themselves had unleashed. The atomic bomb, developed from their theories, killed hundreds of thousands of people and ushered humanity into the age of the Cold War and nuclear deterrence. Knowledge is power—never was this so clearly evident as it was back then. The bomb remains the most horrifying symbol of the revolution in physics that took place a century ago. And yet these same theories also opened up dimensions that humanity had never dreamed of. Most of the technological achievements that have followed since then are based on these theories: electronics, the laser, satellite navigation, the internet, and much more. The computer on which this book was written runs on transistors that would be unthinkable without quantum mechanics. We live in a world created by the intellectual pioneers of that era.

The Patent Stooge

Bern, Friday, March 17, 1905. The clock tower—or *Zytglogge*, as the locals call it—is about to strike eight. A young man in a plaid suit leaves his apartment on the third floor of Kramgasse 49, hurries down the steep, narrow staircase, and rushes over the cobblestones and through the arcades. Many of the passersby might be puzzled by the worn green slippers on his feet, embroidered with little flowers. The young man pays no attention to their stares. He has to get to the post office. It's urgent.

The contents of the envelope in his hand will change the world. The young man's name is Albert Einstein.

Einstein turned twenty-six three days ago, and had become a father ten months before that. Up in the two-room apartment he just left, he lives with his wife Mileva and their son Hans Albert. At the patent office Einstein holds the position of "examiner – class III." Hardly a dream job, but Einstein is happy just to have gotten it. No luck receiving his doctorate, failure to secure an assistant position at the university, the many complications Mileva suffered after their son's birth—and to top it all off, a drawn-out hiring process at the patent office. To pay the rent and support his wife and child, Einstein has to muddle through for a while as a private tutor. He tutors architects, engineers, and lazy long-time students in physics and mathematics. One of his students, from French-speaking Switzerland, writes in his notebook: "His short skull seems extraordinarily wide. His complexion is a dull light brown. A weedy black mustache sprouts above his large, sensuous mouth. His nose is slightly aquiline. His deep brown eyes have a soft, profound radiance. His voice is endearing, like the vibrating tones of a cello. Einstein speaks good French with a slight foreign accent." On the side, Einstein attends lectures in pathology at the University of Bern; the physics lectures are too boring for him. He tries to get a position as a lecturer, but the university turns down his application for a post-doctoral certificate. He's told his qualifications aren't sufficient to exempt someone like him, who doesn't even have his doctorate, from having to write a post-doctoral thesis. Einstein calls the university a "cow college."

“I won’t be teaching there.” Thus founders his first attempt to become a “great professor.” For years now, things simply haven’t been going well for Einstein. In 1896, when he enrolls at the polytechnic university in Zurich at the age of seventeen—not without difficulty: he’d failed the entrance exam on the first attempt and had to obtain a Swiss diploma as a workaround—his father’s firm goes bankrupt. Einstein is left stranded without financial support in the largest and richest city in Switzerland, the city of bankers and business owners. Italian relations help out with a hundred francs a month. He passes his physics courses by the skin of his teeth. In “Introduction to Practical Physics” he gets a reprimand and bad grades; he’s often flagged for absences without valid excuse because he’d rather stay home and study the classics of electromagnetics: James Clerk Maxwell and Heinrich Hertz, plus new works by Ludwig Boltzmann, Hermann von Helmholtz, and Ernst Mach. Einstein is especially taken with Mach, the Viennese physicist who is calling for a new kind of scientific thought and is rethinking physics from the ground up, free from unsubstantiated hypotheses and metaphysical speculation. Only what we can observe exists, says Mach. Physical concepts like speed, force, and energy must be based on sensory experience. Notions of an absolute space and absolute time, which since Newton have been considered dogma and since Kant have served as the extrasensory preconditions of sensory experience, are just some of the metaphysical clutter that Mach would like to clear out. There is no absolute time. There are only the ticking hands and ringing bells of the Zytglogge.

To the question of whether atoms exist, Mach likes to respond with a question of his own: “Have we seen ‘em?” He assumes that the answer has to be “no.” But that’s in the process of changing. Proof of the existence of atoms is demonstrated by the “uranium rays” that Henri Becquerel and the Curies have observed and investigated, and Einstein isn’t the kind to deny what he sees—though for now he sees it only in the theory that he’s currently developing.

Einstein resigns himself to being “a mediocre student” and passes the final exam, ranking fourth out of a class of five. The physics professor Heinrich Friedrich Weber takes on all the graduates as assistants—all, that is, except Einstein. Two attempts to gain a doctorate fail because the professors "refuse" Einstein's theses. Einstein himself later calls them "my two worthless first papers."

Einstein's girlfriend, Mileva Marić from Serbia, is one of the first women to study physics. She fails the final exam, becomes pregnant, fails a second time, and gives birth to a daughter, Lieserl. Mileva and Albert keep the child a secret from friends and family and give her up for adoption; her father never lays eyes on her. Einstein is in Bern by then. Mileva comes to join him there, the two of them marry—against the wishes of Einstein's mother. Not exactly what people at that time would have called "respectable circumstances."

Still, once Einstein finally gets the job at the patent office, their money troubles at least are behind them. The "tidy salary" of 3,500 francs a year is enough for the family to lead a comfortable bourgeois life. But now the stress really begins. The office is located above the post- and telegraph office. Every workday, Einstein has to be at his desk at eight o'clock and spends the next eight hours examining patents. Afterwards he gives at least one private lesson. He has little knowledge of mechanical engineering or technical drawings, meaning that in the beginning he himself has to take lessons from his boss.

No one would hold it against Einstein if, cut off as he is from the centers of research in physics, he were now to concentrate on pursuing a career as a Swiss bureaucrat. But it is here, left out in the cold by academia, that Einstein flourishes. He needs the distance from the physics establishment in order to form his own thoughts. But he's not the solitary genius, not the "lone wolf" that he likes to see himself as. Since their time together in Zurich, Mileva has been a clever, congenial discussion partner and collaborator; it's sometimes hard to say which ideas are hers and which are Einstein's.

In a tight circle of friends who call themselves the "Olympia Academy," Einstein has discussions and sounds off about physics and philosophy without having to bother with scholarly conventions. Einstein sends out invitations to these sessions—at which absences without valid excuse are not tolerated—and signs them "*Albert Ritter von Steissbein*"—Albert, Knight of the Coccyx. He can sit longer and talk louder than anyone else in the realm.

On top of this, Einstein regularly attends the evening meetings of the Bern Naturalist Society, which take place every two weeks in the club room at the Hotel Storchen. Retired professors, high school teachers, doctors, and pharmacists lead learned discussions. On December 5, 1903, Einstein gives a talk on his "theory of electromagnetic waves." Later it will be known as the "theory of relativity." "As of yet the work is still in the conceptual stage," says Einstein. The society moves on to the next topic, veterinary medicine.

When Einstein reads Max Planck's 1900 paper on black-body radiation, he is the first to recognize the full significance of Planck's discovery: "It was as if the floor beneath one's feet had caved in, and there was no firm ground anywhere in sight upon which one could start building." If light consists of "quanta," as Planck's paper suggests, how can we still trust in Maxwell's theory of light waves? Einstein resolves to take Planck at his word and risk venturing out onto unstable terrain.

For more than half a century, ever since James Clerk Maxwell published his research, light has been a wave phenomenon. As Planck was struggling with the problem of black-body radiation, he finally brought himself to accept, though it ran counter to his intuition as a physicist, that energy is absorbed and emitted in tiny lumps. Energy doesn't flow in an even stream; rather it is given off and absorbed in the smallest of discrete units—quanta. Still, Planck, like every other physicist, remained convinced that electromagnetic radiation consisted of constantly oscillating waves. What else could it be? These pesky lumps of energy must somehow be formed when radiation and matter interact. The revolutionary spirit that Planck lacked burns within Einstein. Light, and indeed all electromagnetic radiation, does not consist of waves, Einstein argues, but rather of particle-like quanta. This audacious claim is contained in the manuscript that is folded inside the envelope that Einstein takes to the post office before work on March 17, 1905. The envelope is addressed to the editor of *Annalen der*

Physik—“Annals of Physics”—the most important physics magazine in the world. The manuscript bears the title “On a Heuristic Viewpoint Concerning the Production and Transformation of Light.” Einstein knows that his idea is even more radical than Planck’s. To regard light as a stream of particles: this borders on heresy.

For the next twenty years basically no one other than Einstein will believe in light quanta. He knows from the outset that it’s going to be a tough fight. By using the word “heuristic,” he admits that he doesn’t consider his “viewpoint” a fully worked-out theory, just a working hypothesis, an aid for better understanding the mysterious behavior of light. Einstein thus makes it easier for his fellow scientists to at least begin to acknowledge and accept his approach. He is a signpost pointing the way to a new theory of light.

But even this is too much for his contemporaries, who think about light the way Maxwell taught them to think and are incapable of thinking otherwise. It takes them decades to follow Einstein into the new dimensions he has already begun to explore from his desk at the patent office in 1905.

And this is just the start of what the third-class patent examiner from Bern will force physicists to confront in that year of 1905. In May a letter from Einstein reaches his friend Conrad Habicht, who left Bern for the canton of Graubünden a few months earlier to teach math at a village school. The letter has clearly been written in haste; the handwriting is erratic, the page is covered in ink stains and many words are crossed out. Einstein didn’t even bother to date it. He starts off with a few insults, calls Habicht a “frozen whale” and “a canned chunk of dried-up soul” for whom he, Einstein, feels a mixture of “seventy percent scorn and thirty percent pity.” This is Einstein’s way of showing his affection. He misses Habicht, he misses the meetings of the Olympia Academy.

Next Einstein promises to send his friend four papers that he hopes will be published before the year is out. The first is the one about light quanta. The second is his doctoral thesis, in which he describes a new way to measure the size of atoms. In the third Einstein explains Brownian motion: the jittery dance of particles, like pollen, in fluid that scientists have been puzzling over for eight decades.

"The fourth paper is in the conceptual stage," writes Einstein, "and is a study of the electrodynamics of objects in motion utilizing a modification of the doctrine of space and time." Doing physics in his spare time, Einstein has followed through on the inspiration he received from Ernst Mach and reinvented space and time. Max Planck, who reviews submissions to *Annalen der Physik*, gives the theory the name that will practically become Einstein's middle name: "the theory of relativity."

But it's not this theory that Einstein calls "very revolutionary" in his letter to Habicht, but rather his theory of light quanta. It's the first time that he has used this word—revolutionary—to describe one of his ideas. Reviewing the paper, Planck, who still considers the quanta that he himself brought into the world to be a temporary expedient, useful for making calculations, doesn't at all agree with Einstein's particle theory of light. But he does agree to have it published. Planck has to wonder: Who is this hobby physicist in Bern from whom all these grand, audacious theories are coming all of a sudden?

Taken alone, the papers that Einstein lists in his letter to Habicht would easily have sufficed to earn him a place in scientific history for all eternity. Einstein produces them in his spare time in the span of a few months. Never before has there been such an explosive outpouring of creativity from a scientist. And then he writes a fifth paper on top of that, which he doesn't mention in the letter to Habicht. In it he derives the formula $E=mc^2$.

In January 1906, Einstein receives his doctorate from the University of Zurich, and in response the patent office in Bern promotes him to, as he puts it, "patent stooge – class II."

His yearly salary is increased to 3,800 francs. In early 1907 Einstein writes in a letter to a friend: "I'm doing well; I'm a venerable Swiss ink-shitter with a decent salary. On the side I keep riding my old mathematical-physics hobby horse and scraping away at the violin—both within the narrow limits that my two-year-old lad has granted me for such frivolous things."

A Son Finds His Father

Göttingen, a sunny afternoon in June 1922. Two men are walking up the Hainberg, deep in conversation. Even from afar the contrast between the two of them is visible. One takes energetic strides; he has to check himself to keep from speeding on ahead. The other moves as if he were thinking about every step.

The older man is nearing forty, his hair is beginning to gray. He wears a sober suit, holds his head pitched forward; his face is serious, with a tall forehead and striking, bulbous eyes. He takes deliberate strides and speaks German with a strong Danish accent. The other man could be the older one's son. He's barely half his age, twenty years old, and looks even younger, with short blond hair, bright blue eyes, and the face of a schoolboy. He's clearly accustomed to long walks.

Seeing the two of them walk together, one could get the impression they were father and son, or old friends. But they're meeting each other for the first time today.

Niels Bohr, the elder of the two, who just a few months later will be awarded the Nobel Prize, is in Göttingen to deliver a series of lectures meant to share his knowledge of the atom. That Bohr would make the trip to Germany just a few years after the First World War is no small matter. Denmark remained neutral in the war and is now involved in a dispute with Germany over the Schleswig region on the border between the two countries. Travel in Germany is difficult. Coal is scarce as a result of the reparations. What coal there is to be had is of poor quality. The trains run slowly, and sometimes stop for hours between stations when they run out of fuel.

There's no need for Bohr to go to such trouble. He no longer has to travel around to learn from other physicists. Now they come to him. On March 3, 1921, the *Universitets Institut for Teoretisk Fysik* opened in Copenhagen—known as the Bohr Institute for short. Before its opening, the growing Bohr family had already moved into a seven-room apartment on the ground floor of the new building, located across the street from the beautiful Fælledparken city park. The Bohr Institute is a place of calm in a Europe plagued by war and crisis.

These are lean years in Germany, but calm ones, relatively speaking. The people suffer under the reparations and the global economic crisis, but at least there isn't a war on, and inflation isn't yet rising so quickly that they have to carry their money around in wheelbarrows to buy bread and milk. For most people there's just enough food to survive. A few days after Heisenberg and Bohr meet, however, the German foreign minister, industrialist, and writer Walther Rathenau will be shot by radical right-wing students, a harbinger of the terror of National Socialism.

Werner Heisenberg, the physics student from Munich, likewise has enough not to starve but too little to eat his fill every day. Although his family are among the more well-off in Munich, they cannot afford to send their highly talented son to Göttingen. Heisenberg's doctoral advisor Arnold Sommerfeld pays for the train ticket out of his own pocket.

Coming at this time, Bohr's trip to Germany is also a political statement. Like Einstein, Bohr reviles Germany's militarism and its striving to be a great power. But he also objects to the attempts made by some of his colleagues to exclude German scientists from the international scientific community. Revenge won't bring peace.

And so, not long after the war ended, Bohr reestablished contact with his peers in Germany. In 1920, just two years after the armistice, he gave a lecture in Berlin, where he met Max Planck and Albert Einstein. "Not often in my life has a person brought me such joy by sheer virtue of his presence as you have," Einstein wrote in a letter thanking Bohr for his visit, and Bohr mirrored his sentiments: "Meeting you and speaking with you was one of the greatest experiences I have ever had," he wrote back, "and I cannot tell you how grateful I am for all the kindness you showed me during my visit to Berlin."

This, then, is the atmosphere in which Bohr now travels to Göttingen to put on his “Bohr Festival,” as his lecture series is dubbed in reference to the Händel Festival taking place in the city at the same time. More than a hundred physicists, old and young, theoreticians and experimentalists, have travelled to Göttingen from all over Germany to hear from Bohr’s own mouth how he envisions the atom, among them Otto Hahn, Lise Meitner, Hans Geiger, Gustav Hertz, Georg von Hevesy, and Otto Stern.

Bohr is able to explain the order of the elements on the periodic table in relation to the arrangement of electrons around the nucleus. He speaks of “electron shells” that surround the nucleus like the layers of an onion. Every shell has room for a certain number of electrons. Elements with the same chemical properties carry the same number of electrons in their atoms’ outermost shell, Bohr explains. Chemistry has become physics.

Bohr brings to light a numerical harmony never before seen in nature. According to his model, the eleven electrons of a sodium atom are found in overlapping shells of two, eight, and one electrons apiece. In a cesium atom, the fifty-five electrons are arranged into six shells of two, eight, eighteen, eighteen, eight, and one electrons apiece. Because in both elements the outer shell is only occupied by one electron, they have similar chemical properties. Bohr’s atomic theory predicts all of this—and more still. The as-yet-unknown element with the atomic number seventy-two will resemble the elements zirconium and titanium, which are found in the same column higher up on the periodic table, and not the “rare earth” metals located next to and below it.

Not everyone in the lecture hall in Göttingen is enthusiastic about Bohr’s bit of artistry. Where are the proofs, the formulas, where’s the hard math? But they’re all impressed by his ideas. Bohr is happy. “The entirety of my stay in Göttingen was a wonderful and instructive experience for me,” he writes after his return to Copenhagen, “and I cannot express how happy it made me feel to have received the kindness that was shown me everywhere I went.” He no longer feels alone, underappreciated and misunderstood—the feeling that has taken root within him in the last few years is somewhat assuaged. He has set out in search of quantum theory. He is on the verge of uncovering the world's innermost mechanisms. And hardly anyone notices. But in order to say what he has to say, Bohr needs his voice to resonate. He's not the self-sufficient genius that Einstein is. He had suffered from the isolation that the world war imposed on European physicists, even though he was able to spend the war on the safe side of the border.

On this summer's day, Bohr gives his third lecture in the morning. The summer sunlight shines through the large windows of the auditorium, where the seats in the front rows are reserved for Göttingen's scientific luminaries.

Heisenberg has to listen to Bohr's remarks from way in the back, where the Dane's quiet voice is scarcely audible. Naïve as he is, after Bohr has finished his lecture, the young man dares to raise his hand, stand up, and express doubt in Bohr's postulations. The room goes quiet. Heads turn. Something's got to be off here, Bohr hears the German saying.

It has to do with spectral lines, a favorite topic among physicists studying the atom at that time. If you shine white light through various elements in their gaseous state and then use a prism to separate the light out into a spectrum, characteristic black lines can be seen. By reading the pattern formed by these lines, physicists can reliably and definitively identify the elements through which the light has passed. But how do these lines form? The answer must lie in the structure of the atoms—in the mystery that physicists have been trying to solve.

Now Bohr is claiming that with his atomic model he can explain the division of spectral lines in electric fields, the so-called "quadratic Stark effect" discovered a few years earlier by the German physicist Johannes Stark. Bohr can explain it—or to be more precise, he can have it explained. Bohr likes to leave such details for his collaborators to sort out, in this case his Dutch assistant, Hendrik Kramers. Kramers has carefully calculated the interaction between atoms and light in electric fields as imagined by Bohr and published these findings in a research paper. Heisenberg is familiar with this paper, he had to study it in Sommerfeld's seminar—and found mistakes in it. Crunching numbers isn't

Bohr’s strong suit. He recognizes that Heisenberg has exposed an awkward point and responds with magnanimity. He invites Heisenberg to take a walk with him after the lecture.

As the two of them start making their way towards the Hainberg, a tall hill on the north side of town, Bohr doesn’t mess around with small talk for long. One shouldn’t take his atomic model, now nine years old, all too seriously, he says, but one should most certainly take seriously the question of why atoms are so stable, and why the atoms of a single element are so perfectly identical and remain identical as they go through myriad chemical and physical processes. It seems to him a miracle, Bohr philosophizes, incomprehensible from the viewpoint of conventional physics. A new physics is needed.

Heisenberg can’t believe his ears. Did Bohr just cast doubt on his own atomic model? The model which physicists all over the world use in their calculations, which is taught at universities and exhibited in museums? Indeed he did. And that’s not all. Bohr not only casts doubt on his own model, but also on the very possibility of a visualizable atomic model. The idea of an atom as a miniature solar system might be pretty, says Bohr, but such images are conceptual aids at best. At worst they give us the deceptive feeling that we understand something when in fact we don’t understand it. Then there’s the question of how atoms manage to remain stable as they endure all these stresses and chemical reactions, and why an atom of one element perfectly resembles another atom of the same element. A complete mystery from the perspective of classical physics. No mini-solar system could remain stable throughout all the stresses and chemical reactions that atoms go through. No system known to physics could.

Heisenberg, the high achiever, is used to being the first to grasp everything. That’s what it’s like in Sommerfeld’s seminar in Munich. Now though he listens intently, only interrupting once in a while to ask a question. He’d like to know, Heisenberg says, what the significance of quantum theory is. What does it mean? Beyond all these calculations, all this predicting of spectral lines and quantum numbers: what does quantum theory say about the nature of physical reality? What do these strange formulas mean?

“What do they mean?” Bohr replies. “There are several ways in which language can mean something.” He’s ready to launch into a philosophical excursus. “If a single speck of dust consists of billions and billions of atoms,” says Bohr, “then how can one speak meaningfully of something so small?” Where atoms are concerned, he continues, our language is useful to us only in a poetic sense. Just as a poet doesn’t worry so much about facts, and instead concentrates on images and conceptual associations, so the purpose of the models quantum physics employs is only to capture as much as possible of what we can know and say about atoms with our inadequate modes of thought and expression. What reason is there to hope that our way of thinking, developed as it was for the world of people, trees, and buildings, will also be suitable to the world of atoms? “The images that we form of atoms are drawn, or, if you like, invented, from experience; they aren’t derived from any kind of theoretical calculations,” says Bohr.

“I hope that these images describe the structure of atoms well enough, but indeed only as well as is possible in the visual language of classical physics. We have to understand that language in this instance can only be used in a way similar to the way it is used in poetry, where the point is not to provide a precise depiction of some factual scenario but rather to evoke images and produce associations in the mind of the reader.”

An insight that Heisenberg finds hard to take seriously. A few decades prior, the Viennese physicist Ludwig Boltzmann had vehemently argued that atoms weren’t just the made-up abstractions that they had been considered ever since they were first spoken of by the atomists of antiquity; that indeed they were not metaphors, but concrete things, smaller, true, than the chairs we sat on, but just as real. Boltzmann took his own life in 1906 when he saw that he couldn’t convince his colleagues of the existence of atoms. After his death, however, more and more physicists had come to accept atomic theory.

And now Bohr is claiming that these most minute building blocks of the material world are nothing more than a manner of speaking, a pretty but ultimately unsatisfying figure of speech? Essentially, yes, but with a twist that makes his argument different from the old fight over atoms. Bohr doesn't deny that atoms exist—far from it. What he's saying, however, is that physicists cannot hope to describe them as they are. Maybe for atoms there is no "as they are." Our conventional intuitions of the physical world, of matter, of where things are and how they move, break down at the smallest level. But then of course these intuitions are all we have, it is with them that we've learned to comprehend the world. We can't simply throw them overboard.

What Bohr is explaining in his quiet way is unsettling to Heisenberg. Up until now he has discussed formulas with his peers and with Professor Sommerfeld and thought of them as tools, helpful for making calculations and forming experimentally verifiable hypotheses. Now he's learning to inquire after the nature of the world they describe.

So then what does quantum theory mean, Heisenberg asks Bohr again. What kind of world is hidden behind all the elaborate calculations, behind the spectral lines and quantum numbers? What is the physics behind the formulas? Bohr has no definitive answer to give him, and certainly not a simple one. No, the classical models of the atom can't be accurate. But they aren't completely wrong either. They're the best conceptual aids we have. The trick is to find models that capture as much as possible of what there is to say about atoms. One model alone won't be enough; it will take several models to complement, but also contradict one another. Bohr calls this idea the "complementarity principle." An electron can be thought of as both a particle and a wave.

Both ideas are true, but not entirely. In some respects, the electron behaves like a particle, in others like a wave. Our intuition might struggle with the dual nature of the electron. But that's just how the world is. The two physicists stop for something to eat at the Rohns coffeehouse before climbing to the top of the Hainberg, where they'll be able to look out over the entire city. Is Bohr saying that the nature of things is beyond the human capacity for knowledge, Heisenberg asks. Is there no hope of us ever really understanding the atom? “Certainly there is,” Bohr replies. “But in doing so we’ll first have to learn what the word ‘understand’ means.”

Heisenberg is starting to realize that Bohr is wired quite differently from nearly all the other physicists gathered here in Göttingen, this stronghold of mathematical physics. There’s no shortage of brilliant mathematicians and clever experimentalists. Bohr’s strength lies elsewhere: in his intuition. He is feeling his way around, trying to discover the structure of the world. The Dane doesn’t crunch numbers, he philosophizes. He struggles to find the right words for things, like a poet. Later, Heisenberg calls him the “only person who understands anything about physics in the philosophical sense.”

For Heisenberg it’s like discovering physics all over again. As he will later recall, “my actual development as a scientist first began” with this walk. What’s more, a friendship forms between Bohr and Heisenberg that will result in breakthroughs representing some of the most important steps toward the formulation of a new theory of quanta. The friendship will last for nineteen years, then fall apart.

By the time the two men leave the coffeehouse and set out for the summit of the Hainberg, Bohr has long since recognized Heisenberg’s extraordinary talent. He is taken with the younger man’s insatiable thirst for knowledge. He asks Heisenberg what his plans are, invites him to join him in Copenhagen as a visiting researcher, even holds out the prospect of a paid fellowship. Heisenberg never would have dreamed of such an honor. He gets to go to Copenhagen, to join the great Bohr, his scientific idol! The destination holds a very special significance for Heisenberg, because his biggest rival, Wolfgang Pauli, is also headed to Copenhagen . . .