Albert Einstein's Special Theory of Relativity

Emergence (1905) and Early Interpretation (1905–1911)

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Arthur I. Miller

Department of Physics
Harvard University

Department of Physics and Applied Physics
University of Lowell, Lowell, Massachusetts

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Albert Einstein as a patent clerk in Bern. (Copyright © by Lotte Jacobi)

PREFACE

Midway into the most productive period of his life, 1902-1909, Albert Einstein wrote his first paper on electrodynamics entitled, "On the Electrodynamics of Moving Bodies." In 1905 the young scientist's intent, however, was not to develop electrodynamics as it was customarily interpreted, but to criticize it and then to propose a new basis for it. This he later referred to as the relativity theory, and the paper on electrodynamics became known as the relativity paper. Page for page Einstein's relativity paper is unparalleled in the history of science in its depth, breadth and sheer intellectual virtuosity. Whereas the consequences of the special relativity theory changed mankind's very view of its relation to the cosmos, this occurred neither immediately upon its publication, nor for several years afterward. This book is a biography and analysis of the relativity paper set into its historical context.

First as a student of physics, and then as a physicist, what struck me forcefully about the relativity paper was how Einstein had developed one of the most far-reaching theories in physics in a literary and scientific style that was parsimonious, yet not lacking in essentials; in a pace that, whenever necessary, possessed a properly slow cadence, yet was not devoid of crescendos and *tours de force*. It seemed as if Einstein's seminal paper on the relativity theory contained virtually everything the advanced undergraduate student needed for learning the basics of relativity theory – e.g., the relativity of simultaneity. On another level, for the mature physicist it could draw out in strong relief, and tie together, the fundamentals of the relativistic approach to mechanics and electrodynamics that more advanced texts clothe in elegant mathematics. My transition, some years ago, from physicist to historian of science owed itself in large part to my desire to know more about the relativity paper and its author. Through pursuance of the themes that underlay my research in the history of science – the nature of scientific discovery and the origin of scientific concepts – I discovered that there was more between the lines of Einstein's relativity paper than I had ever realized. It also became clear to me that there were no historical analyses available that attempted to connect the relativity paper in its entirety with the physics of its time. This lacuna was another impetus for my writing this book. Indeed, it is now strange to note, but prior to 1960 there were very few serious historical studies of Einstein's work on special relativity theory. The historical studies of Gerald Holton and Martin J. Klein were the first to begin filling in the pre-1905 background. As T. Hirosige and others have noted, it was Holton's 1960 essay, "On the Origins of the Special Theory of Relativity," that started the new interest in historical research on the special relativity theory, and that raised many of the modern questions, which Holton has continued to pursue in his subsequent essays. Klein, starting in

1962, has written extensively, and chiefly, on the effect of thermodynamics and statistical mechanics on Einstein's view of physical theory.

I have developed the history, philosophy and physics with an eye toward presenting to the widest possible audience the state of fundamental physical theory during 1890–1911. Against the background of Einstein's paper, set in its proper historical context, the book contains a detailed discussion of the internal structure of the paper using mathematics and physics at the sophomore or junior undergraduate level; an investigation of the genesis of Einstein's thoughts on relativity theory; and discussions of the philosophical and scientific (experimental and theoretical) currents of the times. Indeed, we shall see that Einstein presented the special relativity theory using no advanced mathematics at all. He performed only one integral in order to solve the rather straightforward problem of calculating the kinetic energy of an electron moving in an electrostatic field; later in 1905 he realized the deep meaning of this result – the equivalence of mass and energy. On the other hand, certain more advanced notions of mathematics and electrodynamics enter into my discussions of the state of electrodynamics in 1890–1905 and the early interpretation of relativity theory. With a view toward keeping the text self-contained, whenever necessary I have developed in footnotes the requisite mathematics and electrodynamics.

The analysis of Einstein's relativity paper is intended as a step toward improving scientific, philosophical and historical analyses of what Einstein did or did not accomplish or assert in 1905, and the multidisciplinary approach of modern historical scholarship may help to show the place this fascinating and complex episode has in the history of ideas.

Acknowledgements

My greatest intellectual debt I owe to my teacher Professor Gerald Holton. Without his generous assistance, encouragement and example as a scholar my transformation from physicist to historian of science would have been incomplete. I owe to Professor Holton the concept of this book. In 1972 he suggested that we analyze the internal structure of Einstein's 1905 relativity paper. There resulted a jointly written draft manuscript of 1972 which was circulated privately. During the ensuing years, the course of my own research expanded the plan for the full-fledged product, and this book is the result. Professor Holton graciously read most of the chapters in one form or another, and I am grateful for his comments.

I have benefitted much from Professor Martin J. Klein's writings and from our conversations. Dr. Rudolf Morf's critical comments on a version of my translation of Einstein's special relativity paper were most helpful. Among colleagues who contributed to the manuscript's final stages I mention Professors Edward M. Purcell, Silvan S. Schweber, John Stachel, and Kenneth Brecher. I thank Andrei Ruckenstein, and particularly Peter Galison, for checking details in portions of the manuscript.

Most of the research and writing for this book took place in the Department of Physics, Harvard University, to which I am most grateful for providing me with a "secular cloister."

It is a pleasure to acknowledge permission from the Algemeen Rijksarchief, The Hague, and the Estate of Henri Poincaré to reproduce correspondence between H. A. Lorentz and Henri Poincaré and to quote from other letters in their possession; from the American Philosophical Society (Archive for History of Quantum Physics) to quote from a letter from Walter Kaufmann to Arnold Sommerfeld; and from The Estate of Albert Einstein to quote from Einstein correspondence. I am grateful to the Poincaré family for opening to me for the first time their collection of Henri Poincaré's letters and manuscripts. The richness of this collection is made manifest in the two letters that I reproduced here, which shed new light on physics during the first decade of the 20th century. I thank Dr. Spencer R. Weart, Director, Center for History of Physics, for providing funds from the Friends of the Center for History of Physics of the American Institute of Physics that enabled me to arrange to microfilm the Poincaré archival materials.

For the travel and research funds essential for historical research I acknowledge grants from the Section for History and Philosophy of Science of the National Science Foundation, the Centre National de la Recherche Scientifique, the Lorentz Fund, Leiden, and the American Philosophical Society. A Fellowship from the John Simon Guggenheim Memorial Foundation affords me the luxury of completing this book while moving on to other studies.

For editorial assistance I have had the good fortune to have availed myself of the services of Dr. Marcel Chotkowski La Follette and Mrs. S. S. Stevens.

It is especially important in a book as complex as this to emphasize that old caveat that I alone am responsible for any textual errors and all conjectures.

ARTHUR I. MILLER

AUTHOR'S NOTES TO THE READER

In order to avoid a nesting of footnotes that contain no information other than a page number, I use abbreviations of the sort [Einstein (1907c)] which means the paper listed in the Bibliography (pp. 417–440) under Einstein and dated 1907c. Papers written by an author in a single year are listed in the Bibliography in the chronological order of their publication. Wherever necessary in the narrative I give the date a paper was received or its date of presentation as a lecture.

References to quotations from Einstein's 1905 special relativity paper, "On the Electrodynamics of Moving Bodies," are keyed to the line numbers of my translation in the Appendix (pp. 391–415). For example, [§1, 1–5] refers to lines 1–5 of §1. For convenient reference, certain of Einstein's equations in this paper are noted by a code; for example, [§8.15] indicates the fifteenth equation in §8 of the special relativity paper.

Attempting to retain the essence of the mathematical notation used in 1905, while excluding both Gothic letters then widely used and certain symbols that might confuse the modern reader (e.g., V for the velocity of light in vacuum c), has prevented me from standardizing notation. The remaining redundancies should not be confusing. For example, in this book when the letter E is used for the electric field, it is not likely to be confused with the quantity energy which is written as E, E^e, E_T, E_0, E_0^e or combinations thereof. I have taken care to define symbols such as E whenever they appear.

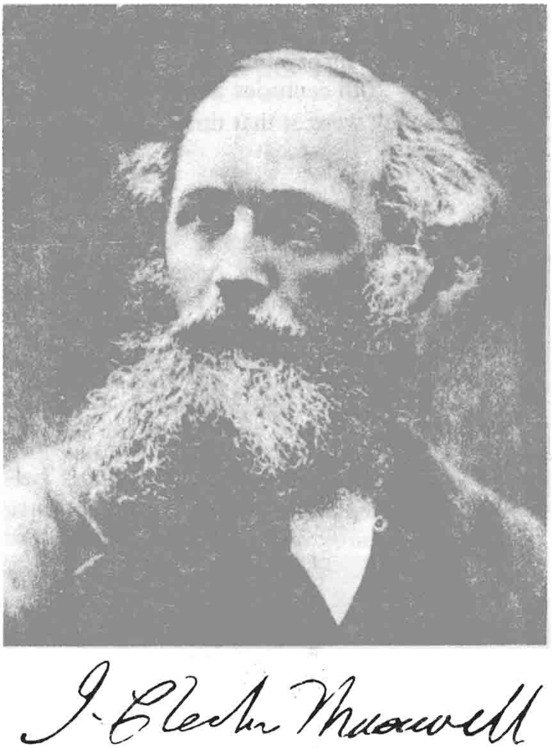
CAST OF CHARACTERS

The *dramatis personae* of fundamental physical theory during the late 19th and early 20th centuries are depicted as they were at that time.

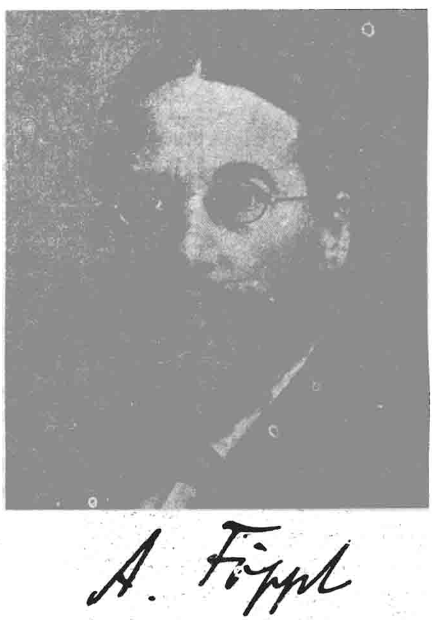
By 1911 many physicists agreed that Isaac Newton's mechanics, as well as his views of space and time, from the 1687 *Principia* had to be revised. Of Newton Einstein wrote, "You found the only way which, in your age, was just about possible for a man of highest thought and creative power." (Courtesy of AIP Niels Bohr Library)

Augustin Fresnel's deduction in 1818 of the dragging coefficient was one of the most important results of 19th-century optics. (From A. Fresnel, *Oeuvres*)

Michael Faraday's 1831 law of electromagnetic induction served as a cornerstone for theories of electromagnetism. In 1851 Faraday investigated a particular sort of electromagnetic induction—unipolar induction, whose explanation became a subject of intense research, particularly by engineers and scientists in German-speaking countries. By the end of the 19th century Faraday's law of induction had ushered the Western world into the age of technology. (Courtesy of AIP Niels Bohr Library/Argonne National Library)



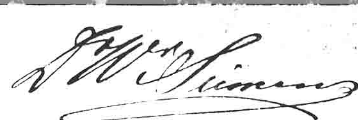
Newton's mechanics of 1687 had unified terrestrial and extraterrestrial phenomena. The next great synthesis occurred not quite 200 years later, during the 1860s, when James Clerk Maxwell unified electromagnetism and optics. (Courtesy of AIP Niels Bohr Library)



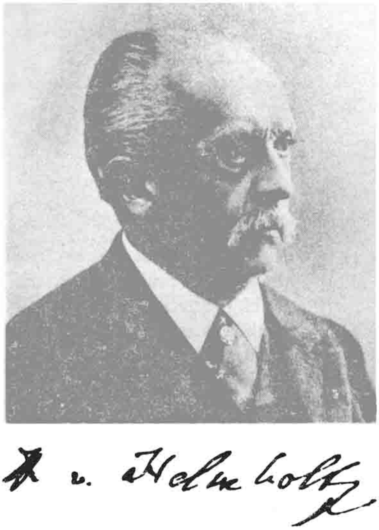
While a student at the ETH, Einstein learned a great deal about Maxwell's electromagnetic theory from independent study of August Föppl's text, *Einführung in die Maxwell'sche Theorie der Elektricität.* (From *Beiträge zur technischen Mechanik und technischen Physik, August Föppl* [Berlin: Springer-Verlag, 1924, courtesy of Springer-Verlag])

Although in 1895 Einstein failed the entrance examination to the ETH, Einstein's high scores on mathematics and physics led one of the school's illustrious professors, Heinrich Friedrich Weber, to encourage him to try again. By 1900 their relationship had deteriorated, owing chiefly to a clash of personalities. (From *Schweizerische Bauzeitung*)

Werner von Siemens was the great German industrialist and scientist who founded the vast Siemens electrical industries. In 1867 von Siemens discovered the principle of the electrical dynamo and, in that year, with the assistance of his friend Kirchhoff, designed and built the first unipolar dynamo. In 1886 von Siemens donated funds toward establishing an institute for science and engineering at the ETH, which was to be directed by another friend, Heinrich Friedrich Weber. Einstein studied at this institute during the period 1896–1900. (From W. von Siemens, *Personal Recollections*)

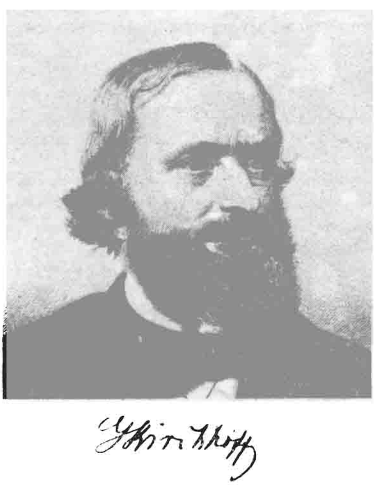


Hermann von Helmholtz, Ludwig Boltzmann, and Gustave Kirchhoff were three of the masters of physics that Einstein studied at home during his ETH period.



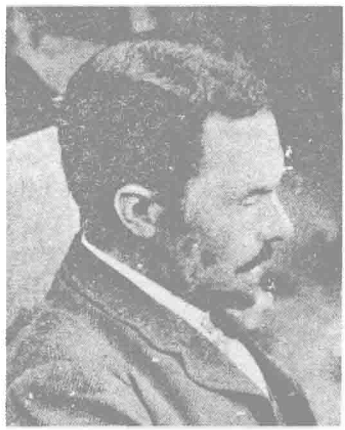
(From H. von Helmholtz, *Wissenschaftliche Abhandlungen* [Leipzig: Barth, 1895])

(From L. Boltzmann, *Gesammelte Schriften* [Leipzig: Barth, 1909], courtesy of J. A. Barth, Publishers)



(From G. Kirchhoff, *Gesammelte Abhandlungen* [Leipzig: Barth, 1882])

In 1888 Heinrich Hertz empirically verified an important prediction of Maxwell's electromagnetic theory—electromagnetic waves. Hertz's fundamental theoretical research on Maxwell's theory influenced both Lorentz and Einstein. (From H. Hertz, *Miscellaneous Papers*)

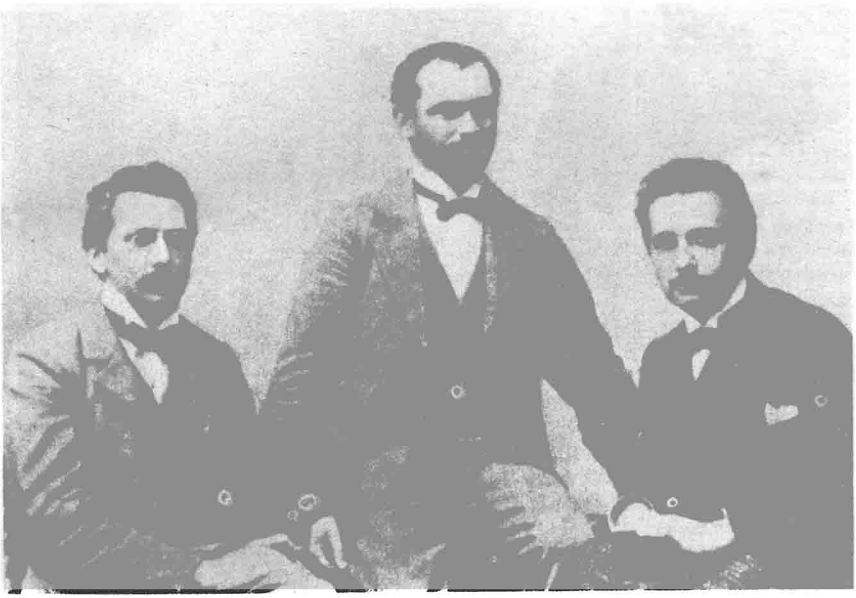


The British physicist and electrical engineer, Oliver Heaviside, calculated the electromagnetic fields originating from a charged body in uniform linear motion. These results were fundamental toward theoretical research on the velocity-dependence of the electron's mass. (From the Heaviside Centenary Volume, courtesy of Institution of Electrical Engineers)

Einstein admired greatly the "incorruptible skepticism" of the philosopher-scientist Ernst Mach. (Courtesy of AIP Niels Bohr Library/Burndy Library)

Henri Poincaré was France's greatest living mathematician and among the first ranks of scientists and philosophers. His philosophical position led him to resist Einstein's views of space and time. (Courtesy of AIP Niels Bohr Library)

This photograph depicts H. A. Lorentz circa 1890. Of Lorentz, Einstein wrote, "for me personally, he meant more than all the others I have met on my life's journey." (From H. A. Lorentz, *Collected Papers*, vol. 1, courtesy of Martinus Nijhoff, Publishers)

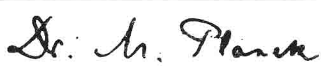


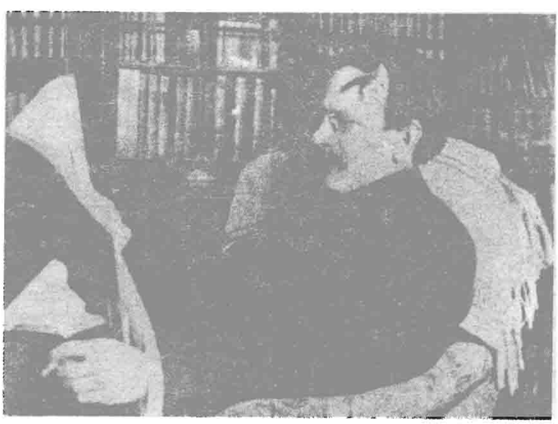
Conrad Habicht, Maurice Solovine, and Einstein were the charter members of the "Olympia Academy," which met informally in Bern during 1902–1904.

Marcel Grossmann's meticulous notes at the ETH permitted Einstein the luxury of cutting classes in order to study at home such subjects as Maxwell's electromagnetic theory. In 1902 Grossmann's father was instrumental in obtaining for Einstein a job at the Patent Office in Bern, and in 1912 Grossmann taught Einstein the mathematics necessary for Einstein's final push toward the 1915 generalized theory of relativity. (Courtesy of ETH Bibliothek, Zürich)

Michele Besso was Einstein's life-long friend. In the special relativity paper Einstein thanked Besso for "several valuable suggestions." (Courtesy of the AIP Niels Bohr Library/Besso Family)

Max Planck made two great discoveries in his lifetime—the quantum of energy and Albert Einstein. (Courtesy of AIP Niels Bohr Library/Burndy Library)





The photograph shows J. J. Thomson sitting in his study in a chair that had been used by Maxwell. Thomson's experiments at Cambridge University in the period 1897–1899 demonstrated conclusively that cathode rays were composed of negatively-charged "corpuscles," i.e., electrons. Lord Rayleigh wrote that Thomson's "attitude towards relativity was that of a looker-on." (From Lord Rayleigh, *The Life of Sir J. J. Thomson*, courtesy of Cambridge University Press)