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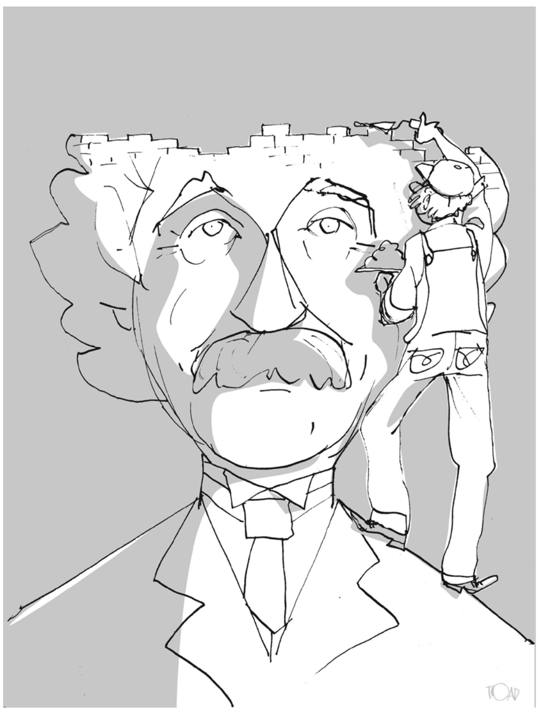
I

The Einstein Phenomenon



Preview

At the beginning of the twentieth century, Albert Einstein was twenty-one years old, recently graduated from the Polytechnic, the Federal Institute of Technology (now ETH) in Zurich, and desperately searching for a position that would allow him to provide for the family he intended to create with his fellow student Mileva Marić. About twenty years later, in 1921, after profoundly changing the understanding of the physical world as it was then seen by the scientific community, he won the Nobel Prize in Physics. At the end of the century, he was chosen by *TIME* magazine as "Person of the Century," followed by Mahatma Gandhi and Franklin Roosevelt.

The first phase of the Einsteinian revolution began in 1905, the so-called miraculous year, when Einstein was still employed by the patent office in Bern, Switzerland. Thus, the critical papers he produced during that year were conceived and written outside the realm of the centers of learning where the questions he addressed were extensively debated and researched by the prominent players in the contemporary arena of physics. In these papers, Einstein profoundly modified the classical concepts of space, time, matter, and radiation. This raises questions: How could Einstein, as an outsider, cause such a revolution in physics? And, following on from the first question, what is a scientific revolution? Numerous Einstein biographies have attempted to answer the former. Thomas Kuhn and many historians and philosophers of sciences have attempted to answer the latter. This book is neither a biography nor another philosophical analysis of a scientific revolution. It is not even a scientific biography. The biographical discussion in this first section treats both personal and scientific aspects and is intended, for the case of Einstein's upheaval of physics, to lay the groundwork for answering both of these questions in subsequent sections.

This requires going beyond the scope of his personal scientific biography, by placing this upheaval in the broader context of the history of science and the evolution of knowledge. We also critically look at Kuhn's description of the nature of scientific revolutions, with his notion of change of paradigm[1] having become a popular way of interpreting such upheavals. We instead present the Einsteinian revolution as a transformation of the knowledge system of classical physics that spanned several decades. Systems of knowledge are understood here as comprehensive unities of theories, concepts, and practices, including the instrumentation and the knowledge required to utilize them. They are socially transmitted via education, shared practices, textbooks, and the material culture included in such instrumentation.

That we are dealing with a more complex, protracted process than is suggested by the notion of a "paradigm shift" is suggested by the dual nature of Einstein's "relativity revolution," exemplified by the revolution of space and time that began in 1905 with his formulation of the special theory of relativity, which shortly after was seen to be incomplete. Attempts to fit Newton's well-established law of gravity into the framework of this theory did not succeed, at least not without abandoning basic principles of mechanics. Although this problem did not lead to urgent empirical questions, it brought Einstein to question the special theory's concepts of space and time and inspired him to continue the transformation of knowledge with his 1915 general theory of relativity.

While Einstein was working, beginning in 1907, on the implications of relativity for the understanding of gravity, his papers on the constitution of matter and radiation advanced his career and eventually led to his call to Berlin in 1913. There was hope that he would make decisive advances toward a theory of matter that would connect both physics and chemistry, but Einstein concentrated primarily on the problem of finding a new theory of gravity. He pursued this quest despite the resistance of his established colleagues and, initially, with few prospects for success. Eventually, however, in 1919, his prediction of the bending of light due to gravitation was spectacularly confirmed during a solar eclipse expedition. Thus, the myth of Einstein as a solitary genius was born.

Einstein was committed to the search for a comprehensive scientific worldview, a quest that first emerged in the context of his early readings of popular scientific literature and philosophical textbooks. It evolved during his further scientific odyssey and later formed the framework of his *Autobiographical Notes*. Einstein's scientific achievements were developed in loose conjunction with his views on epistemology and the philosophy of science. These views also guided him on his road to general relativity and in his later quest for a unified field theory. His commitment to these views, however, made him a dissident of the emerging and widely accepted quantum worldview.

The extent to which Einstein's achievements constituted revolutionary breakthroughs, or rather represented a continuation of the work of his predecessors, was an issue that he was aware of himself. When considering Einstein's contribution to the evolution of physics as a transformation of the knowledge systems of classical physics, we must enter a dialogue with his own epistemological reflections. Indeed, understanding his breakthroughs from the perspective of a historical epistemology, as is proposed here, owes much to his own thinking about conceptual transformations in science. We return to this dialogue throughout the book.

a. Childhood and Youth

In the following discussion, we concentrate on the intellectual landscape of physics that the breakthroughs of 1905 and 1915 emerged from, as well as the dynamics of Einstein's interaction with this landscape. These dynamics do, of course, involve his early personal development, which affected the way that he later appropriated the shared knowledge of contemporary physics. For this reason, we briefly review his youth and family background.

Einstein's introduction to science was already favored by his birth in Ulm, Germany, in 1879, into an assimilated Jewish family whose livelihood was in the field of electrical technology. In 1880, the Einstein family moved from Ulm to Munich, where Einstein's father, Hermann, together with his brother, the engineer Jakob Einstein, founded a firm producing generators, and arc and incandescent lamps, as well as telephone systems.

When Albert was about ten years old and enrolled in the Luitpold-Gynasium in Munich, his parents invited a young, orthodox Jewish medical student from Lithuania, Max Talmud, to their home to teach young Albert about the principles of Judaism. Talmud surpassed their expectations, and to their dismay, young Albert demanded that they observe the rules of the Sabbath and respect kosher in the home. However, this period was short-lived and later referred to by Einstein as a "religious paradise of youth."[2] Still, Talmud had a lasting impact on Einstein's life. He gave young Albert a geometry book and, in later recollections, Einstein would refer to the encounter with this book as the impetus that led to him to become a scientist. The possibility to prove surprising statements with certainty, such as the claim that the three altitudes in a triangle intersect at one point, seemed miraculous to him. The sense of wonder generated by the possibility of reaching unexpected truths through pure thought alone remained with him throughout his life.

Talmud also recommended that Albert read the popular books on natural science by Aaron Bernstein, a Jewish author, reformer, and scientist from Danzig, Poland, who earned a reputation as a popularizer of science. He had been a supporter of the failed 1848 democratic uprising and since then had hoped to promote the ideals of progress and democracy through the popularization of science. His books offered readers a fascinating and encyclopedic overview of contemporary natural science. Reading Bernstein's books provided Einstein with a remarkably broad knowledge that also familiarized him with the international spirit of science, including some of its philosophical and political implications. Through these books, the young Albert learned how concepts such as "atoms" or "ether' could help to uncover mysterious and surprising relations between different areas of knowledge that were otherwise separated by specialization into various scientific disciplines. Furthermore, several of the conceptual tools used by Bernstein and other authors to establish connections between different areas of physics and chemistry made an impression on Einstein and arguably influenced his understanding of the readings and lectures he would later encounter as a student.

Behind the numerous ideas and speculations that Einstein developed as a student and discussed with his friends was a fascination with the notion that one can discover unity in natural phenomena by using mental models and thought experiments. This fascination also had its roots in his earlier reading of popular scientific books. At the age of sixty-seven, Einstein still remembered this formative educational experience:

> When I was a fairly precocious young man I became thoroughly impressed with the futility of the hopes and strivings that chase most men restlessly through life. . . . As the first way out there was religion, which is implanted into every child by way of the traditional education-machine. Thus, I came—though the child of entirely irreligious (Jewish) parents—to a deep religiousness, which, however, reached an abrupt end at the age of twelve. Through the reading of popular scientific books I soon reached the conviction that much in the stories of the Bible could not be true. The consequence was a positively fanatic [orgy of] freethinking coupled with the impression that youth is intentionally being deceived by the state through lies; it was a crushing impression. Mistrust of every kind of authority grew out of this experience, a skeptical attitude toward the convictions that were alive in any specific social environment—an attitude that has never again left me, even though, later on, it has been tempered by a better insight into the causal connections.[3]

A "fanatic [orgy of] free thinking" and a "mistrust of every kind of authority" remained with him throughout his scientific journey, in his political activities and philosophical thinking. Einstein's introduction to the natural sciences of his time through the reading of Bernstein's books inspired his hope of achieving a conceptual unity of their numerous specialized branches. As a result of having such reading material as a starting point, Einstein developed a different view of physics than many of his established physicist colleagues, who sometimes lacked the vision of the overarching connections between the special topics they were investigating.

These readings shaped young Einstein; science became his orientation in life and a replacement for religion. For him, science held the promise that with its aid one could rise above the void of earthly hopes and ambitions. The popular books by Bernstein, in particular, portrayed science as a human enterprise, not only to be revered but also one in which one could participate. In contrast to contemporary compartmentalized academia, Bernstein drew no sharp boundaries between the sciences or between science and life.

Advancements in electrotechnology during this time led to a rapid increase in electric lighting in urban areas. The Einstein family's involvement in this increasing electrification provided the young Albert with rich intellectual stimuli and challenges. In 1885, the enterprise expanded, employing up to two hundred people, until competition with large firms in the increasingly specialized electrical industry prompted the Einsteins to move their business activities to Pavia in Northern Italy in 1894, following the loss of a major municipal contract for the electric lighting of central Munich. Albert had to stay in Munich to continue his studies at the Luitpold-Gymnasium, one of the most progressive high schools in Germany in mathematics and science instruction at the time. Contrary to popular misconceptions, he achieved excellent grades not only in mathematics and the sciences but also in the humanities. But the program was too authoritarian for his taste and, at the end of the year, Albert suspended his formal schooling to join the family in Italy. With his father's assistance, he succeeded in renouncing his German citizenship, with the consequence that he was no longer subject to compulsory military service.

After only two years, the firm established in Pavia had to be sold in 1896, and a new firm was founded in Milan, which was also liquidated after two years. Following this, the Einsteins embarked on a new direction, installing power plants for electric lighting in small towns close to rivers, which were used as a power source. This venture turned out to be moderately successful and created the expectation that young Albert might join the activities of his father. Despite his father's attempt to persuade him to join the family business, he was deterred by his extensive exposure to the uncertainties of the business world, with its harsh competition and threat of financial uncertainty. Several documents from this time demonstrate that the young adolescent had other plans for his life. In a school essay on his future plans, dated 1896 and written in French, he stressed that he preferred the independence of a scientific profession, mentioning his inclination for abstract and mathematical thinking.[4] This, however, was not the only reason for paving his own path. At an early age, he already felt estranged from the bourgeois concerns of his family. In letters to friends, he mocked their philistine attitude and extolled the benefits of solitary living, akin to that of the philosopher Arthur Schopenhauer.

The young Einstein was aware of the central topics of physics even before his formal academic studies. Inspired by the family business, he developed his own scientific ideas on electricity and magnetism. They centered around the physical meaning of the mysterious ether, considered an elastic substance that fills all of space and acts as a carrier of electromagnetic phenomena and light. At the age of sixteen, he wrote an essay, "On the Investigation of the State of the Ether in a Magnetic Field." This essay may be considered his first scientific paper, which he sent to his beloved uncle Caesar Koch. In an accompanying letter, he admitted that the text was "rather naïve and imperfect, as might be expected from such a young fellow like myself."[5] Still, the content of the letter demonstrates a distinct imagination and curiosity. In this first scientific work, he investigated the alteration of the ether caused by the magnetic field around an electric current. Such an alteration was thought to affect the velocity of propagating electromagnetic waves within it. These were the first indications of the problems at the borderline between mechanics and electrodynamics that would still intrigue him in 1905, forming the point of departure for the special theory of relativity.

At the same time, another problem occupied his mind. In one of his most well-known thought experiments, he posed the question: What does a light beam look like to somebody moving alongside it at the speed of light? This raises the question of the velocity of a light beam measured by an observer moving at a certain velocity in relation to it. Einstein would answer this question ten years later in the context of the special theory of relativity.

In Italy, Einstein devoted himself to studying for the entrance examination for the Polytechnic, the Federal Institute of Technology in Zurich, later the Eidgenössische Technische Hochschule (ETH). He was permitted to take this test even though, at sixteen, he was two years younger than the required admission age. His first attempt resulted in failure. He passed mathematics and physics but was unsuccessful in modern languages, zoology, and botany. To improve his chances of admission, Einstein followed the suggestion of the director of the Polytechnic and enrolled in a Swiss secondary school in Aarau, a town outside of Zurich. After completing his studies there with impressive marks, he passed the entrance exams in the summer of 1886, becoming one of the youngest students ever admitted to the Polytechnic at age sixteen and a half.

b. The Student Years

As a student of physics at the Polytechnic from 1896 to 1900, Einstein first had to hone his knowledge of the physics of the time before he could shape his already abundant ideas into substantial scientific contributions. This period of learning did not proceed without conflicts and disappointments; he hated rote learning and the mindless memorization of facts. He learned a great deal through independent study and reading. The main mission of the Polytechnic was to train engineers. In Einstein's year, there were only five students on the science track. Among them was Marcel Grossmann, a student of mathematics who became Einstein's close friend.[6] For the lecture contents, Einstein often relied on Grossmann's notes. Also among the science students was Mileva Marić, who came from Serbia and began her studies of mathematics at the Polytechnic in 1896 as the only woman in her class. The friendship between Albert and Mileva soon evolved into a love story, with the prospect of becoming a work-and-life partnership, although Einstein's parents disapproved. Their marriage in 1903 ended in a bitter divorce in 1919.

As a student, Einstein continued to explore his wide-ranging interests. This is now well documented by the love letters he and Mileva exchanged.[7] These letters are an invaluable historical resource, providing insight into Einstein's intellectual development during this time. They reveal a whole range of previously unknown scientific interests, among them his participation in experiments concerning X-rays, which had recently been discovered, as well as his passion for research on metals. Additionally, Einstein's early correspondence indicates that he was an eager reader of contemporary textbook literature and contributions to professional journals. From these letters, we also learn about his self-assuredness in criticizing the work of renowned scientists. This is one manifestation of the mistrust of authority that he acquired in his earlier years from reading the books of Bernstein.

Einstein's student years were shaped by a certain ambiguity in his relation to mathematics. In his autobiographical recollections, the accomplished scientist, who meanwhile had since come to recognize the powers of mathematics, reflects on his student years, wondering what he may have missed and why he chose physics rather than mathematics as the primary focus of his life. Mathematics appeared to him to consist of a diversity of domains of detailed specialization, and any one of them could consume a lifetime. Only after years of research did he realize the fundamental role of mathematics in gaining physical insights, citing his struggle to develop a general theory of relativity and his search for the field equation in particular.[8] In 1912, he wrote to Arnold Sommerfeld that he had gained great respect for mathematics, "whose more subtle parts, I considered until now, in my ignorance, as pure luxury!"[9]

In contrast, in physics he learned early on to sense which pieces of the extensive and seemingly disparate collection of experimental data to disregard and which would lead to fundamental insights. Einstein's assistant in the 1940s, Ernst Straus, recalls that Einstein often told him about his student-years dilemma between mathematics and physics. As a student, he thought he would never be able to decipher which of the many beautiful questions in mathematics were pertinent and which were peripheral. In physics he could see which were the most central questions.[10] The problems he chose to work on at the beginning of his career confirm the older Einstein's recollection of young Einstein's dilemmas and choices.

A short time after completing his studies, Einstein submitted a doctoral dissertation to Alfred Kleiner, professor of physics at the University of Zurich. He submitted it to the university because, at that time, the Polytechnic was not yet authorized to grant doctoral degrees. The thesis no longer exists, but we know that it dealt with molecular forces in gases. Einstein wrote to Mileva that Kleiner would not dare reject the thesis. Kleiner did not reject it, but after reading it, he suggested that Einstein should withdraw it voluntarily. Apparently, Kleiner did not like Einstein's criticism of the work of leading physicists, including Ludwig Boltzmann. Einstein reluctantly withdrew it.

Following his failure to secure a position at the Polytechnic in 1900, Einstein briefly worked as a teacher in a secondary school outside of Zurich. In 1902, he left this position and moved to Bern, applying for a position at the Swiss patent office there. For the first time in the history of the patent office, the announcement of a vacant position specified that applicants must have a university education with a background in physics. Einstein began his work at the patent office in June 1902 as a "Technical Expert Class III." It was his friend Grossmann who helped him find and secure this position when he was desperately in need of a job. This position enabled the intensive and difficult scientific work that preceded his breakthrough in 1905.

c. Einstein in Bern—The Miraculous Year and Beyond

The correspondence with Mileva also provides a glimpse into a youthful Bohemian world where Einstein's rebellious spirit was formed, and where his resistance to the authority of the physics community found support and encouragement. This attitude was formed during his student years and continued to develop during his years in Bern. He was surrounded by friends with whom he could discuss fundamental questions of science without having to respect disciplinary boundaries or the authority of established paradigms. In this community of rebels, which had much in common with the community of Bohemian artists of the same period, scientific questions became questions about life itself. Einstein met his close friend, Maurice Solovine, a young student of philosophy, when Solovine responded to Einstein's advertisement in the *Newspaper of the City of Bern*, offering private lessons in mathematics and physics to students and pupils. However, instead of conducting lessons on physics, they spent their time together exchanging ideas about the open problems of physics. Their first encounter evolved into a lifelong friendship. They decided to read books by prominent authors together and discuss them. They were soon joined by the mathematician Conrad Habicht in this endeavor. The meetings usually took place in Einstein's apartment and lasted until late into the evening and sometimes into the early hours of the morning. They called these meetings "Akademie Olympia" (Olympia Academy). Solovine reported that Marić attended the meetings, listened attentively, but never took part in the discussions. The "Akademie" did not last long, as Habicht left Bern in 1904 and Solovine in 1905. Einstein often cited this group's gatherings as an episode that contributed to his scientific work in years to come. Throughout his life, he would prefer this academy to the official ones.

The favorite readings at the social meetings of the Olympia Academy were works that critically reviewed conceptual and methodological questions of contemporary science. These included books by philosopher-scientists Ernst Mach and Henri Poincaré, as well as philosophers, such as Baruch de Spinoza and David Hume, but also writers like Miguel de Cervantes and Charles Dickens. As such, this academy and its circles were by no means an immature college clique but a serious collective of thinkers.

In addition to Solovine, Habicht, and Mileva, another friend—Michele Besso—was also one of Einstein's most important influences. They met as students in Zurich, where Besso studied mechanical engineering. They later became colleagues at the patent office and continued their intensive discussions on the foundations of physics. A supportive and challenging discussion partner, Besso came to Bern just at the right time for Einstein. They talked on their way to and from work, and whenever they found the time. In Einstein's 1905 paper on relativity, Besso was the only person to be acknowledged because, as Einstein later recalled, the decisive idea came to him during a conversation with Besso. We return to this in detail in section IVf.

In the years 1902 to 1904, Einstein published three papers on statistical mechanics. He derived the laws of thermodynamics from the statistical behavior of the components of matter (atoms, molecules). This was a continuation of the pioneering work by Boltzmann and a parallel to the work of Josiah Willard Gibbs. We discuss these papers and the new elements they introduce in detail in section IVa. Here, we only wish to emphasize that Einstein's work was based on the conviction that atoms and molecules exist and were part of his self-induced mission to demonstrate their reality, which was not yet accepted by many prominent physicists and even chemists at the time. Einstein's work on statistical mechanics was a milestone on his road to revising the foundations of classical physics. In 1905, it provided the theoretical tools for understanding black-body radiation, for demonstrating the existence of atoms, and for transiting to modern statistical and quantum physics. His other historic work from the same year was what later came to be called the special theory of relativity, which revised the Maxwell-Lorentz theory of the electrodynamics of moving bodies. It introduced a new understanding of the concepts of space and time and established the equivalence between mass and energy expressed in the well-known scientific equation, known even beyond the world of physics, $E = mc^2$. This combination of five characters has become a cultural symbol associated with Einstein's name. It appears on numerous commercial products, and it seems that virtually every country in the world has issued a postage stamp featuring this equation.

One refers to the year 1905 as Einstein's miraculous year because of his outstanding revolutionary achievements. But, the circumstances of these achievements are also miraculous. Einstein was only twenty-six years old and was not working at an academic institution but at the patent office as a clerk. Consequently, everything he did was essentially done in his free time and on his own. In addition to his scientific research, he devoted time to another activity, apparently to increase his income. He published reports in the *Annalen der Physik* on articles that appeared in scientific journals outside of Germany, particularly in France and Italy. In 1905, he published twenty-one such reports.

Einstein worked at the patent office from 1902 until 1909. These seven years were extremely productive and creative. In 1905, in addition to the famous papers, he also completed his doctoral dissertation, which served as the precursor to his paper on Brownian motion. Because of his dissertation, he was promoted to "Technical Expert Class II" with an increase in salary of 4500 francs a year. In 1908, the University of Bern appointed him *Privatdozent* of theoretical physics. This position is roughly the equivalent of an American adjunct professor. Finally, in 1909, he secured his first full-time faculty appointment as *Extraordinariat* (essentially the position of an associate professor) of theoretical physics at the University of Zurich. In the same year, he was awarded an honorary degree by the University of Geneva. In September of that year, he was invited to a conference of German-speaking scientists in Salzburg, where he first met Max Planck. Wolfgang Pauli referred to Einstein's talk at that conference as one of the cornerstones of modern physics. Two years later, in 1911, he was appointed full professor (*Ordinarius*) at Charles University in Prague. In the same year, he was invited to participate in the first Solvay conference. These conferences brought together the leaders of the European physics community to discuss the problems raised by the emerging quantum physics. The first Solvay conference hosted twenty renowned participants, including Planck, Marie Curie, Poincaré, and Lord Rutherford. Einstein, at the age of thirty-two, was the youngest participant. His involvement at this conference marked his transition from patent office clerk in Bern to scholar at the forefront of physics.

One may wonder what would have happened if Einstein had worked at a university as an assistant to an experienced and known professor. Maybe he would have had to get involved in an ongoing research program and adapt to the dominant academic environment. We can safely conclude that the fate that brought him to the patent office at the beginning of his scientific career benefitted him and the world of science.

d. A Tale of Three Cities—The General Theory of Relativity

The special theory of relativity increased a tension that already existed between electrodynamics and Newton's theory of gravity. Electrodynamics is concerned with effects that propagate in space with a very high but finite velocity. Newton's law of gravity, however, does not seem to be directly reconcilable with the demand that gravitational effects should also propagate in space with a definite speed, demand that had become a fundamental requirement on any physical interaction as a consequence of special relativity.

Like a few of the other contemporary physicists, Einstein concentrated on the solution to this "remaining problem" of conflict between classical mechanics and special relativity. One of the basic principles of mechanics challenged by Einstein's attempt to incorporate gravitation into his special theory of relativity was Galileo's principle. This principle states that all bodies fall at the same rate regardless of their mass or their constitution. For Einstein, it was inconceivable that such a fundamental principle be abandoned, as initially seemed to be required by an adaptation of Newton's law to special relativity. He, therefore, decided to maintain Galileo's principle and sought a generalization of his original relativity theory that would allow for this. Einstein began his work on the problem of gravitation in 1907. He soon arrived at the "equivalence principle," which states that the effects of a homogenous gravitational field are equivalent to the inertial effects in a linearly accelerated frame of reference. The formulation of this principle allowed him to reach several surprising insights very quickly, such as his prediction that the direction of light propagation and its frequency are affected by the action of gravity. This was a formative step on Einstein's journey to the general theory of relativity. However, it took eight more years until it was complete in November 1915.

Section V of this book is a detailed analysis of Einstein's convoluted road to reach this goal. Here we present a short account of this process to set the stage for a discussion, in the following section, of Einstein's pathway to general relativity in detail. This short account mirrors the overview in our book *The Road to Relativity*, which describes Einstein's odyssey as a tale of three cities—Prague, Zurich, and Berlin—each representing a phase of this process, using the breakthrough of 1907, when he was still in Bern, as a starting point.

A short time after his appointment as an adjunct professor at the University of Zurich, Einstein was offered an even more prestigious position as a full professor at the German-speaking part of Charles University in Prague. Despite appeals from University of Zurich students to university leaders to make every effort to keep Einstein in Zurich, he moved to Prague in April 1911. There he wrote eleven papers, six devoted to relativity. In the first paper, he discussed the bending of light and the gravitational redshift, which he had already discovered in 1907 but now discussed as observable effects. In the Prague papers, he focused on developing a consistent theory of the gravitational field based on the equivalence principle. Just like in Newton's theory, and unlike in the final theory of general relativity, the gravitational potential was still represented by a single scalar function. Nevertheless, some basic features of the final theory were already formed then. Among them was the understanding that the source of the gravitational potential is not only the mass of physical bodies but also the equivalent mass of the energy of the gravitational field itself.

In 1911, Grossmann was appointed dean of the mathematics-physics department of the Polytechnic. One of his first initiatives as dean was to ask Einstein if he would consider returning to Zurich to join the Polytechnic. Einstein agreed, declining an earlier offer from Utrecht and an opportunity to go to Leiden, where he would have been close to the Dutch physicist Hendrik Antoon Lorentz. Whatever reasons he had for choosing Zurich, it was the right decision at the time. By the time he left Prague and arrived in Zurich, he realized that the gravitational potential has to be represented by a mathematical object, a tensor, composed of ten functions of space and time. He also realized that this implied a non-Euclidean structure of space and time, or rather of the four-dimensional entity, spacetime. All this required sophisticated mathematical methods, which Einstein was unfamiliar with at the time.

Shortly after returning to Zurich in August 1912, Einstein began an intensive and fruitful collaboration with Grossmann. This collaboration is documented in Einstein's famous "Zurich Notebook," which allows us to "look over his shoulder" as he struggles with the challenge of reconciling physical insights and mathematical methods.[11] As we see in more detail later, this research notebook from 1912/1913 gives us insights not only into a single scientist's intellectual world but also into the mechanism behind the transformation of a system of knowledge. The notebook constitutes a most important document in the history of science and is of great importance for our understanding of the origins of the general theory of relativity.

The Zurich Notebook essentially contains the blueprint for the final, generally covariant theory but, as later described in section V, Einstein abandoned this theory because he had not yet reached a full physical understanding of its mathematical implications. Instead, with Grossmann, he published the "Outline of a Generalized Theory of Relativity and of a Theory of Gravitation," which has since been termed the *Entwurf* theory (*Entwurf* means outline in German). Although this theory did not meet Einstein's initial requirement regarding its mathematical features, he convinced himself that this was the best that could be done and was satisfied with it until the summer of 1915.

In 1913, shortly after Planck was elected secretary of the Royal Prussian Academy of Sciences, he launched a campaign to elect Einstein to the academy and bring him to Berlin. In July 1913, he went to Zurich with the influential Berlin physical chemist Walther Nernst, to present a three-part proposal to Einstein. They offered him: membership in the academy with generous financial support, directorship of the Kaiser Wilhelm Institute of Physics without administrative duties, and a professorship at the University of Berlin without teaching obligations. Einstein accepted and moved to Berlin. Shortly after he arrived, World War I broke out. Confronted with the realities of the war, he stepped down from the ivory tower of science to become a political opponent of Germany's involvement in the war. In Berlin, Einstein encountered the phenomenon of anti-Semitism and became increasingly aware of his Jewish identity. At that time, his relationship with Mileva deteriorated to the point of separation, and she and the children returned to Zurich. In the midst of all this, Einstein ardently pursued his scientific work. He continued to work on the *Entwurf* theory and suggested new arguments for its validity. In 1914, he summarized this theory in a review article, "The Formal Foundation of the General Theory of Relativity."[12] It took him less than a year to regret it. His doubts about the *Entwurf* theory began to form in the summer of 1915. He eventually abandoned it and, in a spurt of creativity and hard work, completed the general theory of relativity in November of that year.

Einstein joined Planck, Nernst, and many others in Berlin, the world capital of physics at the time. Even during the hardships of the war years, the city maintained an inspiring atmosphere and working culture in the physics community. Gerald J. Holton, a pioneer of Einstein scholarship in the historical and philosophical context, addressed the question:

> How much did these facts contributed to Einstein's unique ability and daring to develop, between 1915 and late 1917, his General Relativity Theory in Berlin? Could he have done so if he had accepted a grand offer from a city in another country?[13]

Holton's clear answer was:

> No other man than Einstein could have produced General Relativity, and in no other city than in Berlin, with its critical mass of close colleagues at the Academy and the University–Max Planck, Walther Nernst, Max von Laue, Fritz Haber, among many.[14]

On closer inspection, however, these prestigious colleagues were less interested and offered less support to Einstein's struggle with general relativity than his Zurich friends and colleagues, Grossmann and Besso. It was not until 1919, when a British solar eclipse expedition, under Sir Arthur Eddington's direction, observed the deflection of light rays in the sun's gravitational field as predicted by general relativity, that Einstein's theory was widely accepted, and he became world-famous. The confirmation of a theory created by a Jewish German holding a Swiss passport by an English expedition so shortly after the end of World War I turned out to be an international media event, confirming the universal character of the scientific enterprise.

e. The Emergence of a Quantum Worldview

Around the end of the nineteenth century, one of the prominent problems on the agenda of classical physics was a borderline problem between thermodynamics and electrodynamics, which concerned the thermal equilibrium of electromagnetic radiation in a cavity enclosed by reflecting walls. The distribution of the energy of this radiation over the different frequencies, namely, the spectrum of the radiation, had been measured with ever greater accuracy because of the technical relevance of this problem for modern industry. This spectrum depends only on the temperature of the cavity and not on the shape and composition of its walls. The phenomenon itself is known as "black-body radiation." A black body is the mental model of an ideal source of thermal radiation that is assumed to absorb all incident electromagnetic radiation. This concept, coined by Gustav Kirchhoff, became the basis of theoretical and experimental studies of electromagnetic radiation in thermal equilibrium. Until the very end of the nineteenth century, all attempts to formulate a theory that could adequately explain the shape of the energy distribution failed.

In 1900, following five years of work on this problem, Planck derived a formula, which describes, with great accuracy, the observed frequency distribution of black-body radiation. His path to this result was anything but straight, and it led him to explore the limits of the conceptual system of classical physics, introducing the notion of a discrete energy quantum. Confronted with Planck's result, Einstein knew he needed to go beyond those limits. For Planck, on the other hand, the notion of an energy quantum was a merely mathematical device that, at most, explained how energy was absorbed or emitted when electromagnetic radiation interacted with matter. He was reluctant to accept the revolutionary consequences of his own discovery and the quantized nature of radiation. Thus, he unwillingly became the pioneer of the quantum revolution. In contrast, in his light quantum paper of 1905, Einstein was the first to realize that not only was Planck's formula a break with classical theories of radiation but also that the introduction of quanta cannot be restricted to just one branch of physics.

Einstein's first contribution to broadening the quantum hypothesis began in 1907 when he extended his quantum ideas to the study of the thermal behavior of solids. He could derive a formula for the specific heat that was in better agreement with experiments than classical explanations. "This quantum question is so extraordinarily important and difficult that everybody should take the trouble to work on it," Einstein wrote to a colleague in 1909.[15] Yet initially its study attracted only a few outsiders. Slowly, interested scientists began networking; their exchanges and cooperation led to a gradual understanding of the true dimensions of the problems being faced.

Einstein's result happened to match a line of investigation pursued by Nernst, who had formulated a heat theorem that was later elevated to the third law of thermodynamics. Nernst was so impressed with the parallels between Einstein's work and his own that he used his experimental results as an excuse to visit Einstein in Zurich. He thus became one of the most prominent supporters of Einstein and was the driving force behind his invitation to the Solvay conference and his call to Berlin. Nernst and his colleague Haber expected a significant contribution from Einstein in connecting the conceptual breakthroughs of theoretical physics with the experimental research on physics and chemistry that was increasingly being pursued, with the invitation to bring both disciplines closer together. This would align with the clear relationship, particularly in Germany, between the chemical industry and advances in physical chemistry. In this industry, there was significant interest in attaining a deeper theoretical understanding of chemical processes. Of particular importance were the insights that could be derived from the emerging atomic and molecular understanding of these processes as well as from that of their thermodynamic properties. Thus, Einstein was called to Berlin to modernize chemistry, but he devoted most of his time to solving the ancient riddle of gravity. Yet he did not turn away completely from the conceptual changes within physics that were connected with the emerging quantum theory, and that were inspired by his work on the quantum nature of radiation and matter between 1905 and 1912.

The spectral analysis of chemical compounds, especially the multitude of spectral line patterns seen in a flame sample, could be interpreted as clues to an extremely complex internal structure of atoms and molecules. Such a structure, however, could not be reconciled with knowledge derived from classical physics. In 1913, Niels Bohr constructed an atomic model based on the astronomical model of a planetary system. In order to explain the spectral line patterns, Bohr's model, later elaborated by Sommerfeld and his school, assumes that electrons circle in discrete orbits. An atom's emission and absorption of light are associated with a transition of electrons between such fixed orbits. This combination of classical and quantum building blocks resulted in a kind of semiclassical atomic theory that later became the springboard for the full quantum theory.

For a long time, Einstein searched in vain for a theory of light that could be considered a fusion of wave and particle theories. In 1916, in two groundbreaking papers, he developed a model of the interactions between atoms and radiation, providing additional insight into the particle properties of light quanta. He showed that light particles must possess a direction and an impulse, similar to particles of matter. He further introduced the idea of stimulated emission of light quanta, which he referred to as a "brilliant idea" in a postcard to Besso.[16] Forty years later, this brilliant idea inspired the invention of lasers. Although Einstein received the 1921 Nobel Prize in Physics for his law of the photoelectric effect, the light quantum hypothesis, which forms the basis of this law, was still met with widespread skepticism in 1922. It was Compton's experiment in 1923 that led to the breakthrough that quelled these doubts. The experiment showed that X-rays collide with electrons in accordance with the classical model of particle collision and in blatant contradiction to the idea of light as a wave. His results were the first that convinced a majority of physicists of the justification of the light quantum hypothesis.

In his doctoral dissertation in 1924, Louis de Broglie showed that applying wave properties to particles is also plausible. Using his idea of matter waves, he could explain key components of Bohr's atomic model. Einstein was elated by this idea. It was fortuitously timed, as the need for new foundations of quantum physics was becoming ever more apparent. Analyzing the interaction of light and matter (in which Einstein's ideas from 1916 play an important role) paved the way for establishing these new foundations. The basis of a new conceptual beginning emerged from reinterpreting formulas that describe the scattering (dispersion) of light on atoms. Based on this, in 1925 Werner Heisenberg published an authoritative paper effectively founding quantum mechanics as we know it. His formalism could be extended to a calculus of matrices and interpreted as a quantum translation of the dynamical equations of analytical mechanics, as was soon realized by Born and Pascual Jordan. He showed that this theory, rather than simply using numbers, involved infinitely large tables of numbers, called matrices. One of the most well-known implications of the new quantum mechanics is Heisenberg's uncertainty principle. It states that two complementary physical parameters, like the position and the momentum of a particle, cannot be measured simultaneously with any degree of accuracy.

Following Einstein's thoughts about the dualism of waves and particles, Erwin Schrödinger took a different route to complete the quantum theory. In 1926, he expanded de Broglie's idea of matter waves by introducing a wave equation for electrons, where its solutions were states of the Bohr-Sommerfeld atom. Soon afterward, Schrödinger found proof that his formalism was essentially equivalent to Heisenberg's. In Schrödinger's formulation of quantum mechanics, the state of a system (e.g., a particle) is characterized by a "wave function," which is a function of parameters like the position (q) and momentum (p) of a particle and time. According to a rule formulated by Born, the wave function can be interpreted as predicting the probability of finding a definite value of the parameter q (or p) at a given time. This probability can also be found empirically by reproducing the same state many times and averaging the results of many measurements of that parameter. Let us look at two ways to interpret the result of a single measurement of, say, q. One possibility is that the value measured is the value of that parameter before the measurement. In that case, the wave function is not a complete description of the system because it only tells us what we know from many measurements.

The other possibility is that the measured value, implied by the wave function, is produced by the measurement itself, namely, that no objective value of that parameter, independent of measurement, exists. In that case, the wave function describes the system completely.

The difference between these two possibilities was at the core of the grand debate between Einstein and Bohr in the 1920s, particularly at the Solvay conference in 1927. Bohr interpreted Heisenberg's uncertainty principle as an expression of the limited applicability of our concepts to the microworld. He argued that there are complementary pairs of physical qualities of a particle, which cannot be measured simultaneously with an arbitrary degree of accuracy. Einstein reacted by conceiving thought experiments aimed at proving the opposite. Bohr rebutted his arguments by pointing out that measuring instruments are also subject to the uncertainty principle. Einstein did not accept the idea that there is no objective reality independent of observation. He would not abandon the causal nature of classical mechanics or the field theories of electromagnetism and gravitation and would not accept the probabilistic character of quantum theory. He presented one argument after another and invented a succession of thought experiments to challenge the theory. Bohr disputed every argument, but Einstein remained unconvinced. At a later stage, instead of claiming that the theory was wrong, he argued that it was incomplete and would be replaced by a comprehensive causal theory in the future.

The essence of this argument is represented in the, now famous, "Einstein-Podolsky-Rosen Paper," published in 1935.[17] This paper has become known under the label "EPR paradox." The authors argued that the wave function cannot provide a complete description of physical reality. Einstein used the existence of "entangled states" to support his conviction that quantum theory was incomplete. In such states, the properties of different particles depend on one another. Consequently, Einstein concluded that measurements of one particle's location (or velocity) should allow one to infer the values for the other particle, remotely separated from the first one, without actually disturbing it. Thus, he argued that the second particle must have both a definite velocity and a definite position. However, that would mean that quantum mechanics is incomplete since, according to its rules, only one of the two values can be determined exactly. Contrary to Einstein's argument, experiments performed in the 1980s showed that quantum mechanics is *not* incomplete. These achievements were honored by the Nobel Prize in Physics in 2022.

For most physicists, the quantum theory was a final theory and, therefore, a cornerstone of every future comprehensive theory of the physical world. Einstein's opinion was the direct opposite:

> It is my opinion that the contemporary quantum theory represents an optimal formulation of the relationships, given certain fixed basic concepts, which by and large have been taken from classical mechanics. I believe, however, that this theory offers no useful point of departure for future development.[18]

He believed that a future fundamental theory of all of physics would be based on the extension of the general theory of relativity. He believed that the general theory of relativity was an intermediate step towards a unified field theory, which would include gravitation and electromagnetism in the same framework and provide a substitute for the probabilistic character of quantum mechanics as the ultimate theory of matter. Einstein devoted the last twenty years of his life to an unsuccessful search for such a theory.

Einstein was an architect of the quantum worldview and made historic contributions to the early stages of its evolution. When the quantum revolution reached its first conclusion in the mid-1920s with the formulation of quantum mechanics and became an all-encompassing fundamental revision of the classical ideas of matter and radiation, Einstein did not join the general consensus. He was a dissident until the end of his life. In his essay "Physics and Reality" (1936), Einstein highlights the success of quantum mechanics and thus indicates the magnitude of the challenge to replace it with another theory:

> Probably never before has a theory been evolved which has given a key to the interpretation and calculation of such a heterogeneous group of phenomena of experience as has quantum theory. In spite of this, however, I believe that the theory is apt to beguile us into error in our search for a uniform basis for physics, because in my belief, it is an *incomplete* representation of real things. . . . The incompleteness of the representation leads necessarily to the statistical nature (incompleteness) of the laws.[19]

f. The Einstein Myth and His Iconic Status

Albert Einstein has left his mark not only on the physics of the twentieth century but also on the public image of science and scientists. The photographs from the second half of his life, in particular, evoke an image of a friendly nonconformist. He was an eccentric who defied authority and convention, to the extent that he did not wear socks and refused to groom his hair. The famous picture of Einstein sticking out his tongue represents a certain unworldliness, a protest against the well-bred majority, but also a shrewd and witty handling of the mass media. The origin of Einstein's myth is not only in the joy of discovery but in a certain detachment from the fragility of the human condition. It is a bemusement akin to that granted only to the gods in the Greek theater of antiquity. But, apart from his outward appearance, how unconventional was the real Einstein? And what role did his nonconformity play in the scientific revolution that he supposedly induced?

Since the beginning of the twenty-first century, the real conflicts, both societal and scientific, that were the source of Einstein's estrangement have largely been forgotten. There is little mention of them in the occasional reports about his discoveries or his love life that find their way into today's headlines. Also, as he has entered the pantheon of cultural history, Einstein has himself become a member of the establishment, as evidenced by the many honors bestowed in his memory. His popularity, even in today's Germany, the country from which he was forced to emigrate, represents a level of normalcy that until recently was unthinkable. The memory of Einstein's tense relationship with Germany and the Germans has begun to fade, giving way to the all-pervading Einstein myth.

One of the unique traits of the Einstein phenomenon is that his work has left its mark on the cultural history of the twentieth century in areas far beyond his expertise. His deep influence is evident in many areas, from philosophy to psychology, and even in art. For example, Jean Piaget, child psychologist and founder of genetic epistemology, referred to a suggestion from Einstein in his analysis of the development of spatial and temporal thinking in children.

The spectacular success of his theory of relativity, in conjunction with his anti-militarist position during the World War I, distinguished Einstein as a symbol of pacifism in the Weimar Republic. This laid the roots for his role as the world's conscience and sage, taking a position on all pressing issues, from German reparations to the condition of Jews from eastern countries living in Germany. Later, after World War II, Einstein continued in this role, engaging in the arms control effort and supporting world government. In 1952 he was even offered the presidency of Israel.

Today, more than sixty-five years after his death, public interest in his life and science continues unabated. Centennials of the milestones of his creativity have been celebrated worldwide through public events, international conferences, workshops, television programs, and a spate of new books. His image decorates so many commercial products and is one of the most recognizable faces on the planet.

Progress in science and new cosmological observations remind us time and again that Einstein was right and also underline the unending nature of the quest for knowledge. When new discoveries related to Einstein's work occur, such as the recent detection of gravitational waves, people around the globe, irrespective of their understanding (or indeed because of their lack of understanding) regarding the discovery, are fascinated by the appeal of science and the iconic image of its most discernible figure—Albert Einstein.

The presence of Einstein in modern culture is all-encompassing—in art and literature, movies and television programs, and also in digital media. In 2008, Don Howard, a prominent scholar of Einstein's science and philosophy, began his generally favorable review of a biography of Einstein by Walter Isaacson with the question, "Still, there are too many books on Einstein. Shall we call for a moratorium?"[20] This question seems not to have been taken seriously. Searching online for books about Einstein published after 2008, we find more than eighty English titles related to his life and specific domains of his activities (this number excludes the numerous children's books, comic books, and books for professional physicists). This increase in publications about Einstein attests to his enduring legacy and presence in the public mind, while also contributing to it. Thus, we can expect this to continue for many years.

Can all this simply be the consequence of his unquestionably groundbreaking research results? Apparently not. So, what is so special about Einstein? His iconic status is certainly also due to specific historical circumstances, in particular, the role of the emerging mass media at the beginning of the twentieth century. Einstein became one of the first media stars of science at a time when the world was hungry for such celebrities. This public image endured throughout his lifetime. It evolved and expanded in many directions and continues even today. Einstein himself contributed to this image in many ways. He was constantly in the public eye. In numerous articles, interviews, correspondence with peers, and public addresses, he expressed his views on various public, political, and moral issues, such as nationality and nationalism, war and peace, and human liberty and dignity, relentlessly denouncing all forms of discrimination.

Einstein's views and activities outside of physics were not simply accessories to a life devoted to science; they were evidently driven by the same inner urge as his quest for scientific knowledge. These two aspects of Einstein's commitments and activities reflect, in his own personality, the fundamental tensions of science in the modern world. This is probably the most profound reason why Einstein is still very much alive today and will continue to be so in the foreseeable future: science is becoming increasingly relevant to all aspects of modern societies, but science also raises questions about the capability of humankind to understand the natural world and its role in it, and how to utilize this understanding to shape its own fate. Einstein endures as the pioneer who squarely confronted this human condition, not just as a brilliant scientist but also as a thoughtful philosopher and a caring humanist, aware of both his individual and our collective limits.

Taking a predominately biographical perspective, one might reasonably assume that Einstein's unconventional stance, above all, created the conditions for his scientific revolution and its subsequent impact on culture in general. Indeed, his status as an outsider in physics appears to have made his extraordinary achievements possible. It is undoubtedly important to consider the biographical circumstances that made the Einsteinian revolution possible, which we have already done to some extent in this section and will continue to do so in sections IV and V. But focusing exclusively on a personal biographical perspective brings with it the risk of propagating the Einstein myth. Ultimately, this myth ascribes to his personality or to his personal situation a simplified version of what actually was the outcome of a complex process. Indeed, one of the factors at play was his unique genius. However, one must also take into account the cultural environment in which he lived and worked and recognize that his breakthroughs were a part of the long-term intellectual development of science. The latter requires taking a more extensive historical perspective than is typically assumed in biographical accounts that instead pay great attention to every minute detail of Einstein's life. Taking an extensive historical perspective demands a discussion of the standing of the Einsteinian revolution in the history of physics and the evolution of knowledge.

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