1
INTRODUCTION

The Meaning of Relativity, also known as *Four Lectures on Relativity*, is Einstein's definitive exposition of his special and general theories of relativity. It was written in the early 1920s, a few years after he had elaborated his general theory of relativity. Neither before nor afterward did he offer a similarly comprehensive exposition that included not only the theory's technical apparatus but also detailed explanations making his achievement accessible to readers with a certain mathematical knowledge but no prior familiarity with relativity theory. In 1916, he published a review paper that provided the first condensed overview of the theory but still reflected many features of the tortured pathway by which he had arrived at his new theory of gravitation in late 1915. An edition of the manuscript of this paper with introductions and detailed commentaries on the discussion of its historical contexts can be found in *The Road to Relativity*.[1] Immediately afterward, Einstein wrote a nontechnical popular account, *Relativity—The Special and General Theory*.[2] Beginning with its first German edition, in 1917, it became a global bestseller and marked the first triumph of relativity theory as a broad cultural phenomenon. We have recently republished this book with extensive commentaries and historical contexts that document its global success. These early accounts, however, were able to present the theory only in its infancy.

Immediately after its publication on 25 November 1915, Einstein's theory of general relativity was taken up, elaborated, and controversially discussed by his colleagues, who included physicists, mathematicians, astronomers, and philosophers. Einstein himself also made further fundamental contributions to the development of his theory, exploring consequences such as gravitational waves and cosmological solutions, elucidating concepts such as that of the energy and momentum of the gravitational field, and even reinterpreting basic aspects of the theory. A turning point was the confirmation of the bending of light in a gravitational field, which, as predicted by general relativity, was observed during a solar eclipse in 1919. These were the *formative years* of relativity in which the theory essentially received the structure in which it later became one of the pillars of modern physics. *The Meaning of Relativity* is the paradigmatic text of this period, reflecting not only Einstein's own efforts but also the engagement of his contemporaries with the theory. Einstein evidently returned to the theory of relativity in many later publications, both specialized and popular. He later also enriched *The Meaning of Relativity* with appendixes discussing further developments. But he never made another attempt at such an all-encompassing presentation in which he painstakingly motivated, explained, and discussed its basic principles and their consequences.

In this book, we place *The Meaning of Relativity* in the context of the formative years of general relativity, which extended from 1915 until around the blossoming of quantum mechanics in the late 1920s and early 1930s, when more and more leading physicists turned their attention to this booming new field. This is the period when the basic ideas and principles of relativity theory crystallized and were refined, when the first solutions of the field equations were derived and analyzed, and when the cosmological consequences of the theory were debated. All of these events happened in the context of an expanding albeit fragile network of scientists who, at least for a certain time, became interested in the theory and enriched it with their contributions: from Hendrik Antoon Lorentz to Erwin Schrödinger, from Karl Schwarzschild to Willem de Sitter, from David Hilbert to Hermann Weyl, from Moritz Schlick to Hans Reichenbach. Einstein's text not only reflects the considerable maturation that the theory of general relativity had undergone since its creation, it also represents a key document of the scientific sociodynamics characterizing its formative years.

As a characteristic stage in the development of the theory, these formative years have, remarkably, received less attention from historians than subsequent periods, such as the "low-water-mark period" (Jean Eisenstaedt) immediately following it,[3] in which, also due to the Second World War, the fragile network mentioned above was partly destroyed and the general theory of relativity was perceived, with the exception of its cosmological implications, as a rather esoteric subject outside of mainstream physics. A "renaissance" (Clifford Will) of relativity would only come more than a decade after the war and in connection with new astrophysical discoveries in the 1960s, such as those of quasars.[4] Actually, as has recently been argued, the renaissance of general relativity had begun even earlier, essentially as the result of a community-building effort turning the theory into a universally applicable framework.[5] This revival was followed by what has been called the "golden age" (Kip Thorne) of relativity,[6] which witnessed new conceptual insights, such as those into the nature of spacetime singularities, and turned the theory into the foundation of modern astrophysics and observational cosmology.

Still, the advances made in the formative years were considerable. These years saw the further pursuit of the conceptual revolution that Einstein had started in 1907, when he first introduced the equivalence principle and began his search for a comprehensive theory describing both gravitation and inertia within a relativistic framework. At the end of 1915, he had found the field equations of this theory, but their meaning and implications were still far from being obvious. Scientific revolutions are hardly the result of a sudden paradigm shift in the sense characterized by the historian of science Thomas Kuhn.[7] The gravitational field theory published in November 1915 was the result of a laborious process that involved integrating the classical knowledge about gravitation embodied in Newton's theory with the relativistic concepts of space and time established by Einstein in 1905 in the context of what later came to be known as special relativity.

The profound conceptual and far-reaching technical consequences of the theory were, in this first moment, still unexplored territory. Even the extent to which the very principles that had formed Einstein's heuristic starting point were actually realized by the definitive formulation of the theory was not clear. The formative years thus saw—and this is one of the hallmarks of this period—a fundamental revision and reinterpretation of just these basic principles, including the relativity principle itself. In this process of revision, clarification, and reinterpretation, the theory became increasingly independent from the elements of classical physics that Einstein's impressive edifice had used as its scaffolding.[8]

More and more, general relativity became an autonomous conceptual framework in its own right. This process was not completed by the end of its formative years and still continues today. With the publication of *The Meaning of Relativity*, however, a turning point was reached, because Einstein's masterful exposition made it possible to study and understand the theory in its own right.

The Meaning of Relativity is based on the five lectures delivered by Einstein as the Stafford Little Lectures at Princeton University over five consecutive days, starting on 9 May 1921. The first two lectures, attended by large audiences, were popular accounts of the special and the general theory of relativity. The other three lectures were given to smaller audiences of scientists. The lectures were delivered in German. It was agreed from the outset that the lectures would be published according to the following plan:

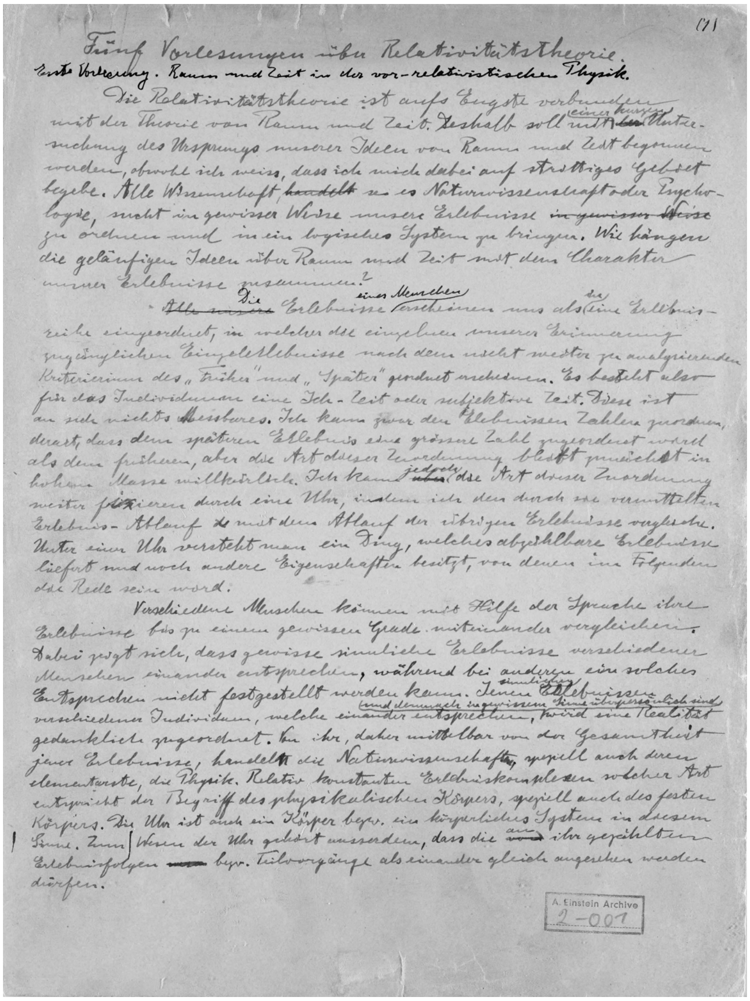
> A German stenographer is taking notes of the lectures as they are delivered. The plan of procedure is to have her write her notes out in German and then Professor Edwin P. Adams of the Department of Physics will go over them and check up those scientific portions which may have caused trouble. After Professor Adams has completed this part of the work, the lectures will be submitted to Professor Einstein for revision and final approval. When he has returned them, they will be translated into English and published.[9]

Each lecture was summarized orally in English by Professor Adams. These summaries were published on the days following each lecture in the *New York Evening Post* (the first four lectures) and in the *New York Times*. The extensive press coverage of these lectures demonstrates the great public interest generated by Einstein's visit to Princeton.

Between the beginning of September 1921 and early January 1922, Einstein summarized the Princeton lectures for publication. He produced a manuscript entitled "Four Lectures on the Theory of Relativity," which he submitted to his German publisher, Vieweg.[10] The manuscript is divided into five lectures, but in the published version the first two are combined into one. The first German edition was published in 1922, followed soon after by a second edition in 1923. The English translation by Edwin P. Adams, entitled *The Meaning of Relativity*, was published in London by Methuen in 1922 and then by Princeton University Press in 1923. Subsequent English editions, in which Einstein still had an input, appeared in 1945, 1950, 1953, and 1956.

Einstein's introduction to the first German edition, which was not reproduced in the English editions, reads:

> In the present elaboration of the four lectures I gave at Princeton University in May 1921, I wanted to summarize the principal thoughts and mathematical methods of relativity theory. In this I have made an effort to leave out everything that is less essential, but to treat the fundamentals in such a way that the whole may serve as an introduction for all those who master the elements of higher mathematics, but do not want to spend all too much time and effort on the subject. This short treatment evidently makes no pretense to completeness, in particular as I have not dealt with the more subtle, more mathematically interesting developments founded in variational calculus. My principal aim was to let the fundamentals in the entire train of thought of the theory emerge clearly.[11]



(1)

Fünf Vorlesungen über Relativitätstheorie.

Erste Vorlesung. Raum und Zeit in der vor-relativistischen Physik.

Die Relativitätstheorie ist aufs Engste verbunden mit der Theorie von Raum und Zeit. Deshalb soll mit einer kurzen Untersuchung des Ursprungs unserer Ideen von Raum und Zeit begonnen werden, obwohl ich weiss, dass ich mich dabei auf strittiges Gebiet begebe. Alle Wissenschaft, sei es Naturwissenschaft oder Psychologie, sucht in gewisser Weise unsere Erlebnisse zu ordnen und in ein logisches System zu bringen. Wie hängen die geläufigen Ideen über Raum und Zeit mit dem Charakter unserer Erlebnisse zusammen?

Die Erlebnisse eines Menschen erscheinen uns als in eine Erlebnisreihe eingeordnet, in welcher die einzelnen unserer Erinnerung zugänglichen Einzelerlebnisse nach dem nicht weiter zu analysierenden Kriterium des „Früher" und „Später" geordnet erscheinen. Es besteht also für das Individuum eine Ich-Zeit oder subjektive Zeit. Diese ist an sich nichts Messbares. Ich kann zwar den Erlebnissen Zahlen zuordnen, derart, dass dem späteren Erlebnis eine grössere Zahl zugeordnet wird als dem früheren, aber die Art dieser Zuordnung bleibt zunächst in hohem Masse willkürlich. Ich kann jedoch die Art dieser Zuordnung weiter fixieren durch eine Uhr, indem ich den durch sie vermittelten Erlebnis-Ablauf mit dem Ablauf der übrigen Erlebnisse vergleiche. Unter einer Uhr versteht man ein Ding, welches abzählbare Erlebnisse liefert und noch andere Eigenschaften besitzt, von denen im Folgenden die Rede sein wird.

Verschiedene Menschen können mit Hilfe der Sprache ihre Erlebnisse bis zu einem gewissen Grade miteinander vergleichen. Dabei zeigt sich, dass gewisse sinnliche Erlebnisse verschiedener Menschen einander entsprechen, während bei anderen ein solches Entsprechen nicht festgestellt werden kann. Jenen sinnlichen Erlebnissen verschiedener Individuen, welche einander entsprechen und demnach in gewissem Sinne überpersönlich sind, wird eine Realität gedanklich zugeordnet. Von ihr, daher mittelbar von der Gesamtheit jener Erlebnisse, handelt die Naturwissenschaft, speziell auch deren elementarste, die Physik. Relativ konstanten Erlebniskomplexen solcher Art entspricht der Begriff des physikalischen Körpers, speziell auch des festen Körpers. Die Uhr ist auch ein Körper bzw. ein körperliches System in diesem Sinne. Zum Wesen der Uhr gehört ausserdem, dass die an ihr gezählten Erlebnisfolgen bzw. Teilvorgänge als einander gleich angesehen werden dürfen.

A. Einstein Archive 2-001

FIGURE 1: The first page of the manuscript *Five Lectures on the Theory of Relativity*.

As mentioned above, in 1917 Einstein had published his book *Relativity—The Special and the General Theory (A Popular Account)*, through which he intended to make the basic ideas of the theory accessible to a general audience. Its introduction begins with a concise description of the book's aim:

> The present book is intended, as far as possible, to give an exact insight into the theory of relativity to those readers who, from a general scientific and philosophical point of view, are interested in the theory, but who are not conversant with the mathematical apparatus of theoretical physics.[12]

In his Princeton lectures, in contrast, Einstein intended to present these ideas in a coherent fashion to the scientists "who master the elements of higher mathematics."[13]

In our view, however, this is not the most important difference between these two canonical texts. What is more important is that there is a five-year interval between them. During these years, in extensive correspondence with colleagues and in several publications on the fundamental questions and ideas of the theory of relativity, Einstein responded to critical remarks and participated in debates about the physical and cosmological implications of general relativity. As a consequence, *The Meaning of Relativity* includes new formulations of the basic principles and ideas and a change of emphasis on specific issues. It represents a significantly more advanced stage in the development of general relativity, in the understanding of its implications, and in the reception of the theory by the scientific community.

In this book, we trace the roots of these developments in the contemporary research of Einstein and others, and at the same time we comment on how these developments are reflected in Einstein's text, with the aim of making it accessible to modern readers in a new way, as the key document of these formative years.

The book is divided into four parts. Following this introduction, chapter 2 in part I sets the historical context for Einstein's visit to Princeton in May 1921. Chapter 3 of this part discusses the structure and content of his book. Then, in part II, we offer a detailed portrait of the formative years of general relativity. In part III, Einstein's text is reproduced together with the appendixes.

Each of the chapters of part II analyzes a specific dimension of this historical period and at the same time serves as a reading aid to Einstein's book, describing the relevant developments in his thinking and how they are reflected in his text. Our commentaries do not aim to explain Einstein's text, which has remained one of the most lucid expositions of his theory to this day. We instead focus on those issues that will set *The Meaning of Relativity* into the historical context of what we have called the formative years. Occasionally, we also point to advances that were still to come in later periods of the development of general relativity. While Einstein's text employs mathematical formulas to explain his theory, our historical commentaries are aimed at a wider audience and endeavor to present the relevant concepts and developments without using such formalism, making them more broadly accessible.

Chapter 1 of part II deals with the ongoing debate about the meaning of Einstein's theory in the formative years, with particular attention to the relation between physics and geometry. Einstein himself devoted major interpretational efforts to this theme, as in his famous paper "Geometry and Experience" or in his musings about the role of the ether concept in the theory of general relativity. This chapter also compares Einstein's thinking on this issue with that of the French mathematician and philosopher Henri Poincaré and deals with the role of symmetry in the theory of relativity, one of Einstein's enduring legacies. The role of symmetry becomes evident, for instance, in the lecture on special relativity, in which it is shown how relativistic invariance, a symmetry property of the spacetime continuum, shapes Maxwell's equations and other laws of physics. In the period under consideration, the understanding of symmetry is deepened by the emergence of Emmy Noether's famous theorems, for which the theory of general relativity was an important source of inspiration.

Chapter 2 of part II deals with the question of what the theory actually achieved and specifically reexamines the meaning of the relativity principle. This question of its meaning was raised by critical observers whose comments led to a partial reinterpretation of general relativity. The German physicist Erich J. Kretschmann argued that the principle of general covariance has no physical content and only constitutes a mathematical requirement. This contention generated an exchange of letters in which Einstein conceded Kretschmann's criticism, but Einstein does not mention Kretschmann's remarks explicitly in his book. We shall discuss these developments and correlate them with his correspondence with colleagues and with other texts he published during the formative years.

The formative years also saw a first wave of the exploration of exact solutions to Einstein's gravitational field equations, beginning with the work of Karl Schwarzschild, Johannes Droste, Willem de Sitter, Alexander Friedmann, Hans Reissner, Gunnar Nordström, and Georges Lemaître, which is discussed in chapter 3.

Chapter 4 deals with the early exploration of observational and experimental consequences of general relativity, ranging from Erwin Freundlich's failed attempts to verify gravitational light bending and the redshift to the triumphal confirmation of light bending during a solar eclipse by Arthur Eddington's expedition, and finally to Hubble's discovery of the redshift of distant galaxies, which established the notion of an expanding universe.

Chapter 5 highlights the background for the emergence of relativistic cosmology. A specific interpretational issue, which is treated in this context, is the role of Ernst Mach's principle and the first exploration of the cosmological consequences of general relativity. Here Einstein's main interlocutor was the Dutch astronomer Willem de Sitter. But during the years 1916 to 1918, Einstein also exchanged letters with the mathematicians Hermann Weyl and Felix Klein. This correspondence has been referred to as the Einstein–de Sitter–Weyl–Klein debate. This debate not only focused on specific cosmological models but also helped to clarify the meaning of such fundamental issues as coordinates and energy-momentum conservation in the theory. The discussion of cosmology in the final Princeton lecture is influenced by this debate. This chapter also addresses the appendix "On the Cosmological Problem," which was added to the second English edition in 1945. It emphasizes the implications of Hubble's discovery.

Chapter 6 addresses one of the key themes of modern general relativity: gravitational waves. In 1916 Einstein performed the first relevant calculations, including a first derivation of the celebrated quadrupole formula, which, however, contained a mistake that he corrected in 1918. The corrected formula became the basis for the long-term search and the first observational verification of these waves. These calculations provoked a discussion about the reality of these waves, which continued well into the 1950s and beyond. This is the only major topic debated during the formative years that has no trace in *The Meaning of Relativity*. Had we restricted our commentaries to the contents of Einstein's book, there would be no reason to mention gravitational waves; however, it would be inconceivable to talk about the formative years without thoroughly discussing them. What is worth emphasizing in this context is how Einstein's predominant interest in this phenomenon, which developed immediately after the completion of his general theory, had faded away completely by the time he delivered the Princeton lectures.

Chapter 7 addresses the philosophical debate surrounding general relativity in its formative period, from Einstein's own writings on methodological and epistemological aspects of the theory to the first reactions by philosophers such as Moritz Schlick, Ernst Cassirer, and Hans Reichenbach. The focus is on the philosophical investigations clarifying and reinterpreting the conceptual foundations of general relativity.

In the formative years, starting with David Hilbert in 1915 and culminating in the works of Hermann Weyl, Theodor Kaluza, Oskar Klein, Arthur Eddington, and of course Einstein himself, general relativity was often seen as a partial or incomplete theory to be generalized, encompassed, or superseded by an overarching unifying theory that would also explain the constitution of matter, typically by including gravity and electromagnetism. Chapter 8 is dedicated to the contemporary debates of this issue and Einstein's role in it. Specifically, the chapter addresses the question of *why* general relativity was perceived to be an incomplete theory by many contemporary scientists, including Einstein himself. It will also discuss the second appendix, entitled "Generalization of Gravitation Theory," which Einstein added to the third edition of *The Meaning of Relativity*. This appendix was modified in subsequent editions, and its last version was entitled "Relativistic Theory of the Non-symmetric Field." It reflects Einstein's struggle in his search for a unified field theory, which in the last ten years of his life was based on the notion of a non-symmetric metric. We reproduce here the last two versions of this appendix, which are included in the fourth and the fifth editions.

Chapter 9 discusses the emergence of a tradition of writing textbooks on relativity and of teaching the subject. How did practitioners and students of relativity learn the theory and what were the different modes of access to it? Around 1920, in addition to Einstein's books and articles, a series of influential monographs and textbooks appeared, including those of Hermann Weyl, Wolfgang Pauli, Max Born, Max von Laue, and Arthur Eddington. We will compare these different presentations and analyze their influence on the later development of the theory. Alongside these monographs, which advanced the progress of scholarship in this new and expanding field, there was also an extensive anti-relativity literature. It can easily be discarded today as physical misunderstanding, as a trend serving the goals of rising nationalism in Germany, or as pure anti-Semitism. Nevertheless, that literature was part of the formative years and cannot be ignored in the present discussion as it also reflects on the broader social dynamics of the reception of the theory. Chapter 10 offers an outlook on the further transformations of Einstein's theory after the formative years.

Part IV of this book is dedicated to the first two popular lectures Einstein delivered in Princeton, which were not included in the published version. Chapter 1 offers an introductory commentary, while chapter 2 reproduces the extant text of these two lectures. These lectures have never before been published in English.

Because the formative years were a period in which the advancement of general relativity was furthered by Einstein's exchange with an ever-wider circle of physicists, astronomers, mathematicians, and philosophers who had become interested in his work, we will devote, in part V, biographical notes to some of Einstein's outstanding interlocutors of this period, among them Willem de Sitter, Felix Klein, Hendrik Lorentz, Hermann Weyl, Moritz Schlick, Hans Reichenbach, Ernst Cassirer, Gunnar Nordström, Gustav Mie, and Erich Kretschmann. Taken together, they illustrate that general relativity was maturing also in the sense that it was now becoming a community effort, even if this early community still remained fragile. The fervent debates and exchange of ideas are best reflected in the extensive correspondence between Einstein and its key players. To demonstrate the dynamics of these interactions, we frequently quote from this correspondence. In addition, we include as inserts or boxes in the main text brief explanations of basic concepts. We also reproduce historical documents such as newspaper articles or letters that illustrate the historical context of Einstein's Princeton lectures and their role as a pivotal moment in the history of modern physics.

NOTES

1. Gutfreund and Renn, *Road to Relativity*.
2. A centennial edition of this text with extensive commentaries is now available: Gutfreund and Renn, *Relativity: The Special and the General Theory*.
3. Jean Eisenstaedt, "The Low Water Mark of General Relativity, 1925–1955," in *Einstein and the History of General Relativity*, ed. D. Howard and J. Stachel (Boston: Birkhäuser, 1989), pp. 277–292.
4. Clifford Will, "The Renaissance of General Relativity," in *The New Physics,* ed. P. Davies (Cambridge: Cambridge University Press, 1989), pp. 7–33.
5. See Alexander Blum, Roberto Lalli, and Jürgen Renn, "The Reinvention of General Relativity: A Historiographical Framework for Assessing One Hundred Years of Curved Space-time," *Isis* 106 (2015): 598–620; and Alexander Blum, Roberto Lalli, and Jürgen Renn, "The Renaissance of General Relativity: How and Why It Happened," *Annalen der Physik* 528 (2016): 344–349; Alexander Blum, Domenico Giulini, Roberto Lalli, Jürgen Renn (eds.), "The Renaissance of Einstein's Theory of Gravitation," Special Issue *EPJ H,* 2017. See also Bernard F. Schutz, "Thoughts about a Conceptual Framework for Relativistic Gravity," in *Einstein and the Changing Worldviews of Physics*, ed. C. Lehner, J. Renn, and M. Schemmel (New York: Birkhäuser, 2012), pp. 259–269.
6. Kip S. Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: Norton, 1994), pp. 258–299.
7. Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago IL: University of Chicago Press, 1962).
8. See Michel Janssen and Jürgen Renn, "Arch and Scaffold: How Einstein Found His Field Equations," *Physics Today* 68 (November 2015): 30–36.
9. *Princeton Alumni Weekly*, 11 May 1921, pp. 713–714.
10. Albert Einstein, *Vier Vorlesungen über Relativitätstheorie* (Braunschweig: Vieweg, 1922).
11. CPAE vol. 7, p. 499 (German version) Translation by the authors.
12. Gutfreund and Renn, *Relativity: The Special and the General Theory*, p. 10.
13. See n. 11 above.