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Introduction

This volume brings together fourteen essays by historians and philosophers of science on various aspects of the writings of Albert Einstein. Together they are meant to provide a guide to Einstein's work and the extensive literature about it. The essays can be read independently of one another, though most of them gain from being read in conjunction with others. All of them should be accessible to a broad audience. The use of equations, for instance, has been kept to a minimum throughout this volume. The first ten essays deal with Einstein's contributions to physics and with various philosophical implications of these contributions. The next three essays directly address some of Einstein's more philosophical writings and the impact of his work on the twentieth-century philosophy of science. The final essay is on Einstein's political writings. In this introduction we give a brief overview of Einstein's life and career to provide some context for this collection of essays and highlight some themes addressed more fully in the individual contributions to this volume.

Albert Einstein (1879–1955) was born in the Swabian city of Ulm, the first child of upwardly mobile Jewish parents, Hermann and Pauline (née Koch).[1] In 1880, Hermann's featherbed business failed and he moved his family to Munich, where with one of his brothers he started a gas and water installation business. In 1885, they founded an electrotechnical factory. Growing up around dynamos and electromotors, Einstein developed an early interest in electrodynamics, the field in which he would develop his special theory of relativity. In his "Autobiographical Notes,"[2] he recalled two other experiences that drew him to science at an early age: being shown a compass by his father when he was four or five years old and reading a book on Euclidean geometry at the age of twelve (Einstein 1949a, 9).

In 1894, when the family business was faltering, Einstein's father and uncle moved their factory to Pavia in Italy. His parents and his only sibling, his younger sister Maja,[3] moved to Milan and then to Pavia, while Einstein stayed behind in Munich to finish high school at the Luitpold *Gymnasium*. He soon dropped out, however, and joined his family in

Pavia. In October 1895, at the age of sixteen, he traveled to Switzerland to take the entrance exam to the Federal Polytechnic, now known as the *Eidgenössische Technische Hochschule* (ETH), in Zurich. Although he did well on the science and mathematics portions of the exam, he failed the exam overall (CPAE 1, 10–12). After completing his secondary education at the Aargau Cantonal School in Aarau,[4] he was admitted to the ETH the following year, still only seventeen, and began his studies to become a high school mathematics and physics teacher. Among his classmates were Marcel Grossmann, on whose notes he relied to pass exams as he frequently skipped class, and Mileva Marić, who would become his first wife.

In 1900, Einstein graduated fourth in a class of five. Initially, he could only find employment as a substitute teacher and a private tutor. With the help of Grossmann he eventually landed a job at the Patent Office in Bern. In June 1902, he took up a position there as patent examiner third class. He had become a Swiss citizen the year before, after having renounced his German citizenship back in 1896. Meanwhile, Marić had given birth to the couple's first child. It appears that this child, a girl they named Lieserl, was given up for adoption and died in childhood, but exactly what happened to her has never been established.[5] Marić had been struggling at the ETH and the pregnancy effectively put an end to her studies. In January 1903, the couple finally married. Einstein's parents had strongly opposed the match. His father had been on his deathbed in October 1902, broken by a string of business failures, when he had finally relented and given his consent.[6] The couple would have two more children, two sons, Hans Albert and Eduard.[7] The scientific partnership they had envisioned when they were both students at the ETH never materialized (Stachel 1996). Marić did not become a member of the mock Olympia Academy that Einstein formed around this time with his friends Maurice Solovine and Conrad Habicht to discuss readings of shared interest, mostly in philosophy. It is not clear whether Marić participated in these discussions even though they were sometimes held at her and Einstein's own apartment.[8]

Thanks to a list by Solovine (Einstein 1956b, viii), we have a record of the readings of the Olympia Academy, which included works by Baruch Spinoza,[9] David Hume, John Stuart Mill, Hermann von Helmholtz, Ernst Mach, and Henri Poincaré. As a teenager, at the recommendation of Max Talmud (later changed to Talmey), a medical student who regularly dined with the Einstein family, he had read Immanuel Kant's *Critique of Pure Reason*. Einstein would make creative use of the ideas of these authors in his own thinking – of Hume and Mach, for instance, in the development of special relativity (Norton 2010) and of Mach in the development of general relativity (see Chapter 6).

Another friend with whom Einstein discussed scientific and philosophical matters during his early years in Berne was Michele Besso. Their lifelong friendship began while they were both students at the ETH. In 1904, on Einstein's recommendation, Besso joined Einstein at the Patent Office. Besso became an important "sounding board" for Einstein's developing ideas. The 1905 paper introducing special relativity famously has no references but acknowledges the help of one person – Besso.

In the years 1902–4, Einstein published three papers on statistical mechanics, now sometimes referred to as the "statistical trilogy" (Einstein 1902b, 1903, 1904; analyzed in Renn 2005c and Uffink 2006). Many of the results presented in these papers had been found earlier by Ludwig Boltzmann and Josiah Willard Gibbs. At the time, Einstein only knew some of Boltzmann's work and none of Gibbs's. Even though Einstein's results were not new, they played an important role in his subsequent work. The interpretation of probabilities as time averages led him to consider fluctuations, which became the central tool in his attempts to understand microphysics. In the final installment of the statistical trilogy, Einstein finally did something highly original. He applied the formalism developed to deal with fluctuations in gases to fluctuations in heat or black-body radiation, setting the stage for some of his signature contributions to quantum theory in the years ahead.

Then, seemingly out of nowhere, came the papers of the *annus mirabilis*, Einstein's year of miracles.[10] Other than the statistical trilogy, there are few sources to document the development of Einstein's thought leading up to them. Largely on the basis of scattered clues in his correspondence with Marić and later recollections of both Einstein and Besso, his main scientific confidant at the time, Robert Rynasiewicz and Jürgen Renn (2006) have speculated that prior to 1905 Einstein was trying to lay a new atomistic foundation for all of physics. By 1905, they argue, Einstein had come to realize that this attempt was premature. The papers of his miracle year, on this view, should be seen as those parts of a much larger effort that Einstein felt were ready to be presented to the scientific community, each establishing some secure "fixed point from which to carry on" (Rynasiewicz and Renn 2006, 6).

In Chapter 1, expanding on their earlier joint paper, Renn and Rynasiewicz discuss the various strands leading to the papers of the *annus mirabilis* as well as the connections between those strands and papers. Using the notion of what Renn (2006) has called a "Copernicus process," they show how Einstein's innovations of 1905 consisted largely of a reconfiguration of existing bodies of knowledge inherited from such acknowledged masters of classical physics as Boltzmann, Hendrik Antoon Lorentz, and Max Planck. The next three essays each focus on one of the three most important papers of the *annus mirabilis* and on Einstein's other contributions to the more specialized field to which each one belongs. John D. Norton (Chapter 2) discusses the relativity paper (Einstein 1905r); A. J. Kox (Chapter 3) the Brownian motion paper (Einstein 1905k); and Olivier Darrigol (Chapter 4) the light quantum paper (Einstein 1905i).

Einstein's strategy of trying to establish fixed points for further development amounted to looking for constraints on future theories covering a particular domain. Einstein adopted this strategy when he recognized that an attempt to formulate a complete theory for the relevant phenomena would be premature. One of us has argued that Einstein's famous distinction between "constructive theories" and "principle theories" (Einstein 1919f),[11] to which we will return toward the end of this introduction, was intended, at least in part, to capture this difference in strategy: trying to find concrete theoretical models for a group of phenomena versus trying to find constraints on such models (Janssen 2009, 40–1). Though Einstein made the principle/constructive distinction in an article on relativity theory, its heuristic use is perhaps best illustrated by Einstein's early work on quantum theory. In this area, Einstein's "fixed points" strategy was especially successful.

A striking example of the strategy is provided by the central argument for the light quantum hypothesis, cautiously called a "heuristic viewpoint" in the title of the only paper of his *annus mirabilis* that Einstein himself, in a letter to Habicht, called "very revolutionary" (CPAE 5, Doc. 72). For this argument, which one commentator has called "Einstein's miraculous argument" (Norton 2006), Einstein considered a box with black-body radiation. The "fixed points" used as premises for the argument are Boltzmann's principle relating probability and entropy and Wien's law for the spectral distribution of the energy of black-body radiation in the high-frequency regime. The latter, in conjunction with some standard results from thermodynamics, gave Einstein a formula for the entropy of this radiation. Using Boltzmann's principle, he turned this into an expression for the (exceedingly small) probability that, due to some random fluctuation, all radiation in the box would at some point be found concentrated in a small subvolume of it (see Norton 2006 for a careful analysis). The expression for this probability has the exact same form as the expression for the probability that, due to a random fluctuation, all molecules of an ideal gas in some container would at some point be found in a small subvolume of that container. Therefore, Einstein concluded, black-body radiation in the high-frequency regime behaves as a collection of ideal gas molecules with energies proportional to the frequency of the radiation. The conclusion is as secure as its premises – the laws of thermodynamics, Boltzmann's principle, and Wien's law.

Einstein provided further support for the light quantum hypothesis by showing that it could readily explain some phenomena that were utterly mysterious from the point of view of the wave theory of light. The most important of these is the photoelectric effect, in which light shining on a metal plate releases electrons from its surface. The energy of these photoelectrons turns out to be proportional to the *frequency* of the light, as predicted by Einstein's hypothesis, and not, as one would have expected on the basis of the wave theory, to its intensity, proportional to the square of the waves' *amplitudes*. Because of this explanatory feat, the light quantum paper is often remembered as the "photoelectric effect paper" but its centerpiece was the fluctuation argument for the particle behavior of light. The photoelectric effect was just icing on the cake.

In 1909, once again deploying his "fixed points" strategy, Einstein (1909b, 1909c) published two further fluctuation arguments (one for energy, one for momentum) showing that it follows from Planck's law for black-body radiation and some general results in statistical mechanics that any satisfactory future theory of light would have to ascribe both particle and wave characteristics to light. Einstein is quite explicit about the strategy he followed to arrive at this result: "We consider Planck's radiation formula as correct and ask ourselves whether some conclusion about the constitution of radiation can be inferred from it" (Einstein 1909c, 823).[12]

Several years later, in a paper that laid the theoretical foundation for the development of the laser decades later, Einstein showed that one can derive Planck's law from the condition for thermal equilibrium in a simple model for the interaction between matter and radiation (Einstein 1916n). In this model, generic Bohr atoms with discrete energy levels emit and absorb corpuscular light quanta. Einstein introduced his famous A and B coefficients for the probability of such emission and absorption. Despite his later dictum that God does not play dice,[13] Einstein thus introduced – reluctantly and, he hoped, temporarily – a stochastic element into the basic laws of physics. Einstein now also explicitly added the assumption that light quanta carry momentum as well as energy. In the second part of the paper, Einstein showed that this assumption is crucial for his model to give the right momentum fluctuations in a situation analogous to the one he had analyzed earlier (Einstein 1909b, 1909c; Einstein and Hopf 1910). While fully recognizing the provisional character of his model (it completely failed to do justice, e.g., to the wave aspects of light), Einstein, as in 1905 and in 1909, had good reason to believe that it was a step in the right direction.

None of his arguments, however, could overcome the resistance of the physics community to the light quantum hypothesis. Interference phenomena clearly showed that light plus light could sometimes give darkness, which seemed to rule out that light could consist of particles. Robert Millikan's confirmation in 1915 of Einstein's formula for the photoelectric effect convinced the physics community of the formula but not of the light quantum hypothesis from which the formula was derived. And Einstein won the 1921 Nobel Prize for his formula for the photoelectric effect, not for the theory behind it.[14] The physics community only came around to Einstein's point of view in 1923, when Arthur Holly Compton published the results of X-ray scattering experiments and showed that they could be analyzed in impressive quantitative detail in terms of relativistic collisions of high-frequency light quanta and electrons (Stuewer 1975). Even then there were some holdouts, notably Niels Bohr. This staunch opposition to the light quantum hypothesis is the central topic of Roger H. Stuewer's essay in this volume (Chapter 5).

In the early 1920s, Einstein considered a dual theory of light in which corpuscular light quanta are guided by waves. He also tried to design experiments to decide between a wave and a particle theory of light (Einstein 1922a; CPAE 13, Doc. 29). These experiments proved to be either inconclusive (as in the case of experiments by Hans Geiger and Walther Bothe in 1921; discussed in Klein 1970a) or fraudulent (as in the case of experiments by Emil Rupp later in the 1920s; discussed in van Dongen 2007a, 2007b). These episodes are touched upon in the essays of Darrigol (Chapter 4) and Christoph Lehner (Chapter 10) in this volume.

A particularly clear-cut example of Einstein's strategy of finding and proceeding from certain fixed points – and one of the examples he had in mind when he made the distinction between principle and constructive theories in 1919 – is the way in which he presented what came to be known as the special theory of relativity in the most famous of his *annus mirabilis* papers, "On the Electrodynamics of Moving Bodies" (Einstein 1905r). In an oft-quoted passage of his "Autobiographical Notes," Einstein recounted why he had opted for a "principle theory"–approach in this case:

> By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results. The example I saw before me was thermodynamics. (Einstein 1949a, 53)

Following the example of thermodynamics, Einstein derived all of his special theory of relativity in the 1905 paper from two postulates, the relativity postulate and the light postulate.

In older popular histories of relativity and in older textbooks, the light postulate used to be presented as a straightforward generalization of the result of the famous Michelson-Morley experiment of 1887.[15] The experiment, in modern terms, showed that the velocity of light is the same for all observers in uniform relative motion with respect to one another. The Michelson-Morley experiment, however, is not mentioned anywhere in the 1905 relativity paper, even though Einstein was well aware of it by 1905 (Stachel 1987, 45). The formulation of the light postulate, moreover, makes it clear that the experiment was not the origin of the postulate. The postulate does not say, as one would expect if it were linked to the Michelson-Morley experiment, that the velocity of light is independent of the motion of the *observer* (although this is a direct consequence of the conjunction of the two postulates), but rather that it is independent of the motion of the *source*. In fact, the result of the Michelson-Morley experiment would readily be explained if the velocity of light *were* dependent on the velocity of its source. The result of the experiment is thus perfectly compatible with the *negation* of the light postulate, which, all by itself, would seem to rule out that the postulate originated in the experiment.

The real origin of the light postulate, as Einstein made clear on many occasions, is to be found in Maxwell's equations for electrodynamics.[16] These equations predict the existence of electromagnetic waves propagating at the speed of light, regardless of the direction in which they travel and regardless of the velocity of the source by which they are emitted. It was thought in the nineteenth century that this prediction could only be true in a frame of reference in which the ether, the medium thought to be the carrier of these electromagnetic waves, is at rest. It followed that Maxwell's equations could also only hold in such privileged frames of reference. Electromagnetic theory thus seemed to violate the relativity principle, familiar from mechanics since the days of Galileo. As there were good reasons to assume that the Earth was moving with respect to the ether, Maxwell's equations were not expected to hold in the Earth's frame of reference. It should thus be possible to detect the Earth's presumed motion through the ether with experiments in optics and electromagnetism. Yet no experiment ever showed any sign of this motion. In the decade before 1905, Lorentz developed a theory that could account for the negative results of most of these so-called ether drift experiments (Janssen 1995, 2002b, 2009). The theory was a combination of a purely mathematical result and a far-reaching physical hypothesis. The mathematical result was that Maxwell's equations have a remarkable symmetry property. They are invariant under what are now called Lorentz transformations. The physical hypothesis, in effect, was that all other physical laws have this same property. This hypothesis fit with the view of several prominent physicists at the time that all laws of physics could ultimately be reduced to those of electrodynamics (McCormmach 1970; Kragh 1999, ch. 6).

Illustrating the claim in the contribution by Renn and Rynasiewicz (Chapter 1) that the breakthroughs of Einstein's *annus mirabilis* consisted to a large extent of a reinterpretation of existing bodies of knowledge, the mathematical formalism used in Einstein's 1905 paper on special relativity is essentially the same as that of Lorentz's theory. Einstein, however, recognized that Lorentz invariance went beyond the laws of electrodynamics and had to do with the structure of space and time.[17] Einstein introduced his new ideas about space and time in the "Kinematical Part" of the paper.[18] In the "Electrodynamic Part," which gave the paper its title, he showed that, with these new ideas, Maxwell's equations do satisfy the relativity principle after all. If they hold in one frame of reference, they hold in all frames in uniform motion with respect to that one. That it had looked as if they do not was because physicists had tacitly used (what are now called) Galilean transformations rather than Lorentz transformations to relate quantities pertaining to two such frames to one another.

One can read Einstein's 1905 relativity paper as an investigation into what has to give for Maxwell's equations to satisfy the relativity principle. Einstein, however, set it up somewhat differently. He investigated what has to give to render *one important consequence of* Maxwell's equations compatible with the relativity principle: the proposition that light propagates with a fixed velocity independently of the velocity of its source. He showed that this requires changes in our commonsense concepts of space and time. Most importantly, he showed that it is a direct consequence of his two postulates that two observers in uniform motion with respect to one another will disagree whether two events taking place at different locations happen simultaneously or not. This result is known as the relativity of simultaneity. The Lorentz transformation equations for the space and time coordinates of two frames of reference in uniform motion with respect to one another incorporate this effect, as well as two further consequences of the postulates, known as length contraction and time dilation (see the Appendix for details).

As mentioned above, the way in which Einstein presented his theory in his relativity paper nicely illustrates his "fixed points" strategy. Einstein could not use Maxwell's equations as part of the foundation of a new physics. Given his conviction that light sometimes displays particle behavior, he had to reckon with the possibility that these equations, which seemed to vindicate the opposing view that light is a pure wave phenomenon, would have to be altered some day. As it happened, only their interpretation had to be changed, but Einstein had no way of knowing this in 1905.[19] Fortunately, all he needed from Maxwell's equations was the prediction that the velocity of light is independent of the velocity of its source. He was willing to bet the house on this one consequence of Maxwell's equations. And the conjunction of this one element and the relativity postulate sufficed to derive the new ideas about space and time that could be used as the foundation for a new physics.

Before he published the light quantum hypothesis and special relativity, Einstein presumably had convinced himself of their compatibility. Two results were especially reassuring on this score. The simple linear relation between the energy and the frequency of his light quanta is preserved under Lorentz transformations (Rynasiewicz 2005, 44). And because of the way velocities add in special relativity, the theory is compatible both with a particle and a wave theory of light.[20]

The new ideas about space and time for which special relativity is best known can be understood independently of the problems in electrodynamics they were introduced to solve (see the Appendix). However, one cannot properly understand the genesis of the theory and its reception by the physics community without taking into account the electrodynamical context.[21] In his contribution to this volume (Chapter 2), Norton thus presents a reconstruction of Einstein's electrodynamically driven path to special relativity. He does so without relying on the mathematical formalism of electrodynamics typically presupposed in such reconstructions in the history of physics literature.[22]

Unlike the light quantum hypothesis, special relativity was accepted by mainstream physicists within a few years. Whereas the light quantum hypothesis called into question one of the watershed achievements of nineteenth-century physics, the displacement of the particle theory of light by the wave theory, special relativity was the natural culmination of work in electrodynamics in the preceding decades. Much of the mathematical formalism of special relativity was already in place by 1905. Einstein mainly deserves credit for recognizing the importance of key elements of this formalism beyond electrodynamics. This is true not just for the new notions of space and time encoded in Lorentz's transformation equations, but also for other general relations in physics, such as, most famously, the equivalence of energy and mass, $E = mc^2$, which Einstein first published in a short paper that brought his *annus mirabilis* to a close (Einstein 1905s). Einstein's signature formula is also discussed in Norton's essay.[23]

In addition to his pathbreaking papers, Einstein wrote his PhD thesis in 1905, a feat less astonishing than it sounds as the dissertation only takes up seventeen pages (Einstein 1905j). Meanwhile, Einstein continued to perform his duties at the Patent Office well enough to earn a promotion. In 1906, the year after his *annus mirabilis*, he was promoted from patent clerk third class to patent clerk second class. It was not until three years later that he quit the Patent Office[24] and began his ascent up the academic ladder. Once begun, the ascent was rapid. In 1909 he went from part-time instructor at the University of Bern to assistant professor at the University of Zurich. That same year he first appeared on the program of the large annual meeting of German natural scientists and physicians, held that year in Salzburg. He used the occasion to present the fluctuation argument for wave-particle duality mentioned above, a result he conceivably arrived at years earlier (Chapter 1). In 1911, he accepted a full professorship in Prague. The next year he was back in Zurich, now as a full professor at his alma mater, the ETH. He did not stay long there either. In 1914, he accepted a salaried position created especially for him at the Prussian Academy of Sciences in Berlin. The position did not carry any teaching obligations and allowed him to spend as much time as he wanted on his research. Moreover, Einstein was promised the directorship of a planned Kaiser Wilhelm Institute for Physics, which was finally founded in 1917 but even then existed only on paper. Through the institute, research grants could be awarded but there was no building designated to it.

Showing just how controversial Einstein's light quantum hypothesis still was in 1914, Planck and Walther Nernst, who aggressively recruited Einstein for the Berlin position, made it clear that they wanted him to come to Berlin *despite* his ideas about light quanta. As Planck wrote in a letter recommending Einstein for membership in the Berlin Academy: "That he may sometimes have missed the target in his speculations, as for example, in his hypothesis of light quanta, cannot really be held against him" (CPAE 5, Doc. 445). Planck and Nernst were interested in other applications of Einstein's quantum ideas. In 1907, Einstein had shown that these ideas can be used to account for the puzzling rapid decrease of the specific heat of solids at low temperatures (Einstein 1907a). The quantization of matter was clearly more palatable to the physics community than the quantization of radiation. Einstein's work on the specific heat of solids had attracted the attention of low-temperature specialist Nernst, who was instrumental in the choice of the fledgling quantum theory as the subject of the first in a series of prestigious and influential conferences held in Brussels and paid for by the Belgian industrialist Ernest Solvay. At this first Solvay conference, held in 1911, Einstein emerged as a leader in the new field (Barkan 1993).

The move to Berlin did not just change Einstein's professional life; it changed his personal life, too. Shortly after Einstein and Marić moved to Berlin with their two young sons, their marriage, which had been deteriorating for years, unraveled. Within a few months, Marić, Hans