The Genesis of General Relativity

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The Genesis of General Relativity
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Volume 1

EINSTEIN'S ZURICH NOTEBOOK: INTRODUCTION AND SOURCE

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JÜRGEN RENN

PREFACE

The transition from classical to modern physics in the first half of the twentieth century by quantum and relativity theories affected some of the most fundamental notions of physical thinking, such as matter, radiation, space, and time. This transition thus represents a challenge for any attempt to understand the structures of a scientific revolution. The present four-volume work aims at a comprehensive account of the way in which the work of Albert Einstein and his contemporaries changed our understanding of space, time, and gravitation. The conceptual framework of classical nineteenth-century physics had to be fundamentally restructured and reinterpreted in order to arrive at a theory of gravitation compatible with the new notions of space and time established in 1905 by Einstein's special theory of relativity.

Whereas the classical theory of gravitation postulated an instantaneous action at a distance, Einstein's new relativistic kinematics rather suggested an analogy between the gravitational field and the electromagnetic field, propagating with a finite speed. It is therefore not surprising that Einstein was not alone in addressing the problem of formulating a theory of gravitation that complies with the kinematics of relativity theory. The analysis of these alternative approaches, as well as of earlier alternative approaches to gravitation within classical physics, turns out to be crucial for identifying the necessities and contingencies in the actual historical development.

It is the profound conceptual transformation associated with the establishment in 1915 of a relativistic theory of gravitation that shows that the genesis of this theory, Einstein's general theory of relativity, was a genuine scientific revolution in its own right. The restructuring and reinterpretation of the fundamental concepts of classical physics involved in the development of the theory was a long and complicated process with far-reaching consequences. First of all, the new concepts had to be presented and transmitted to a wider scientific community. The new theory also created the need to reconsider all branches of physics in light of its new concepts and to look for possible experimental confirmation. It gave rise to new conceptual problems and new research programs, such as finding a unified field theory and integrating general relativity with quantum theory. Finally, the revision of the concepts of space and time by general relativity had a considerable impact on epistemological and philosophical discussions, attracting the attention of a non-specialized public and placing relativity theory and its creator at the focus of public discussion.

Einstein's path towards establishing the general theory of relativity has been an important topic in the history of twentieth-century physics. Our reconstruction of his

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unpublished research notes and our examination of the broader intellectual context of the relativity revolution has led to a reassessment and a deeper understanding of this process as a transformation of a comprehensive system of knowledge. These volumes document the results of a joint effort at an in-depth analysis of a scientific revolution undertaken by a group of scholars over more than a decade. The aim was to reach a systematic understanding of both the knowledge base in classical physics that formed the point of departure for Einstein and his contemporaries and the nature of the process through which their research eventually overcame some of the conceptual foundations of classical as well as special-relativistic physics.

For this purpose, it was necessary to cover not only Einstein's individual pathway towards general relativity, but also other approaches to the problem of gravitation before and after the advent of special relativity. The aim was to reach an assessment of the "horizon of possibilities" of reacting to the crisis provoked by the conflict between the understanding of gravitation in classical physics and the challenge presented by the special theory of relativity. The horizon of possibilities is determined by the shared knowledge available to the historical actors. The reconstruction of this shared knowledge and its transformation is based on new approaches for describing the architecture of knowledge and for explaining its developmental dynamics, including the interaction between collective and individual processes.

We have thus attempted to provide a broader context to the reconstruction of Einstein's singular achievement. We surveyed the approaches to the problem of gravitation that existed in late classical physics, to examine the intellectual resources on which the different approaches relied, to determine the extent to which they were adequate to the task of responding to the crisis of classical physics, to explore alternative pathways that could have been but were not realized, and finally to evaluate the reasons why Einstein's general relativity eventually came to be accepted as the resolution of the crisis. The results of our reconstruction are documented in the form of detailed commentaries on the historical sources and in the form of new interpretations of the early history of general relativity.

The four volumes of this work comprise two sets. The first two volumes are dedicated to general relativity in the making, that is, to a detailed reconstruction of the research that led Einstein from special to general relativity in the years between 1907 and 1915. At the center of this reconstruction is the detailed "Commentary" on a key document written between 1912 and 1913, Einstein's so-called "Zurich Notebook." In the first volume this notebook is presented in its entirety for the first time. It is reproduced in facsimile accompanied by a new transcription. The second volume presents the comprehensive "Commentary" so that the reader may directly relate interpretation and historical source. The first two volumes furthermore comprise essays on the development leading up to the period documented in the notebook, assessments of the work documented by the notebook itself, and an analysis of the conclusive period of Einstein's search for the gravitational field equation. Taken together, the work assembled in these two volumes offers an encompassing view of Einstein's contributions to the genesis of general relativity.

The second set of two volumes is dedicated to theories of gravitation in the twilight of classical physics in a more general sense. In this part of the work, alternative approaches to the problem of gravitation around the time of Einstein's work are reviewed in terms of interpretative essays and English translations of key sources. The third volume deals with the tensions between the tradition of mechanics, the canonical place of the problem of gravitation, and the newly established tradition of field theory that raised expectations for a novel solution to this problem. These expectations were then strengthened by the advent of special relativity and led to an intense discussion about a relativistic theory of gravitation that forms the other nucleus of this volume. The fourth volume takes a closer look at possibilities for the establishment of a theory like general relativity along pathways that differed from Einstein's in that they employed more sophisticated mathematical means. The volume thus covers both a reassessment of David Hilbert's work and the suggestion of a fictive but historically plausible scenario for such an achievement.

The work presented in these volumes was originally pursued in the context of the *Arbeitsstelle Albert Einstein*, directed by Peter Damerow and myself, funded by the Senate of Berlin from 1991 to 1996, and hosted by the Max Planck Institute for Human Development and Education, at the Center for Development and Socialization headed by Wolfgang Edelstein. I am deeply grateful to the Berlin Senate, in particular to the former Senator of Science, Barbara Riedmüller, as well as to the former Senate Director, Jochen Stöhr, for the courageous and generous decision to support this unusual initiative, which aimed at exploring Einstein's scientific achievements in their intellectual, cultural, and political contexts. Under the auspices of Wolfgang Edelstein it has served in many ways as a pioneering venture for the foundation in 1994 of the Max Planck Institute for the History of Science. In addition to the collaborators of the *Arbeitsstelle*, Giuseppe Castagnetti, Werner Heinrich, and Tilman Sauer, members of its international scientific advisory board, Hubert Goenner, Michel Janssen, Karl von Meyenn, John D. Norton, Karin Reich, Erhard Scholz, and John Stachel, participated in one way or another in the research process – either by providing helpful comments or by engaging directly in joint projects.

In this way, the *Arbeitsstelle Albert Einstein* soon developed into a meeting point for an international group of scholars working on the history of general relativity and the locus of an unusual cooperation involving both senior experts in the field and young researchers, which continued later at the Max Planck Institute for the History of Science. These meetings involved the core group of authors of the first two volumes as well as the other members of the *Arbeitsstelle* and members of its board. In addition to the names already mentioned, Dieter Brill, Ulrich Majer, James Ritter, David Rowe, Matthias Schemmel, and Dirk Wintergrün also contributed at some point to our co-operation. The innumerable meetings and workshops were unique in their collaborative search for an interpretation of historical sources, with key ideas emerging from lively debate. In a lengthy process, the detailed protocols of these meetings were filtered, reworked, elaborated and reformulated to yield the "Commentary" which constitutes the most distinct outcome of the collective work. In this way, the core group worked together to analyze the sources and reconstruct the knowledge resources that are relevant for understanding the research documented in Einstein's notebooks, his publications, and correspondence. Following ground-breaking papers by John Stachel, John D. Norton, and a few other scholars, the continued investigation and reconstruction of Einstein's discovery process has led to many new insights, among them the identification of two distinct heuristic strategies in this discovery process, a physical and a mathematical strategy. This identification proved to be a breakthrough and an important interpretative tool for understanding Einstein's search for the gravitational field equation, even beyond the phase documented by the Zurich notebook. Our analysis has shed new light on the complex process of interaction between mathematical representation and the construction of physical meaning, a process of crucial importance also in other areas and periods of the history of science. Such epistemological insights were only possible because our joint work was not confined to a painstaking analysis of the historical sources in a traditional sense, but also comprised unusual approaches such as reconstructing the architecture of the shared knowledge at his disposal and actually retracing in detail Einstein's research process in a particular phase of his work. For the epistemological dimension of our discussions and for wider perspectives, the intense participation of Peter Damerow in our research endeavor turned out to be critical. He helped us wherever he could from falling into the traps of specialization and placed our work within the larger framework of a history of knowledge.

As work progressed, it quickly became clear that the clarification reached by deciphering Einstein's research notes from the period 1912–1913 would have serious consequences for our understanding the genesis of general relativity in its entirety. The Zurich Notebook shows that in 1912–1913 Einstein had already come within a hair's breadth of the final general theory of relativity. He failed, however, to recognize the physical meaning of his mathematical results, and turned to the alternative, physical strategy. Eventually he published, jointly with the mathematician Marcel Grossmann, the "erroneous" *Entwurf* ("outline") theory of 1913. Much of our work therefore focused on the question of how Einstein, in the period between 1913 and 1915, was able to overcome the obstacles which at first prevented him from realizing that the correct ansatz was the one obtained in his notebook and not the theory he published in 1913. The answer we found to this question led to the surprising insight that, contrary to what was commonly accepted, the long interval between the publication of the erroneous field equation and the return to the correct equation at the end of 1915 was not simply a period of stagnation. It was rather a period during which Einstein arrived at a number of insights that created the crucial preconditions that made the dramatic events of November 1915 possible. This result made it evident that the establishment and stabilization of the new physical concepts that emerged with general relativity first required an integration of further physical knowledge and a degree of elaboration of the mathematical formalism that went well beyond finding the correct field equation.

Another complementary line of research was, as mentioned above, dedicated to the study of other theories of gravitation before and after the advent of special relativity. In order to identify knowledge traditions that contributed to the emergence of general relativity, the scientific context of Einstein's search for a new theory of gravitation was systematically studied by analyzing a broad range of sources related to the work on alternative approaches, including also the work of less well-known authors.

I am particularly grateful to Michel Janssen who throughout the intricate research and production process leading to these volumes never hesitated to take up whatever challenges arose. He took the main responsibility for bringing the "Commentary," the core of the first two volumes, into the form it is presented here and also helped with critical acumen to sharpen the focus and improve the presentation of other contributions. Matthias Schemmel, who co-edited volumes three and four, and Lindy Divarci, assistant editor of all four volumes, played an essential role in coordinating this extended network of scholarly cooperation. Together with the associate editors, Christopher Smeenk and Christopher Martin, they carefully edited the various contributions, unified and improved the translations of original sources, checked and complemented the bibliographic references, and contributed in many other ways to providing a comprehensive resource for studying the early history of general relativity in context. They were assisted in their editorial work by Heinz Reddner, Stefan Hajduk, Yoonsuhn Chung, Miriam Gabriel, and Shaul Katzir.

The long-term cooperation required to produce the comprehensive analysis of the genesis of general relativity presented in this work was only possible due to the persistent institutional support provided by the Max Planck Society, first at the Max Planck Institute for Human Development and Education and, since its foundation in 1994, at the Max Planck Institute for the History of Science; additional support came from the Archive of the Max Planck Society and its director, Eckhart Henning. The close and ever reliable cooperation with other institutions, in particular with the Albert Einstein Archives at the Hebrew University of Jerusalem and its former Curator Ze'ev Rosenkranz and the Einstein Papers Project at the California Institute of Technology and its former director Robert Schulmann as well as its current director Diana Buchwald, were of great help in the completion of this ambitious project. The authors and editors are particularly grateful for the generous permission to reproduce or quote from Einstein's original documents. Other institutions and individuals offered their generous support as well, either in securing the documentary basis for our enterprise or helping in other ways, among them the Albert Einstein Institute (Max Planck Institute for Gravitational Physics), the Cohn Institute for the History and Philosophy of Science and Ideas at Tel Aviv University, the Institut für Zeitungsforschung, Dortmund, the Manuscript Department of the Staatsbibliothek zu Berlin, the Special Collections Department at the Library of the of the Swiss Federal Institute of Technology Zurich (ETH), the Niedersächsische Staats- und Universitätsbibliothek Göttingen (Manuscripts and Early Imprints Collection) and its director Helmut Rohlfing, the Mathematical Institute at the University of Göttingen, the Federal Archives in Koblenz, the National Science Foundation, the Istituto e Museo di

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The volumes appear in sequel to the International Year of Physics and the Einstein Year 2005, celebrating the centenary of Einstein's *annus mirabilis* and the overturn of the classical concepts of space and time. They propose an in-depth historical analysis of the consequences of this revolution for our understanding of gravity and, at the same time, of the structures of a scientific revolution that can be documented in an exceptionally comprehensive way. Yet the scope of the scientific revolution associated with Einstein's name goes well beyond the intellectual work on a new theory of gravity. Its full understanding also requires an analysis of other aspects such as Einstein's contributions to quantum theory or the role of cultural, technological, personal, and political contexts that could only be touched upon in these volumes. They are more amply treated in other publications, among them the three-volume survey *Albert Einstein – Engineer of the Universe* of Wiley-VCH associated with the exhibition of the same title, the *Einstein Companion* of Cambridge University Press, as well as a forthcoming book on the institutional contexts of the emergence of quantum theory to appear in this series, all of them emerging from the same context of collaboration that has made the present work possible. As research on Einstein's revolution of science is still in progress, parts of these volumes are, together with additional sources and interpretative documents and tools, accessible also via the Internet <http://einstein-virtuell.mpiwg-berlin.mpg.de/intro>.

MICHEL JANSSEN, JOHN D. NORTON, JÜRGEN RENN,
TILMAN SAUER, AND JOHN STACHEL

INTRODUCTION TO VOLUMES 1 AND 2: THE ZURICH NOTEBOOK AND THE GENESIS OF GENERAL RELATIVITY

When Albert Einstein died in April 1955, he left a small notebook among his many papers at the Institute for Advanced Study in Princeton. Its faintly gridded pages are covered with calculations. Some are tidy and unhurried. Others are hasty and incomplete. Some are annotated with a cryptic remark; others are unadorned. Some halt with a fragmented formula; others proceed mechanically to their conclusion. They come from another time and place, a silent trace of strenuous work from decades earlier and a continent away.[1]

Most of the calculations in this notebook date from the winter of 1912–1913. In August 1912 Einstein had left Prague, where he had taught for a year and a half, to become a full professor at his *alma mater*, the *Eidgenössische Technische Hochschule* (ETH) in Zurich. This is why the notebook is known among Einstein scholars as the Zurich Notebook. The bulk of it is devoted to a new theory of gravity, in which the ten components $g_{\mu\nu}$ of the metric tensor field encode the geometry of spacetime and double as the potentials of the gravitational field. Many of the end results of the investigations recorded in the notebook were published in the spring of 1913 in a paper Einstein co-authored with Marcel Grossmann, professor of mathematics at the ETH and one of his former classmates. The paper consists of two parts, a physical part written by Einstein, and a mathematical part written by Grossmann. The title modestly announces an “Outline [*Entwurf*] of a Generalized Theory of Relativity and a Theory of Gravitation” (Einstein and Grossmann 1913). Einstein continued to work on this *Entwurf* theory, as it is generally known in the historical literature, for the next couple of years, initially with Grossmann (see Einstein and Grossmann 1914b) and with Michele Besso, another friend from his college days. With Besso he investigated whether the new theory could account for the anomalous advance of the perihelion of Mercury, a well-known problem in Newtonian gravitational theory. They found that it

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[1] In 1982, the notebook, together with Einstein’s other papers, was shipped from Princeton to Jerusalem, where it is now part of the Einstein Archives at Hebrew University (CPAE 1, Publisher’s Foreword). Its call number is 3-006. A high-quality scan of the notebook is available electronically at the Einstein Archives Online (www.alberteinstein.info).

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could not.[2] These collaborations ceased in the spring of 1914, when Einstein moved to Berlin to become a salaried member of the *Preußische Akademie der Wissenschaften*. In the fall of 1914, he published a lengthy article intended as the authoritative, systematic exposition of the new theory. Its title, “The Formal Foundation of the General Theory of Relativity” (Einstein 1914), stands in marked contrast to the tentative title of the original Einstein-Grossmann paper. A year later, however, Einstein’s confidence crumbled. In a series of four communications to the Prussian Academy in November 1915, he replaced the centerpiece of the *Entwurf* theory, a set of gravitational field equations of severely restricted covariance, by field equations of broad and ultimately general covariance, solving the problem of Mercury’s perihelion in the process (Einstein 1915a, 1915b, 1915c, 1915d).[3] Einstein had thus arrived at the general theory of relativity, the crowning achievement of his career. He consolidated the theory over the next few years. In March 1916, he replaced the premature review article of 1914 by a detailed and self-contained exposition of the new theory (Einstein 1916a). He subsequently applied general relativity to new problems—such as gravitational waves (Einstein 1916b, 1918a) and cosmology (Einstein 1917)—and clarified its foundations (Einstein 1916c, 1917, 1918b, 1918c).[4]

As our joint commentary on the notebook makes clear, the material in the Zurich Notebook holds the key to understanding many aspects of these later developments. To facilitate reading the commentary in conjunction with the notebook itself, we placed the commentary at the beginning of volume two and a facsimile reproduction and a transcription of the notebook at the end of volume one.[5] A number of essays, which make up the balance of the volumes, fill in the background to the research documented in the notebook and address the ramifications of our analysis of the notebook for the reconstruction of the further development of the *Entwurf* theory and the transition to the theory of 1915. These essays are written in such a way that they can be read independently of the commentary and of each other.

The analysis of the notebook was quite a challenge. The notebook consists of working notes and was never intended to be read by others. Its one intended reader needed no narrative to explain the goals and presuppositions of the calculations, their successes and failures, the puzzlements and the triumphs. These would have been all too apparent to Einstein’s eyes. They were not to ours. Our commentary reflects our best effort to understand Einstein’s calculations and to supply some of the connective

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[2] See CPAE 4, Doc. 14 and the editorial note, “The Einstein-Besso Manuscript on the Motion of the Perihelion of Mercury,” on pp. 344–359. For a popular account, see (Janssen 2003). For a history of the perihelion problem, see (Roseveare 1982).

[3] The demise of the *Entwurf* theory and the subsequent developments are detailed in Einstein to Arnold Sommerfeld, 28 November 1915 (CPAE 8, Doc. 153). For analysis of (Einstein 1915c) on the perihelion problem, see (Earman and Janssen 1993).

[4] For a concise history of Einstein’s struggles with the conceptual basis of his theory and further references to the extensive literature on these topics, see (Janssen 2005).

[5] Although the commentary only covers the notes on gravity, facsimiles and transcriptions of notes on other topics are also included. Insights from the analysis of the non-gravitational part of the Zurich Notebook were used in (Büttner et al. 2003).

tissue that he left out. We have reconstructed, as best we can, the content, goals and strategies of the calculations, usually on a line-by-line basis, sometimes even symbol by symbol.

Such efforts cannot hope to recover in full detail what transpired as Einstein made these entries in his notebook. Yet the relative completeness of many of the calculations and the apparent clarity of purpose repeatedly allowed us to discern simple and coherent content in pages that initially looked baffling and disjointed. In another context, Einstein often remarked on a problem not altogether different from the one we faced. Physical theories, he remarked, cannot be deduced from sensory experience. There remains considerable freedom of choice in the concepts and propositions one devises to account for experience. What makes stable theorizing possible is the restricted character of this freedom:

> The liberty of choice, however, is of a special kind; it is not in any way similar to the liberty of a writer of fiction. Rather, it is similar to that of a man engaged in solving a well-designed [cross]word puzzle. He may, it is true, propose any word as the solution; but, there is only *one* word which really solves the puzzle in all its parts (Einstein 1936, 294–295).[6]

Our experience with the Zurich Notebook has been similar. For any given page, one can propose many interpretations. However, when the calculation is relatively complete, and when it connects naturally with other pages, the majority of interpretations fail to solve the puzzle.[7] As readers of the commentary will find, our solution is incomplete in places. It is, however, much more complete than any of us dared hope at the outset. The portions that remain obscure are much smaller than those we now read with clarity. The notebook is open to a new readership.

We should make it clear that we did not have to start from scratch. Norton (1984) had already deciphered several key pages of the notebook before we joined forces. More generally, we drew on research done at the *Einstein Papers Project*[8] and on various studies of the history of general relativity. Many of these were presented at the *History of General Relativity* (HGR) conference series and published in several volumes of the series *Einstein Studies*.[9] Both series were inaugurated by the Nestor of our group, Stachel, who is also the founding editor of the Einstein edition. The anno-

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[6] The handwritten German original has: “Mit dieser Freiheit ist es aber nicht weit her; sie ist nicht ähnlich der Freiheit eines Novellen-Dichters sondern vielmehr der Freiheit eines Menschen, dem ein gut gestelltes Worträtsel aufgegeben ist. Er kann zwar jedes Wort als Lösung vorschlagen, aber es ist wohl nur eines welches das Rätsel in allen Teilen wirklich auflöst” (Einstein Archives, 122–858).

[7] In the course of our collaboration, we hit upon what we have dubbed the “chicken scratch rule”: to inspire confidence, a proposed reconstruction should account for every last scratch on the page.

[8] All five of us were involved in one way or another with the publication of the relevant Vols. 4 through 8 of *The Collected Papers of Albert Einstein* (CPAE), which appeared between 1993 and 2002.

[9] (Howard and Stachel 1989) for HGR1 at Osgood Hill (1986) [Don Howard and Stachel are also the series editors for *Einstein Studies*]; (Eisenstaedt and Kox 1991) for HGR2 in Luminy (1988); (Earman, Janssen, and Norton 1993) for HGR3 in Johnstown (1991); (Goenner, Renn, Ritter, and Sauer 1999) for HGR4 in Berlin (1995); and (Kox and Eisenstaedt 2005) for HGR5 at Notre Dame (1998) and HGR6 in Amsterdam (2002). A volume for HGR7 in Tenerife (2005) is in preparation.

tation of the gravitational part of the Zurich Notebook in CPAE 4, which appeared in 1995, incorporates elements of (Norton 1984) as well as some of the early results of the work of our group.[10] Our joint commentary, however, is the first comprehensive analysis of the gravitational part of the Zurich Notebook. As such, it provides new insights on pages that were not deciphered before and important correctives to the interpretation of pages that were.

Our most important new results are highlighted in sec. 1 of the commentary. Here we want to draw attention to a few that are crucial to understanding the essays complementing the commentary in these volumes. Most of the material in the notebook documents Einstein's search for field equations for his new metric theory of gravity. Two strategies can be discerned in this search. We have labeled them the 'mathematical strategy' and the 'physical strategy'. Each of us would probably flesh out the distinction between the two somewhat differently, but the operative notion is fairly straightforward. Pursuing the mathematical strategy, Einstein scoured the mathematical literature (with the help of Grossmann) for expressions containing derivatives of the metric that could be used as building blocks for gravitational field equations. Pursuing the physical strategy, Einstein tried to find such building blocks drawing on the analogy between the gravitational field in his new theory and the electromagnetic field in the classical electrodynamics of Maxwell and Lorentz. Einstein vacillated between these two approaches in the notebook. The importance of this simple observation for our reconstruction of the research recorded in the notebook can hardly be overstated. The same is true for the reconstruction of the subsequent elaboration of the *Entwurf* theory and of the transition to general relativity in November 1915. The distinction between the two approaches plays a key role in two essays in these volumes, "Pathways out of Classical Physics: Einstein's Search for the Gravitational Field Equations" (this volume) and "Untying the Knot: How Einstein Found His Way Back to Field Equations Discarded in the Zurich Notebook" (volume two).

Another new result that came out of our analysis of the notebook and that needs to be mentioned here is more subtle. One of the requirements constraining the choice of gravitational field equations for Einstein was that they reduce to the field equation of Newtonian theory in the case of weak static fields. Einstein was searching for field equations of broad and, if possible, general covariance, i.e., for equations that have the same form in a broad range of spacetime coordinate systems. Newtonian theory—at least in the standard formulation, which Einstein was using—is formulated in such a way that its equations only retain their simple form under transformations from one inertial frame to another. To compare the equations of broad covariance of Einstein's theory to the equations of limited covariance of Newton's, we nowadays temporarily relinquish some of the covariance of the former. This is done by impos-

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[10] See CPAE 4, Doc. 10 and the editorial note, "Einstein's Research Notes on a Generalized Theory of Relativity," on pp. 192–199. Preliminary results of the work of our group can be found in (Castagnetti et al. 1993), (Janssen 1999), (Norton 2000), (Renn 2005a, 2005b), and (Renn and Sauer 1996, 1999, 2003).

ing extra conditions on the metric field. Such extra conditions are known as coordinate conditions. Once a coordinate condition is imposed, various terms in the Einsteinian equations vanish and the resulting truncated equations can readily be compared to the simple Newtonian equation. As this brief characterization of the role of coordinate conditions shows, they are not essential to the theory. They have the same status as gauge conditions in other field theories. Their purpose is simply to facilitate comparison with Newtonian theory. For the application of the theory to other problems it may in fact be convenient to impose a different coordinate condition. In all of this, the equations of broad covariance remain the fundamental equations of the theory, not the truncated ones obtained with the help of some coordinate condition.

What we found in the Zurich Notebook, however, is that Einstein used such conditions in a manner that deviates sharply from modern usage. He used them to truncate equations of broad covariance and looked upon the resulting truncated equations as the fundamental equations of the theory or candidates for them. The original equations of broad covariance were important to him only in that they made the covariance properties of the truncated equations more tractable. Starting from equations covariant under a well-defined, broad group of transformations, one can, at least in principle, find the covariance group of the truncated equations by determining the covariance properties of the condition used to do the truncating. This is what we see Einstein do over and over again in the notebook. We therefore introduced a special term for such conditions. To distinguish them from modern coordinate conditions we call them *coordinate restrictions*. During the period covered by the notebook, Einstein labored under the impression that coordinate restrictions were needed not just to recover Newtonian theory in the appropriate limit, but also to ensure that the theory be compatible with energy-momentum conservation. It was only in the course of developing the *Entwurf* theory in 1913–1914 that he came to realize that the covariance of the field equations automatically yields energy-momentum conservation, thereby anticipating an important application of one of the famous theorems of Emmy Noether (1918) relating symmetries and conservation laws.[11] Recognizing the role of coordinate restrictions is crucial not only for reconstructing the calculations in the Zurich Notebook, but also for understanding the subsequent elaboration of the *Entwurf* theory and the obstacles that had to be overcome before general relativity as we know it today could be formulated.

The older literature (e.g., Pais 1982, 222) routinely explained Einstein's initial rejection of generally-covariant gravitational field equations by supposing a lack of understanding of the need to use coordinate conditions to compare such equations to their Newtonian counterpart in the case of weak gravitational fields. Then Stachel (1989b) pointed out that Einstein actually compared his *Entwurf* theory's field equations with the field equation of Newtonian theory in the case of weak, *static* fields and that Einstein had presumed an excessively restrictive form for the metric representing

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[11] For details, see "Untying the Knot …" (volume two).

such fields.[12] Einstein expected that the metric tensor for weak static fields would have just one variable component, which would behave like the Newtonian field. This one component would govern the chronometry only. Since the remaining components were assumed to be constant, the spatial geometry would just be ordinary Euclidean geometry. This expectation contradicts the generally-covariant field equations Einstein finally adopted in 1915 and could by itself preclude their adoption. The suspicion that this was the real reason for Einstein's rejection of generally-covariant field equations was reinforced when Norton (1984, 117) drew attention to a page of the Zurich Notebook, on which Einstein rehearsed the now standard mathematical computations needed to reduce generally-covariant field equations based on the so-called Ricci tensor to the Newtonian equation by means of what is known as the harmonic coordinate condition. Presuming that Einstein used this condition as a modern coordinate condition, Norton conjectured that Einstein had rejected generally-covariant field equations based on the Ricci tensor because his expectations for the weak, static field were incompatible with the harmonic coordinate condition.

Einstein's difficulties with the static metric left unexplained, however, why he subsequently abandoned another, apparently serviceable set of gravitational field equations of near general covariance examined in the Zurich Notebook. Our analysis of the notebook makes clear that these gravitational field equations were abandoned largely because Einstein was not then using modern coordinate conditions but coordinate restrictions. Over the next two years, he worked energetically to develop a better understanding of the covariance properties of his *Entwurf* theory. The more sophisticated mathematical methods resulting from these efforts are central in his return to broader covariance in November 1915. That return involved his adoption of modern coordinate conditions. He concluded that the gravitational field equations of near general covariance rejected in the Zurich Notebook were acceptable after all and rushed them into print (Einstein 1915a). Freed of coordinate restrictions, Einstein now needed only weeks to discover his mischaracterization of static fields. He made some final modifications to the field equations published in (Einstein 1915a) and thus arrived at the familiar generally-covariant field equations of general relativity.

Not surprisingly, given this turn of events, Norton's essay, "What was Einstein's "Fateful Prejudice"?," in volume two analyzes the role of coordinate restrictions in Einstein's work. The essay carefully lays out the case for their presence in the notebook. It also reviews why Einstein's use of them is credible, even though they differ so much from the routine modern usage. Two considerations are key here: First, Einstein's use of coordinate restrictions is not unnatural in view of the historical development of his theory. His special theory of relativity was covariant just under Lorentz transformations. His goal was to expand that covariance to embrace transformations to accelerated frames of reference. General covariance goes well beyond this, includ-

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[12] In (Stachel forthcoming) it is shown that Einstein was seriously handicapped in the comparison of his theory to Newtonian theory by the mathematical tools available to him. In particular, he lacked the concept of an "affine connection" (see Stachel's "The Story of Newstein …" in vol. 4 of this series).

ing covariance under transformations not associated with a change of the state of motion, such as transformation from Cartesian to spherical spatial coordinates. So equations of broad covariance could plausibly be used by Einstein purely as an intermediate mathematical step, from which the final equations could be recovered by some harmless restriction of the covariance. Of course, what Einstein found again and again in the notebook was that he needed restrictions that seriously compromised his goal of extending the relativity principle. Second, as already indicated above, Einstein found that the coordinate restrictions he applied were closely associated with energy-momentum conservation in the weak-field limit of the theory. This naturally suggested to him that the full theory could only be made compatible with energy-momentum conservation at the expense of restricting its covariance.

More speculatively, Norton suggests that Einstein's use of coordinate restrictions may have been supported by a tacit reification of spacetime coordinates. In an addendum to the reprint of the *Entwurf* paper in the *Zeitschrift für Mathematik und Physik* in January 1914 (Einstein and Grossmann 1914a), Einstein advanced his notorious "hole argument" [*Lochbetrachtung*] against the physical admissibility of generally-covariant field equations. By his own later admission, he fell into this flawed argument because of just such a tacit reification. What if Einstein tacitly reified spacetime coordinates in just the same way during his calculations in the notebook? If he did, Norton argues, the reification would have forced him to restrict the covariance of the theory, even had he known full well how to use coordinate conditions in the modern sense. The conjecture is that Einstein did indeed reify coordinates in this way. It is essential to the conjecture that this reification remained beneath Einstein's conscious awareness, just as he later admitted it did with the hole argument. Had he been able to formulate it explicitly, he would presumably have recognized its inadmissibility right away.

Norton suggests that Einstein had the modern understanding of coordinate conditions all along, even though, for the reasons laid out above, he used coordinate restrictions in the notebook as well as in the further development of the *Entwurf* theory. In "Untying the Knot …" (volume two), however, Janssen and Renn suggest that Einstein only arrived at the modern understanding of coordinate conditions when he replaced the *Entwurf* field equations by equations of much broader covariance in (Einstein 1915a). This paper contains the first unequivocal example of Einstein applying a coordinate condition in the modern sense.

This disagreement is one of a number of disputes that have not been resolved as these volumes go to press. We make no apologies for this. It is a sign of the vitality of Einstein scholarship. We publish our book on the history of general relativity in the same spirit as Hermann Weyl published his famous book on the theory itself. As Weyl wrote in the preface to the first edition of *Raum-Zeit-Materie*:

> But it was definitely also not the intention of this book to turn the life, which manifests itself so forcefully today on the field of physical knowledge, with axiomatic thoroughness into a dead mummy at the point it happens to have reached this moment.[13]

The reader will note that only the introduction and the commentary are authored by all five of us. The rest of the volume consists of essays by one or two authors. In part, this reflects division of labor and differences in expertise. But it also reflects a lack of consensus about the interpretation of the material. Points of contention, besides the issue of coordinate conditions versus coordinate restrictions, are the relative importance of the mathematical and the physical strategy in the genesis of general relativity (as well as the interpretation of this distinction), the nature of Einstein's *modus operandi* as a creative scientist, and the extent to which the analysis of this particular episode provides insights into the practice of scientific theorizing, its conditions and mechanisms, in general. The first two of these disagreements call for some further comments.

The breakthrough to general relativity of November 1915 has been portrayed as a triumph of the mathematical strategy, prematurely abandoned in the Zurich Notebook in favor of the physical strategy that led Einstein to the problematic *Entwurf* theory (see, e.g., Norton 2000). This portrayal certainly fits nicely with the way in which Einstein presented his new results in November 1915. It is also how he came to remember his own achievement in later years, as has been documented in great detail in (Van Dongen 2002). In "Untying the Knot ..." (volume two), Janssen and Renn nevertheless argue that Einstein made the transition from the *Entwurf* field equations to the field equations of November 1915 following the physical strategy. They reconstruct the developments of that eventful month taking Einstein at his word that the definition of the gravitational field in the *Entwurf* theory as the gradient of the metric was "a fateful prejudice" ("ein verhängnisvolles Vorurteil," Einstein 1915a, 782) and that replacing this gradient by the so-called Christoffel symbols was "the key to [the] solution" ("Den Schlüssel zu dieser Lösung," Einstein to Sommerfeld, 28 November 1915). With this substitution, the variational formalism for the *Entwurf* theory, developed in (Einstein and Grossmann 1914b) and (Einstein 1914) in close analogy with classical electrodynamics, leads almost automatically to the theory of November 1915. In an appendix to "Untying the Knot ...," this insight is used to clarify the mathematical relation between the Einstein field equations and the *Entwurf* field equations.

Concerning Einstein's *modus operandi*, not all of us agree with Janssen's claim in "What Did Einstein Know and When Did He Know It? A Besso Memo Dated August 1913" (volume two) that more room needs to be made for the role of prejudice, wishful thinking, and opportunism in Einstein's work toward general relativity than was done in the accounts we started from (Norton 1984, Stachel 1989b).

Janssen's claim is based primarily on Einstein's handling of what we shall call the problem of rotation. An important test to which Einstein subjected candidate field equations in the notebook is whether they allow the Minkowski metric in uniformly rotating coordinates as a vacuum solution. The point of checking whether this rota-

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[13] "Es lag aber auch durchaus nicht in der Absicht dieses Buches, das auf dem Feld der physikalischen Erkenntnis heute so besonders kräftig sich rührende Leben an dem Punkt, den es im Augenblicke erreicht hat, mit axiomatischer Gründlichkeit in eine tote Mumie zu verwandeln" (Weyl 1918, vi).

tion metric, as we shall call it, is a vacuum solution was that Einstein wanted to make sure that his theory extended the relativity of uniform motion of special relativity to accelerated motion such as uniform rotation. When Einstein published the *Entwurf* field equations, he had satisfied himself that they met this important requirement. It turns out they do not. It took Einstein some time to discover this and even longer to accept it. As part of his collaboration with Besso on the Mercury anomaly shortly after the publication of the *Entwurf* paper, he made a half-hearted attempt to double-check that the rotation metric is indeed a vacuum solution of the *Entwurf* field equations. He was so convinced they were that he missed some factors of 2 and a minus sign in just the right places to bring about the outcome he expected.[14] This error and its eventual discovery in September 1915 are recounted in (Janssen 1999). The conclusion of this paper was that Einstein had simply been unlucky in not discovering his error sooner. However, a memo in Besso's hand bearing the date August 28, 1913, discovered in Switzerland in 1998 by Robert Schulmann, shows that Besso had clearly warned his friend in 1913 that the rotation metric is not a solution. Einstein initially accepted this verdict. He changed his mind again in early 1914.

The reconstruction of this episode in "What Did Einstein Know …" depends crucially on allowing a certain opportunistic streak in Einstein's general methods. Einstein's handling of the problem with the rotation metric is the most clear-cut case, but the Besso memo provides another example. The memo shows not only that Einstein had the key idea for the hole argument sometime in August 1913, but also that he had already taken important steps toward its eventual resolution in 1915. Janssen argues that it is partly because of opportunism that Einstein did not pursue this resolution in 1913. After all, such a resolution would be a most unwelcome reversal after Einstein had tried for months to make the lack of covariance of the *Entwurf* field equations more palatable. The exposure of such opportunistic moves by Einstein should not be seen as damning to his reputation as a scientist. What it shows rather is that creative science is messier and more complicated than many philosophers of science and science educators like to think.

The material discussed so far focuses on one phase in the genesis of general relativity, Einstein's search for field equations in the period 1912–1915. This phase is extremely well documented and has accordingly been discussed extensively in the recent literature on the history of general relativity. Yet, the field equations were only the capstone on the edifice of general relativity. Much of the foundation had been laid before Einstein started looking in earnest for field equations. The cornerstone of the theory—dubbed the equivalence principle in (Einstein 1912, 360, 366) and later singled out by Einstein as "the most fortunate thought of my life" ("der glücklichste Gedanke meines Lebens," CPAE 7, Doc. 31, [p. 21])—dates from 1907. Stachel's essay, "The First Two Acts" (this volume), examines all Einstein source material per-

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[14] This calculation can be found on [pp. 41–42] of the Einstein-Besso manuscript on the perihelion motion of Mercury (CPAE 4, Doc. 14). For further discussion of Einstein's struggles with rotation, see (Janssen 2005).

taining to the early stages of the genesis of general relativity.[15] "Act One" concerns his recognition of the close connection between acceleration and gravitation in Newtonian mechanics, based on the equality of inertial and gravitational mass, and his extension of that connection to all physical phenomena, which he called the equivalence principle. He took this principle, which he believed extended the relativity principle to accelerated frames of reference, as the key to any future relativistic theory of gravitation. In the crucial "Act Two," the quest for generalization of the relativity principle, which distinguished his efforts at a theory of gravitation from those of his special-relativistic competitors, had led him by late 1912 from a scalar to a tensor description of the gravitational field. In the theory for which he was looking, this tensor was to play a dual physical role, serving both as the metric in the line element $g_{\mu\nu}dx^{\mu}dx^{\nu}$ [16] describing the chronometry of time and the geometry of space (by then he had adopted Minkowski's four-dimensional viewpoint), and as the potentials for the inertio-gravitational field. It is at this point that the Zurich Notebook begins. In this reckoning, the search for the field equations, the focus of much of the rest of these volumes, comprises only the third act.

The genesis of general relativity, however, did not quite unfold in the form of a classic three-act drama between 1907 and 1915. The story begins before 1907 and continues well beyond 1915. In the essay that opens this volume, "Classical Physics in Disarray," Renn examines the state of knowledge about gravitation from which Einstein had to start. The work on gravity undertaken on this basis eventually culminated in the publication of the Einstein field equations (Einstein 1915d). This publication, the last of the four communications to the Prussian Academy of November 1915, marks the dramatic end of "Act Three". But the dust did not settle until 1918. Both the status of general covariance and the status of energy-momentum conservation in the theory remain unclear as "Act Three" draws to a close. Einstein himself tied together some of these loose ends in correspondence and further publications.[17] Several contributions by others helped clarify key aspects of the theory. The seminal paper of Emmy Noether (1918) on symmetries and conservation laws already mentioned above grew out of discussions among Göttingen mathematicians around David Hilbert and Felix Klein over energy-momentum conservation in general relativity.[18] The astronomer Karl Schwarzschild (1915)[19] replaced the approximate solution for

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[15] This is the only essay in these volumes that has already been published (Stachel 2002a, 261–292). This collection of Stachel's work on Einstein also contains a reprint of an important earlier paper on "Act Two" (Stachel 1989a)

[16] The indices μ and ν run from 1 through 4 (corresponding to the spacetime coordinates $x^{\mu} = (x, y, z, t)$) and are summed over.

[17] The status of general covariance is clarified in letters to Besso and Paul Ehrenfest in late 1915 and early 1916 (CPAE 8, Docs. 173, 178 and 180). For historical discussion, see, e.g., (Stachel 1989, 1993, 2002b), (Norton 1987), (Howard and Norton 1993), (Howard 1999), and (Janssen 2005). The status of energy-momentum conservation was clarified in (Einstein 1916c, 1918c). For discussion, see "Untying the Knot …" (volume two).

[18] For further discussion, see (Rowe 1999), (Sauer 1999, 2005), and Renn and Stachel's "Hilbert's Foundation of Physics …" in vol. 4 of this series.

the metric field of a point mass that Einstein had used in his paper on Mercury's perihelion by an exact solution. The mathematicians Gerhard Hessenberg (1917), Tullio Levi-Civita (1917), and Hermann Weyl (1918) introduced the notion of parallel displacement, thereby clarifying the geometrical meaning of curvature representing gravity in the new theory.[20] This in turn led to the introduction of the notion of an affine connection, which provides a much more natural way to implement the equivalence principle than the metric tensor, with which Einstein had to make do in the development of the theory.[21]

The longest and most ambitious essay in these two volumes is "Pathways out of Classical Physics …" (this volume) by Renn and Sauer. This paper elaborates on "Classical Physics in Disarray" (this volume) and presents a comprehensive version of "Act Three" of the genesis of general relativity within a framework of historical epistemology that integrates historical analysis, epistemology, and cognitive science. This framework builds on efforts to integrate cognitive science and history of science by Peter Damerow (1996) and is based on adapting such concepts as "frames" and "mental models" introduced by Marvin Minsky (1975, 1987) and others to the needs of an historical analysis of knowledge. Damerow was closely involved with our group's efforts to decipher the gravitational part of the Zurich Notebook and to explore the ramifications of the results for the reconstruction of the genesis of general relativity. One of the advantages of the framework adopted by Renn and Sauer is that it allows them to trace continuities across sharp conceptual divides that separate various stations on Einstein's journey from classical physics to general relativity. The hope is that the application of the framework of historical epistemology to the genesis of general relativity will tell us more about conceptual innovation in general and about related issues in—to use a geological metaphor—the plate tectonics of knowledge.

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[19] See Matthias Schemmel's "An Astronomical Road to General Relativity …" (vol. 3 of this series) for the story of how Schwarzschild came to be interested in these matters.

[20] The importance of this development was acknowledged in (Einstein 1918d), a review of (Weyl 1918); in Einstein's lectures on general relativity in Berlin in 1919 (CPAE 7, Doc. 19, [p. 10]); and in correspondence (see, e.g., Einstein to Hermann Weyl, 27 September 1918 [CPAE 8, Doc. 626]).

[21] See Stachel's "The Story of Newstein …" in vol. 4 of this series.

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JÜRGEN RENN

CLASSICAL PHYSICS IN DISARRAY

The Emergence of the Riddle of Gravitation

1. INTRODUCTION

1.1 A Creation ex nihilo?

The genesis of Einstein's special and general theory of relativity is an odd event in the history of science. From today's perspective, Einstein's theory represents the basis for modern astronomy, astrophysics, cosmology, and cosmogony. It comprises a broad range of observational and theoretical knowledge, covering, among others, phenomena related to planetary astronomy, to black holes, and to the expansion of the universe. Yet little of the knowledge that makes relativity theory a central asset of modern physics was available at the time when Einstein completed it by publishing his paper on general relativity in late 1915. Neither the bending of light in a gravitational field nor the expansion of the universe, let alone gravitational waves or black holes, were even suspected by contemporary astronomers. How then was it possible for Einstein without this knowledge to formulate a theory that has since withstood not one but several revolutions of astronomy and its instrumentation, including the development of radio-, X-ray, and space-borne astronomy?

A closer look at Einstein's investigative pathway does not resolve but rather complicates this puzzle, which may be called the "paradox of missing knowledge." Einstein first encountered the problem of formulating a relativistic theory of gravitation in 1907 when he was a clerk at the Swiss Patent Office in Bern. In the following eight years he pursued this problem with growing intensity, from 1911 to early 1914 as professor in Zurich and Prague, and from April 1914 as a member of the Prussian Academy and from 1917 as Director of the Kaiser Wilhelm Institute for Physics in Berlin.[1] As early as 1907 Einstein formulated several general conditions for the solution of his problem, among them the famous "principle of equivalence" and a generalization of the "principle of relativity." The first principle allowed him to arrive immediately at a number of surprising conclusions such as that of the bending of light in a gravitational field.[2] Five years later, however, he had to acknowledge that,

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[1] See (CPAE 5), Calender/Chronology, pp. 617–636.

[2] See (Einstein 1907, 461).

Jürgen Renn (ed.). *The Genesis of General Relativity,* Vol. 1
Einstein's Zurich Notebook: *Introduction and Source*.

with the mathematical means at his disposal, the problem of formulating a relativistic theory of gravitation could not be solved. To his friend, Heinrich Zangger, Einstein thus wrote around June 1912:

> The further development of the theory of gravitation meets with great obstacles.[3]

Consequently, in the summer of 1912, he turned to his mathematician friend, Marcel Grossmann, who helped him to access more sophisticated mathematical tools, in particular, the absolute differential calculus of Elwin Christoffel, Gregorio Ricci-Curbastro, and Tullio Levi-Civita.[4] But after exploring these tools for about a year, an experience that is documented in the Zurich Notebook, Einstein's conviction grew that the problem he posed in 1907 was actually irresolvable. He thus limited himself to a partial solution, which he first published in 1913 together with Grossmann.[5] Soon after this publication Einstein even believed to have found a proof that his problem could not be solved as originally envisaged. In the following two years, he nevertheless continued to work on a relativistic theory of gravitation largely in isolation from and even against the resistance of the scientific community, which tended to regard his efforts as making little sense. Then, after three dramatic weeks towards the end of 1915 in which Einstein presented to the Prussian Academy week after week a new tentative solution,

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[3] "Die Weiterentwicklung der Theorie der Gravitation stösst auf grosse Hindern[i]sse." Albert Einstein to Heinrich Zangger, Prague, after 5 June 1912, (CPAE 5, Doc. 406). Unless otherwise noted, all translations are based on those in the companion volumes to the Einstein edition.

[4] See (Kollross 1955, 278) according to which Einstein exclaimed: "Grossmann, you must help me or I'll go crazy." ("Grossmann, Du mußt mir helfen, sonst werd' ich verrückt!") See also the preface to the Czech translation (Einstein 1923) of his popular book on relativity where he wrote: "However, only after my return in 1912 to Zurich did I hit upon the decisive idea about the analogy between the mathematical problem connected with my theory and the theory of surfaces by Gauss—originally without knowledge of the research by Riemann, Ricci, and Levi-Civita. The latter research came to my attention only through my friend Grossmann in Zurich when I posed the problem to him only to find generally covariant tensors whose components depend only upon the derivatives of the coefficients of the quadratic fundamental invariant." ("Den entscheidenden Gedanken von der Analogie des mit der Theorie verbundenen mathematischen Problems mit der Gaußschen Flächentheorie hatte ich allerdings erst 1912 nach meiner Rückkehr nach Zürich, ohne zunächst Riemanns und Riccis, sowie Levi-Civitas Forschungen zu kennen. Auf diese würde ich erst durch meinen Freund Großmann in Zürich aufmerksam, als ich ihm das Problem stellte, allgemein kovariante Tensoren aufzusuchen, deren Komponenten nur von Ableitungen der Koeffizienten der quadratischen Fundamentalinvariante abhängen."), (CPAE 6, Doc. 42, 535, n. 4). For more extensive discussion, see "The First Two Acts" (in this volume).

[5] See (Einstein and Grossmann 1913).

each revoking the previous one, he eventually succeeded in definitively solving his original problem.[6] How was it possible that Einstein could, without having an idea of the final solution and eight years before actually attaining it, already formulate the conditions it had to satisfy, and how could he persist in his search against the judgement of contemporary experts and in spite of his numerous failures? What was his explicit or implicit heuristics? And what accounts for its success?

The following is an attempt to prepare the answers to these questions by analyzing the roots of Einstein's achievements in the knowledge of classical and special relativistic physics, and by following the development of his theory until, in the summer of 1912, he recognized gravitation as the bending of space and time. As we shall see in this and the following contributions, both the peculiar emergence and the remarkable stability of Einstein's theory of gravitation with regard to the further development of physics and astronomy become plausible only if the genesis of general relativity is understood, not as a fortunate anticipation of future observational discoveries, but as a transformation of pre-existing knowledge. The next section provides a survey of this knowledge, in particular of classical physics as it became relevant to the emergence of a relativistic theory of gravitation. The concluding third section then attempts to explain how this knowledge became effective in laying the foundations for Einstein's successful heuristics.[7] As a prelude, let us look briefly at the long-term development of the knowledge on gravitation, which provided the presuppositions for Einstein's achievements.

1.2 A Short History of Gravitation

What can one possibly learn from a survey of the history of gravitation in order to understand the genesis of general relativity? Certainly, the long-range history of knowledge on gravitation turns out to be as peculiar as the emergence of general relativity. Above all it is characterized by the longevity of certain basic ideas on gravitational effects, as well as by the radical turnover of these ideas in the course of the historical development. For almost two millennia, the understanding of what we consider to be gravitational effects was dominated by Aristotelian natural philosophy. It divides such effects into two distinct classes; the motions of terrestrial and of celestial bodies. The downward motion of heavy terrestrial bodies is conceived as a "natural motion" towards the natural place of such bodies, the center of the earth. In contrast to the "violent motion" of terrestrial bodies, which is caused by a force, natural motion does not require any external moving cause but is the result of an intrinsic tendency of a heavy body acting in accordance with its nature. The characteristic motion of celestial bodies is, on the other hand, categorically separated from that of terrestrial bodies and conceived as an eternal circular motion.[8]

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[6] See (Einstein 1915a, 1915b, 1915c, 1915d).

[7] For an attempt to provide comprehensive answers to the above questions based on the present analysis, see "Pathways out of Classical Physics …" (in this volume).

The Aristotelian account of gravitational effects was eventually supplanted by that of classical Newtonian physics, dominating their understanding for several centuries until the advent of relativity theory. Like Aristotle's natural philosophy, Newtonian physics also introduced a fundamental distinction between types of motion, in this case between uniform inertial motions and motions that are accelerated due to the action of a force. In Newtonian physics, gravitation is understood as a force acting like any other external force causing acceleration, be it human or natural, terrestrial or celestial. Accordingly, the accelerated motion of falling terrestrial bodies and the accelerated orbital motion of the planets are explained in the same way as being due to a universal gravitational force of attraction. This gravitational force acts without intermediary and without time delay through the intervening space between two bodies.

Since the mid-nineteenth century, yet another distinct idea was discussed and gained increasing support: gravitation as a space-filling field, transmitting the gravitational force not instantaneously but with a limited speed through an intervening medium called the "aether."[9] Finally, in general relativity, gravitation is conceived as a field that represents the curvature of the spacetime continuum itself and that is caused by the distribution of masses and energy in the universe. Since gravitation is not understood here as a force, motions of bodies within this field are no longer distinguished according to their inertial or gravitational character. They are rather all "natural" motions governed in the same way by the intrinsic geometry of spacetime.

What made these distinct conceptions convincing while they ruled the understanding of gravitation, and what eventually overturned them? Was the long-term domination of Aristotelian natural philosophy merely the consequence of its adoption as the official doctrine of the Catholic Church? And was the replacement of the Aristotelian concept of natural motion by the Newtonian explanation of the motion of fall in terms of a gravitational force simply the triumph of a newly introduced scientific method? If so, what accounts for the fact that the Newtonian conception itself was eventually superseded by that of general relativity, which returns to the interpretation of the motion of fall as a "natural" force-free motion, as conceived in Aristotelian natural philosophy? How can it be that, even after the establishment of the "scientific method," history of science was not simply dominated by gradual progress and that even the very foundations of the understanding of gravitation could still be overturned? As the following sketch will attempt to make plausible, the emergence and disappearance of such diverse core notions of gravitation—conceived as natural tendency, force, field, or as curvature of spacetime—becomes understandable on the basis of a history of knowledge that studies the extension as well as the architecture of the knowledge sustained by these core notions.

While the history of science has traditionally limited itself to the knowledge embodied in scientific theories and, more recently, also to that represented by experi-

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[8] For a survey, also of the following, see (Dijksterhuis 1986).

[9] For a survey, see the introduction to vols. 3 and 4 of this series "Theories of Gravitation in the Twilight of Classical Physics" (in vol.3).