The Reinvention of General Relativity: A Historiographical Framework for Assessing One Hundred Years of Curved Space-time

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Abstract: The history of the theory of general relativity presents unique features. After its discovery, the theory was immediately confirmed and rapidly changed established notions of space and time. The further implications of general relativity, however, remained largely unexplored until the mid 1950s, when it came into focus as a physical theory and gradually returned to the mainstream of physics. This essay presents a historiographical framework for assessing the history of general relativity by taking into account in an integrated narrative intellectual developments, epistemological problems, and technological advances; the characteristics of post–World War II and Cold War science; and newly emerging institutional settings. It argues that such a framework can help us understand this renaissance of general relativity as a result of two main factors: the recognition of the untapped potential of general relativity and an explicit effort at community building, which allowed this formerly disparate and dispersed field to benefit from the postwar changes in the scientific landscape.

One hundred years after its creation, the theory of general relativity is still the standard theory of gravitational phenomena, the basis for cosmological research, and, perhaps most important, the theory that makes the most definite statements about what physicists mean when they speak of space and time. In the last thirty years, it has also become an active field of historical investigation. While much work has been done on its prehistory and genesis, and

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some work on its immediate reception, its most striking features—its persistence and resilience—have remained largely unexplored.[1] The persistence of general relativity might not seem that surprising at first glance, given the well-known stories of its immediate spectacular confirmation and Einstein's subsequent rise to scientific superstardom. However, historians of science have found that, not long after its establishment, the theory underwent what Jean Eisenstaedt has called a "low-water-mark" period in which it was mainly considered as providing small corrections to the Newtonian picture and in which the few physicists working on it achieved only modest progress.[2] The majority of theoretical physicists directed their intellectual efforts toward the development of other branches of physics, such as quantum mechanics, nuclear physics, and quantum electrodynamics, touching on the issues of general relativity theory only in an unsystematic manner. Moreover, as we shall discuss later in this essay, in this period general relativity was considered by most—in particular its creator—as merely a stepping-stone toward a larger theoretical framework. This makes it even more remarkable that in the early 1960s general relativity experienced a sudden revival in connection with astrophysical discoveries far removed from its original domain, which had essentially been confined to the solar system.

The physicist Clifford Will coined the phrase "Renaissance of General Relativity" to describe the process through which general relativity became an internationally visible, highly active field of research in which theoretical explorations went hand in hand with new astrophysical discoveries such as quasars and the cosmic microwave background radiation.[3] The systematic exploration of exact solutions, and the understanding of space-time singularities and of the physical reality of gravitational waves, all came only after the low-water-mark period, in the wake of the renaissance of general relativity. While there may be some obvious reasons for these developments, such as the role of World War

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[1] For the genesis of general relativity we refer to Jürgen Renn, ed., *The Genesis of General Relativity*, 4 vols. (Dordrecht: Springer, 2007); and Michel Janssen, "'No Success Like Failure . . .': Einstein's Quest for General Relativity, 1907–1920," in *The Cambridge Companion to Einstein*, ed. Janssen and Christoph Lehner (Cambridge: Cambridge Univ. Press, 2014), pp. 167–227. Several case studies concerning the development and reception of general relativity are in Don Howard and John Stachel, eds., *Einstein and the History of General Relativity* (Einstein Studies, 1) (Boston: Birkhäuser, 1987); Jean Eisenstaedt and Anne J. Kox, eds., *Studies in the History of General Relativity* (Einstein Studies, 3) (Boston: Birkhäuser, 1992); John Earman, Janssen, and John D. Norton, eds., *The Attraction of Gravitation: New Studies in the History of General Relativity* (Einstein Studies, 5) (Boston: Birkhäuser, 1993); Hubert Goenner, Renn, Jim Ritter, and Tilman Sauer, eds., *The Expanding Worlds of General Relativity* (Einstein Studies, 7) (Boston: Birkhäuser, 1999); Eisenstaedt and Kox, eds., *The Universe of General Relativity* (Einstein Studies, 11) (Boston: Birkhäuser, 2005); Lehner, Renn, and Matthias Schemmel, eds., *Einstein and the Changing Worldviews of Physics* (Einstein Studies, 12) (Dordrecht: Springer, 2012); and Mara Beller, Renn, and Robert S. Cohen, eds., *Einstein in Context* (Cambridge: Cambridge Univ. Press, 1993). For the reception of general relativity see also Thomas F. Glick, ed., *The Comparative Reception of Relativity* (Dordrecht: Springer, 1987); Stanley Goldberg, *Understanding Relativity: Origin and Impact of a Scientific Revolution* (Boston: Birkhäuser, 1984); and Stephen G. Brush, "Why Was Relativity Accepted?" *Physics in Perspective*, 1999, *1*:184–214.

[2] Jean Eisenstaedt, "La relativité générale à l'étiage: 1925–1955," *Archive for History of Exact Sciences*, 1986, 35:115–185; and Eisenstaedt, "Trajectoires et impasses de la solution de Schwarzschild," *ibid.*, 1987, 37:275–357.

[3] Clifford Will, *Was Einstein Right? Putting General Relativity to the Test* (Oxford: Oxford Univ. Press, 1986), esp. pp. 3–18; see also George Ellis, Antonio Lanza, and John Miller, eds., *The Renaissance of General Relativity and Cosmology* (Cambridge: Cambridge Univ. Press, 1993). On a similar note, the period from 1964 to the mid 1970s is called the "Golden Age of General Relativity" in Kip S. Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy* (New York: Norton, 1994), esp. pp. 258–299. The starting point of the "golden age" is usually considered the First Texas Symposium of Relativistic Astrophysics, held in Dallas on 16–18 Dec. 1963, in which astrophysicists and relativists joined together to explore the nature of the newly discovered quasars. See Ivor Robinson, Alfred Schild, and Engelbert L. Schücking, eds., *Quasi-stellar Sources and Gravitational Collapse* (Chicago: Univ. Chicago Press, 1965); and B. Kent Harrison, Thorne, Masami Wakano, and John A. Wheeler, *Gravitation Theory and Gravitational Collapse* (Chicago: Univ. Chicago Press, 1965).

II and the increasing societal and military significance of physics after the war and in the Cold War period, the renaissance phenomenon also presents some deeper historiographical riddles. While funding did increase—in particular with contributions from military sources—money alone does not create good physics, and there was no *a priori* reason why big money should have gone into lofty research on general relativity, even if some thought it held the promise of providing anti-gravity devices.[4] Another plausible explanation might be the great technological advances made during the war and in the immediate postwar period, which allowed for new astrophysical observations. But this explanation does not account for the revitalization of the field either, since the theoretical tools used to explain the novel discoveries were developed by an increasing number of theoretical physicists and mathematicians working in the field *before* those observations had actually been made. So the questions remain: Why were relativists in the 1960s able to react so quickly to new astrophysical discoveries such as the observation of quasars? And why were the Kerr solution (describing a rotating black hole) and other theoretical tools, which helped to interpret the discoveries, developed independently of and at about the same time as these new discoveries? More generally, which developments prepared and laid the conditions for the spectacular renaissance of a marginal field, a renaissance that continues to this very day?

Episodes in this later history have become the subject of historical case studies.[5] However, the actual dynamics of this unusual story of dormant resilience followed by splendid “renaissance” remains unexplored. The epistemological implications of this story—the resilience of the concepts of space and time introduced by general relativity—remain equally uncharted territory. While case studies allow for a focus on specific factors in the overall development, treating other circumstances as mere context, we believe that an explanation of the global dynamics requires taking into account the interaction of intellectual developments, epistemological problems, technological advances, the characteristics of postwar and Cold War science, and newly emerging institutional frameworks.

In this essay, we present a framework for such an integrated account, based in part on previous historical studies. We argue that a better understanding of the historical process

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[4] For the role of military funding and anti-gravity research see Joshua Goldberg, “U.S. Air Force Support of General Relativity, 1956–1972,” in *Studies in the History of General Relativity*, ed. Eisenstaedt and Kox (cit. n. 1), pp. 89–102; Dean Rickles, “The Chapel Hill Conference in Context,” in *The Role of Gravitation in Physics: Report from the 1957 Chapel Hill Conference*, ed. Cécile DeWitt and Rickles (Berlin: Edition Open Access, 2011), pp. 7–21; David Kaiser, “Roger Babson and the Rediscovery of General Relativity,” in “Making Theory: Producing Theory and Theorists in Postwar America” (Ph.D. diss., Harvard Univ., 1987), pp. 567–595; Benjamin Wilson and Kaiser, “Calculating Times: Radar, Ballistic Missiles, and Einstein’s Relativity,” in *Science and Technology in the Global Cold War*, ed. Naomi Oreskes and John Krige (Cambridge, Mass.: MIT Press, 2014), pp. 273–316; and Rickles and Donald Salisbury, interview of Louis Witten, 17 Mar. 2011 (unpublished transcript).

[5] For the history of gravitational waves see Daniel Kennefick, *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves* (Princeton, N.J.: Princeton Univ. Press, 2007). For studies of the contextual factors that favored theoretical research in the field of gravitation, especially in the United States, see Kaiser, “Roger Babson and the Rediscovery of General Relativity”; David Kaiser, “A Ψ is just a Ψ? Pedagogy, Practice, and the Reconstitution of General Relativity, 1942–1975,” *Studies in History and Philosophy of Modern Physics*, 1998, *29*:321–338; and Wilson and Kaiser, “Calculating Times.” For the relevance of novel theoretical tools see Jean Eisenstaedt, *The Curious History of Relativity: How Einstein’s Theory of Gravity Was Lost and Found Again* (Princeton, N.J.: Princeton Univ. Press, 2006); and Aaron S. Wright, “The Advantages of Bringing Infinity to a Finite Place: Penrose Diagrams as Objects of Intuition,” *Historical Studies in the Natural Sciences*, 2014, *44*:99–139. For recent overviews see Abhay Ashtekar, “The Last Fifty Years of General Relativity and Gravitation: From GR3 to GR20 Warsaw Conferences,” *General Relativity and Gravitation*, 2014, *46*, art. 1706; and Ashtekar, Beverly K. Berger, James Isenberg, and Malcolm A. H. MacCallum, eds., *General Relativity and Gravitation: A Centennial Perspective* (Cambridge: Cambridge Univ. Press, 2015). See also the several case studies analyzed in the Einstein Studies volumes cited in note 1, above.

requires a study of the *interactions* between internal, structural factors of the pertinent intellectual developments and external, "environmental" factors. The internal factors refer to the resilient, yet flexible, theoretical framework provided by general relativity to physicists working in diverse (and dispersed) fields by explaining gravity in relation to concepts of space and time. The external factors relate to the working conditions of physicists at the time, not only the available technology but also the newly created conditions for the self-organization of a community, for the mobility of young researchers, and for the transfer of knowledge in a growing international community. These external factors created a favorable environment for integrating the dispersed research endeavors under the new heading of general relativity research. This, in turn, created the conditions for the emergence of a coherent investigation of the theoretical core of general relativity for its own sake and for the creation of a community specifically dedicated to this investigation. This is also the sense in which we propose to speak not of a simple renewal of relativity research but of a reinvention of general relativity, which was turned by these dynamics from a theoretical framework into a field of study in its own right.

The historiographical framework presented here is still preliminary and will have to be substantiated and corroborated by detailed historical studies, some of which are currently under way. Preliminary results of this ongoing work have already been integrated in the framework presented here. Further studies will have to take into account the rich and hitherto unexplored archival documents as well as oral history interviews with some of the actors.

The essay is divided into three main sections. In the first, we present a short review of the genesis of general relativity based on recent research pursued by Jürgen Renn in collaboration with a team of historians and philosophers of physics.[6] The main purpose of this review is to introduce key notions, not emphasized in the existing literature on the subject, that will help address the epistemological dynamics defining the internal structure of the theory. In Section II, we discuss the low-water-mark period with a novel focus: rather than merely describing the staleness of the theory and taking its survival for granted, we analyze how general relativity retained its singular position, despite manifold attempts to modify and replace it with more encompassing theories. We address attempts to go beyond general relativity from within (the unified field theories pursued most notably by Einstein himself), from without (the attempts to incorporate general relativity into the framework of quantum theory), and within the specific arena of cosmology. In the third section, we squarely address the question of the renaissance, showing how the internal and external factors interacted and provided the basis for the reinvention of general relativity. We conclude with a brief outlook on post-Renaissance developments.

I. GENERAL RELATIVITY AS A FIELD THEORY OF SPACE AND TIME

The beginning of modern physics was marked by major conceptual transformations in a variety of fields: electrodynamics, thermodynamics, and radiation theory. In his 1905 papers, Einstein contributed to several of these transformations, providing explanations of the electrodynamics of moving bodies, of black-body radiation, of the photoelectric effect, and of Brownian motion. These seemingly unrelated breakthroughs actually have more than one

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[6] The results of this research are to be found in Michel Janssen, John D. Norton, Jürgen Renn, Tilman Sauer, and John Stachel, *Einstein's Zurich Notebook: Introduction and Source*, Vol. 1 of *Genesis of General Relativity*, ed. Renn (cit. n. 1); and Janssen, Norton, Renn, Sauer, and Stachel, *Einstein's Zurich Notebook: Commentary and Essays*, Vol. 2 of *Genesis of General Relativity*, ed. Renn.

hidden connection. For our purposes, the most significant commonality is that they all deal with borderline problems of classical physics. These are problems that can be independently characterized in terms of empirical knowledge but that fall into the domain of (at least) two different conceptual frameworks—for example, electrodynamics and mechanics in the case of the electrodynamics of moving bodies. Because they belong to the domain of distinct conceptual frameworks, they may reveal fundamental tensions, or even contradictions, between these frameworks, such as the conflict between the relativity principle of mechanics and the principle of the constancy of the speed of light that is characteristic of electrodynamics.[7]

General relativity also emerged from a borderline problem, in this case from the border between Newton's theory of gravitation and special relativity. The concrete problem in which this conflict manifested itself was that of free fall in a gravitational field, conceptualized by Einstein in 1907 in terms of the equivalence principle. It helped him bring together Galileo's principle of the universality of free fall and the treatment of accelerated motions according to special relativity. Borderline problems, which reveal conceptual conflicts between two domains of knowledge, typically give rise to a variety of plausible responses. In contrast to some of his contemporaries, Einstein decided to stick with Galileo's principle of the universality of free fall and take its implications seriously enough to begin tinkering with the new concepts of space and time he himself had established just two years earlier when creating special relativity.[8]

The borderline problem of the electrodynamics of moving bodies, embodied in concrete physical experiments such as the Fizeau and Michelson-Morley experiments, involved a clash between two preexisting, fundamental space-time frameworks. One was the framework of classical mechanics, comprising inertial frames and the relativity principle; the other was the framework of classical electrodynamics, comprising the ether and the constancy of the speed of light with regard to the ether frame. It was not immediately apparent that the latter framework was effectively a space-time framework, since the ether was actually considered a physical medium carrying electromagnetic waves. However, it turned out to be impossible to conceive of a physical medium with all the properties required for the ether. It was Einstein's insight that these properties could be more convincingly conceptualized on another level of knowledge: not that of the ontology of physics but, rather, that of its space-time framework. This was only possible, first, because of the universal character of the properties ascribed to the ether and, second, because the classical notions of space and time turned out to be flexible enough to allow for this modification without losing their meaning. The implications of Einstein's insights for a new universal framework of space and time were fully realized in 1908 by Hermann Minkowski, with Minkowski diagrams providing a clear visualization of the space-time properties of special relativity.[9]

The same holds true for the borderline problem that triggered the genesis of general relativity, which, from the perspective of classical physics, was the clash between a particular

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[7] For the notion of borderline problems and their relevance to the genesis of special relativity theory see Jürgen Renn and Robert Rynasiewicz, "Einstein's Copernican Revolution," in *Cambridge Companion to Einstein*, ed. Janssen and Lehner (cit. n. 1), pp. 38–71.

[8] Jürgen Renn, "Classical Physics in Disarray," in *Genesis of General Relativity*, ed. Renn (cit. n. 1), Vol. 1, pp. 21–80.

[9] For the development of Minkowski's view of space-time and his influence on later developments see Peter Galison, "Minkowski's Space-time: From Visual Thinking to the Absolute World," *Historical Studies in the Physical Sciences*, 1979, *10*:85–121; Scott Walter, "Minkowski, Mathematicians, and the Mathematical Theory of Relativity," in *Expanding Worlds of General Relativity*, ed. Goenner *et al.* (cit. n. 1), pp. 45–86; and the historical studies in Vesselin Petkov, ed., *Minkowski Spacetime: A Hundred Years Later* (Dordrecht: Springer, 2014).

field theory and the new space-time framework of special relativity, which imposed conditions on the field theory such as the requirement that no physical effect propagate faster than light. This view of the status of gravity within the special theory of relativity was shared by most of Einstein's contemporaries. Einstein's different perspective on the problem was greatly influenced by his reading of Ernst Mach's critique of classical mechanics. Mach pointed to the possibility that the inertial forces occurring in an accelerated frame may be interpreted as forces between distant masses and hence as comparable to gravitational forces. He thus opened up a perspective that made it possible to conceive of gravitation and inertia as two aspects of the same interaction, though in a very roundabout way. Einstein recalled that electric and magnetic fields were two aspects of the same interaction, which manifested itself differently depending on the chosen frame of reference. This suggested to him a theory of the gravito-inertial field built on the model of electromagnetic field theory but incorporating a generalized principle of relativity. In 1912, five years after these initial insights, he realized that such a theory would have to be built on the metric tensor, which defines the distance between two points in space-time.[10]

What he thus achieved, in hindsight, was a reconciliation of the metric space-time structure of special relativity with the equally universal (though not yet recognized) affine structure. This defines what is meant by parallel directions at distant points in a multidimensional mathematical space and allows for a unified description of gravitation and inertia in classical mechanics. Newton interpreted gravitation as a force; his nineteenth-century followers, including Einstein, interpreted it as a field. Only in the roundabout way whose beginning we have sketched did it gradually become clear that what general relativity resolved was, first of all, a clash between two equally universal structures of space-time, manifested in the borderline problem of free fall as described by the equivalence principle. As John Stachel has pointed out, the awkwardness of this pathway was mainly due to the lack of appropriate mathematical tools to capture one of these structures: the understanding of gravitation and inertia in terms of an affine structure. This was elaborated only after 1915 in the work of Tullio Levi-Civita, Hermann Weyl, and Élie Cartan.[11]

In this manner, general relativity became a theory of space-time, not because of Einstein's predilection for a geometrization of physics, a notion he strongly rejected, but because the "physicalization of geometry," to use Peter Bergmann's expression, emerged from a clash between two preexisting universal space-time structures.[12] Each captured a wealth of physical experiences—in the later language of Jürgen Ehlers, Felix Pirani, and Alfred Schild, the affine (or projective) structures underlying classical mechanics and the light cone or metric structures underlying classical optics and electrodynamics.[13] The wealth of physical experiences

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[10] Alexander S. Blum, Jürgen Renn, Donald C. Salisbury, Matthias Schemmel, and Kurt Sundermeyer, "1912: A Turning Point on Einstein's Way to General Relativity," *Annalen der Physik*, 2012, *524*:A11–A13.

[11] John Stachel, "The Story of Newstein; or, Is Gravity Just Another Pretty Force?" in *Genesis of General Relativity*, ed. Renn (cit. n. 1), Vol. 4, pp. 1041–1078.

[12] Peter G. Bergmann, "Unitary Field Theory, Geometrization of Physics, or Physicalization of Geometry," in *Einstein Symposion Berlin aus Anlaß der 100. Wiederkehr seines Geburtstages, 25. bis 30. März 1979*, ed. H. Nelkowski, A. Hermann, H. Poser, R. Schrader, and R. Seiler (Heidelberg: Springer, 1979), pp. 84–88. Recently, it has been argued convincingly that Einstein himself never viewed geometrization as an essential part of general relativity and instead saw unification (of gravity and inertia) as its main achievement. See Dennis Lehmkuhl, "Why Einstein Did Not Believe That General Relativity Geometrizes Gravity," *Stud. Hist. Phil. Mod. Phys.*, 2014, *46*:316–326.

[13] Jürgen Ehlers, Felix Pirani, and Alfred Schild, "Republication of 'The Geometry of Free Fall and Light Propagation,'" *Gen. Relativ. Gravitation*, 2012, *44*:1587–1609; see also Andrezej Trautman, "Editorial Note to Jürgen Ehlers, Felix Pirani, and Alfred Schild, 'The Geometry of Free Fall and Light Propagation,'" *ibid.*, pp. 1581–1586.

condensed in these structures was, of course, not lost in the transition from classical physics to general relativity, but simply transformed into a more encompassing and coherent overall structure. It is this conservative nature of general relativity, with respect to the knowledge accumulated over centuries in classical physics and even earlier, that accounts to a great extent for both its initial success and its impressive resilience.

The adequate representation and integration of this accumulated knowledge in a coherent mathematical theory was by no means a trivial task, even after Einstein had identified the metric tensor as representing the gravitational potential of his new theory in 1912. Following his pathway to the field equations of general relativity, we observe a fundamental dynamics of theory development that characterizes the later history as well.

Between 1912 and 1915 Einstein followed a double strategy in his search for the gravitational field equation. On the one hand, he started from physically plausible assumptions such as the Newtonian limit, which he then attempted cautiously to generalize. This was his physical strategy. On the other hand, he explored advanced mathematical tools such as the Riemann tensor, trying to extract physically meaningful expressions from them. This was his mathematical strategy.[14]

At first, these strategies seemed to point in different directions. The mathematical strategy delivered candidates that he was unable to reconcile with his physical criteria. The physical strategy eventually led him in 1913 to an acceptable theory—the so-called *Entwurf* theory published jointly with Marcel Grossmann. This theory fell far short of his original ambition, but it did constitute a basis for elaborating the physical consequences of a relativistic theory of the gravitational field, including a detailed, if unsuccessful, calculation of Mercury's perihelion shift. As it turned out, the elaboration of this preliminary mathematical framework constituted an important learning curve that gradually shifted Einstein's physical understanding of the problems at hand, in particular of the role of the Newtonian limit in the new theory. Eventually, the elaborated *Entwurf* theory became capable of functioning like scaffolding—to borrow a notion from Michel Janssen—for reconciling the physical with the mathematical strategies and for constructing full general relativity.[15] All of this took place against the background of an exploration of alternative theories of gravitation as well—in particular of Gunnar Nordström's special relativistic theory of gravitation, which seemed to avoid the radical implications for an understanding of space and time suggested by Einstein's approach.[16] It also occurred against the background of Einstein's tireless efforts to engage astronomers in these issues.[17]

There are many features in this rather unusual history that nevertheless also mark the later development of general relativity. First, the interaction between astronomers and relativists long remained rather limited, in spite of spectacular events such as the solar eclipse and redshift observations mentioned earlier. With few exceptions, physicists and astronomers

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[14] Jürgen Renn and Tilman Sauer, "Pathways out of Classical Physics: Einstein's Double Strategy in Searching for the Gravitational Field Equation," in *Genesis of General Relativity*, ed. Renn (cit. n. 1), Vol. 1, pp. 113–312.

[15] Michel Janssen, "Arches and Scaffolds: Bridging Continuity and Discontinuity in Theory Change," in *Beyond the Meme: Articulating Dynamic Structures in Cultural Evolution*, ed. Alan Love and William Wimsatt (Minneapolis: Univ. Minnesota Press, forthcoming). See also Jürgen Renn, "Standing on the Shoulders of a Dwarf: General Relativity—A Triumph of Einstein and Grossmann's Erroneous *Entwurf* Theory," in *Universe of General Relativity*, ed. Eisenstaedt and Kox (cit. n. 1), pp. 39–51.

[16] John D. Norton, "Einstein, Nordström, and the Early Demise of Scalar, Lorentz Covariant Theories of Gravitation," in *Genesis of General Relativity*, ed. Renn (cit. n. 1), Vol. 3, pp. 413–487.

[17] Klaus Hentschel, *The Einstein Tower: An Intertexture of Dynamic Construction, Relativity Theory, and Astronomy* (Stanford, Calif.: Stanford Univ. Press, 1997).

remained divided by research agendas rooted in disciplinary traditions that were little influenced by general relativity, at least until the renaissance became evident in the 1960s. Second, the complementarity of physical and mathematical strategies remained relevant. Controversies over such issues as the meaning of the energy-momentum pseudo-tensor, of singularities, and of gravitational waves showed that the relation between mathematical formalism and physical interpretation was by no means settled after the publication of the field equations and that, as in the genesis of general relativity, it could only be settled with an exploration of the available mathematical tools and by building up new scaffolding that would lend itself to innovative physical interpretations. Third, the model role of and the interaction with other field theories persisted. In this sense, general relativity did not develop in complete isolation from other parts of physics. Fourth, general relativity continued to compete with other theories, such as alternative proposals for unified field theories and, later, the Jordan-Brans-Dicke theory.[18] Its stability must therefore also be understood as resulting from the exploration and demise of these competitor theories. Fifth, as Jeroen van Dongen has shown, Einstein's mistaken reinterpretation of his own success as the exclusive triumph of a mathematical strategy inspired many physicists, including Einstein himself, to search for unified theories purely on the basis of mathematical generalizations.[19] Sixth, since in the course of the further development of general relativity (at least until the time of the renaissance) no other borderline problem was encountered in which space-time structures of universal significance came into conflict, there was no need on empirical grounds to revise the space-time structure of general relativity further. This is an important factor in accounting for both its stability and its uniqueness in changing our understanding of space and time, with such enduring consequences.

II. GENERAL RELATIVITY AT THE MARGINS

In light of these general remarks, let us now turn to the aftermath of Einstein's creation of general relativity. We shall first consider some theoretical developments, including early attempts to quantize Einstein's theory, and then turn to cosmology and astrophysics. Even in the creation phase, Einstein was not alone but was supported by a network of friends, colleagues, competitors, and interpreters, such as Michele Besso, Marcel Grossmann, Paul Bernays, Erwin Freundlich, Nordström, David Hilbert, Hendrik Lorentz, Moritz Schlick, and many others. After the publication of the theory, this network substantially expanded, though some of the more prominent physicists, such as Max von Laue, remained skeptical.[20] From the beginning, general relativity seemed to point beyond itself, encouraging attempts to modify it or to embed it in larger theoretical frameworks.

When, at a Les Houches meeting in 1963, the Irish mathematician John L. Synge looked back at what he considered to be the rather sparse achievements of the early period, he pointed to this tendency to develop the theory further as one of the reasons: "In those fifty years the progress that has been made is less than one might expect. . . . Another reason is perhaps to be found in the scientific unrest of the twentieth century. Old theories have been

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[18] For the history of the Jordan-Brans-Dicke theory see Hubert Goenner, "Some Remarks on the Genesis of Scalar-Tensor Theories," *Gen. Relativ. Gravitation*, 2012, *44*:2077–2097.

[19] Jeroen van Dongen, *Einstein's Unification* (Cambridge: Cambridge Univ. Press, 2010).

[20] Max von Laue to Moritz Schlick, 19 Aug. 1913, Noord-Hollands Archief Haarlem, Netherlands, Inv.-Nr. 108/Lau-15.

broken up, and the infection of this destructive zeal has incited many to try to modify the new theories. Einstein himself devoted many years to the modification of his 1916 theory."[21]

General Relativity as a Stepping-Stone for Unified Field Theories

Einstein's success set an appealing example for pursuing a purely mathematical strategy. In particular, the use of modified notions of space and time in constructing a new physical theory turned out to be an immensely successful, and thus attractive, heuristic tool. In the early 1920s, scientists such as Niels Bohr believed that quantum theory—in particular, its dual wave/particle description of electromagnetic radiation—might change our notions of space and time as profoundly as had general relativity.[22] Intending to mimic Einstein's alleged path to relativity, many physicists adopted the method of "geometrization" in the sense of using generalized notions of geometry as a new approach to doing physics.

One of the first prominent examples is Hermann Weyl's 1918 attempt to unify gravitation and electromagnetism by introducing a new space-time geometry in which not only the direction but also the length of a vector changes in parallel transport. But, as Einstein objected, in this theory the frequency of the spectral lines would depend on the location and past histories of the atoms, for which there was no evidence.[23] This proposal did not emerge from an empirically motivated borderline problem suggesting a revision of space-time structure but simply introduced a new mathematical option in an attempt at a formal unification. The same holds true for Theodor Kaluza's 1921 proposal to introduce a fifth, space-like, dimension, which achieved a formal unification of gravitation and electromagnetism while arbitrarily restricting the dynamics of space-time in the fifth dimension through a cylinder condition. While these attempts at generalizing the notion of geometry adopted the Einsteinian methodology of constructing a theory as a theory of space-time, they did not bring any new insights into the structure of space-time to the table—or at least none that were in any way related to actual space-time experiences. With the advent of quantum mechanics and quantum field theory, unified field theories receded into the background—a declining research program at the time of the renaissance of general relativity.[24]

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[21] John L. Synge, "Introduction to General Relativity," in *Relativity, Groups, and Topology: Lectures Delivered at Les Houches during the 1963 Session of the Summer School of Theoretical Physics, University of Grenoble*, ed. Cécile DeWitt and Bryce DeWitt (New York: Gordon & Breach, 1964), pp. 4–88, on p. 4.

[22] See, e.g., Bohr's statement in Niels Bohr, "On the Application of the Quantum Theory to Atomic Structure, I: The Fundamental Postulates of the Quantum Theory," *Proceedings of the Cambridge Philosophical Society: Supplement*, 1924, 22:1–42, on p. 35: "The satisfactory manner in which the [light quantum] hypothesis reproduces certain aspects of phenomena is rather suited for supporting the view, which has been advocated from various sides, that, in contrast to the description of natural phenomena in classical physics in which it is always a question only of statistical results of a great number of individual processes, a description of atomic processes in terms of space and time cannot be carried through in a manner free from contradiction by the use of conceptions borrowed from classical electrodynamics, which, up to this time, have been our only means of formulating the principles which form the basis of actual applications of the quantum theory." But by 1927 there was a consensus, at least within the core of the quantum community, that the new quantum mechanics had provided new conceptions, which made a revision of microscopic space-time geometry unnecessary. See Werner Heisenberg, "Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik," *Zeitschrift für Physik*, 1927, 43:172–198.

[23] Albert Einstein to Hermann Weyl, 6 Apr. 1918, in *The Collected Papers of Albert Einstein*, Vol. 8: *The Berlin Years: Correspondence, 1914–1918*, ed. Robert Schulmann, A. J. Kox, Michel Janssen, and József Illy (Princeton, N.J.: Princeton Univ. Press, 1998), p. 710. See also Marco Giovanelli, "'But One Must Not Legalize the Mentioned Sin': Phenomenological vs. Dynamical Treatments of Rods and Clocks in Einstein's Thought," *Stud. Hist. Phil. Mod. Phys.*, 2014, 48:20–44.

[24] For a historical account of the search for unified field theories see Hubert Goenner, "On the History of Unified Field Theories," *Living Reviews in Relativity*, 2004, 7:2, http://www.livingreviews.org/lrr-2004-2; and Goenner, "On the History of

During its low-water-mark period in the 1930s, 1940s, and early 1950s, however, much of the expertise and motivation for exploring Einstein's theory was stored in these traditions of unified field theory, following Einstein's own example of going beyond general relativity.

Just Another Field Theory to Be Quantized

One way of going beyond general relativity, again suggested by the model of electromagnetism, was to quantize it as a relativistic field theory. In the decades following the construction of the first quantum field theories in the late 1920s, immediately after the birth of quantum mechanics, a fair amount of formal progress was made in the quantization of general relativity. Let us give three examples:

- Linearized general relativity was fully quantized by Matvei Bronstein in 1936 and updated to the covariant, renormalized framework by Bryce DeWitt in 1950.
- Techniques were developed for dealing with the constraints imposed by the general covariance of the full theory, as pioneering work by Léon Rosenfeld in 1930 was followed by the development of an elaborate framework of constrained Hamiltonian dynamics by Paul Dirac and Bergmann beginning in the late 1940s.
- Spin ½ particles were integrated into the theory by Weyl and Vladimir Fock in 1929 using the tetrad formulation of general relativity originally developed by Einstein for his unified field theory of teleparallelism.[25]

Still, by the time of the renaissance, this was all there was. There was no theory of quantum gravity to replace general relativity in the way that electrodynamics had been replaced by quantum electrodynamics (QED), a theory that looked quite different from its classical

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Unified Field Theories: Part II (ca. 1930–ca. 1965)," *ibid.*, 2014, *17*:5, http://www.livingreviews.org/lrr-2014-5. For a detailed quantitative study of the literature on unified field theories in the 1920s see Catherine Goldstein and Jim Ritter, "The Varieties of Unity: Sounding Unified Theories, 1920–1930," in *Revisiting the Foundations of Relativistic Physics: Festschrift in Honor of John Stachel*, ed. Abhay Ashtekar, Robert S. Cohen, Don Howard, Jürgen Renn, Sahotra Sarkar, and Abner Shimony (Dordrecht: Kluwer, 2003), pp. 93–150. On Einstein's work on unified field theories see Dongen, *Einstein's Unification* (cit. n. 19); and Tilman Sauer, "Einstein's Unified Field Theory Program," in *Cambridge Companion to Einstein*, ed. Janssen and Lehner (cit. n. 1), pp. 281–305.

[25] The quantization of the linearized gravitational field can be found in Matvei Bronstein, "Quantentheorie schwacher Gravitationsfelder," *Physikalische Zeitschrift der Sowjetunion*, 1936, 9:140–157. Bronstein's work is now famous mainly for his prescient remarks on the difficulties of quantizing the full nonlinear theory, as discussed in Gennady E. Gorelik and Victor Ya. Frenkel, *Matvei Petrovich Bronstein and Soviet Theoretical Physics in the Thirties* (Basel: Birkhäuser, 1994); and John Stachel, "The Early History of Quantum Gravity (1916–1940)," in *Black Holes, Gravitational Radiation, and the Universe*, ed. B. R. Iyer and B. Bhawai (Dordrecht: Kluwer, 1999), pp. 525–534. The pathbreaking works on constrained Hamiltonian dynamics are Peter G. Bergmann and Johanna H. M. Brunings, "Non-Linear Field Theories, II: Canonical Equations and Quantization," *Reviews of Modern Physics*, 1949, *21*:480–487; and Paul A. M. Dirac, "Generalized Hamiltonian Dynamics," *Canadian Journal of Mathematics*, 1950, 2:129–148. The history of early constrained Hamiltonian dynamics, with a focus on Bergmann's work, is discussed in Joshua Goldberg, "Syracuse: 1949–1952," in *Universe of General Relativity*, ed. Eisenstaedt and Kox (cit. n. 1), pp. 357–371; and Donald C. Salisbury, "Peter Bergmann and the Invention of Constrained Hamiltonian Dynamics," in *Einstein and the Changing Worldviews of Physics*, ed. Lehner *et al.* (cit. n. 1), pp. 247–257. The coupling of spin ½ fermions to the gravitational field is introduced in Vladimir Fock, "Geometrisierung der Diracschen Theorie des Elektrons," *Z. Phys.*, 1929, *57*:261–277; and Hermann Weyl, "Elektron und Gravitation: I," *ibid.*, 1929, *56*:330–352. For a historical discussion see Erhard Scholz, "Local Spinor Structures in V. Fock's and H. Weyl's Work on the Dirac Equation," in *Géométrie au vingtième siècle, 1930–2000*, ed. D. Flament, J. Kouneiher, P. Nabonnand, and J.-J. Szesceciniarz (Paris: Hermann, 2005), pp. 284–301. All of the original papers mentioned in this footnote, along with a historical discussion, will be reprinted in Alexander Blum and Dean Rickles, eds., *Quantum Gravity in the First Half of the Twentieth Century: A Sourcebook* (Berlin: Edition Open Access, forthcoming).

predecessor.[26] Quantum gravity offered no empirical predictions: the sole physical quantity to have been calculated was photon-graviton scattering by Rosenfeld in 1930, an absurdly immeasurable quantity. Most important in this context, the attempts at applying formal quantization techniques to general relativity provided no insights into how the resulting theory would modify the picture of space-time offered by classical general relativity.

In fact, a new view of space-time was not the goal of the work on quantum gravity undertaken at the time. Basically, this was the case until the 1970s, when new ways of conceiving of space and time were introduced by Roger Penrose and when string theory, originally conceived in the context of the strong nuclear interaction, established a connection with gravitation.[27] Instead, in the 1950s, the hope was that the quantization of a theory like general relativity—a classical field theory with unique properties—would deliver a better quantum field theory than the renormalized QED and the problematic nuclear field theories of the time. The special property of general relativity at the focus of many such expectations was the determination of the equations of motion for matter through the vacuum field equations alone, as laid out in 1938 by Einstein, Leopold Infeld, and Banesh Hoffmann.[28] Just as the vacuum field equations of general relativity defined the equation of motion of point-like particles through the Einstein-Infeld-Hoffmann procedure, it was hoped that a quantum theory of gravity would similarly give the quantum mechanics (or even the quantum field theory) of matter "for free." John A. Wheeler's invention of geons seems to be the clearest attempt at bringing the geometrical insights of general relativity to bear on outstanding problems in quantum field theory by eliminating particle singularities.[29] Bergmann's first studies of constrained Hamiltonian dynamics were also guided by the goal of obtaining the equations of motion of point singularities in a quantized gravitational field.[30]

Like the tradition of unified field theories, quantum gravity research also fed into the renaissance. It preserved much of the expertise and motivation for exploring general relativity during its low-water-mark period. More specifically, it suggested problems relevant for quantum field theory that turned into problems of intrinsic interest within general relativity. A striking example is the study of particle-like solutions, such as Wheeler's geons, which were supposed to deliver a nonsingular description of quantum matter particles and ended up stimulating the study of topologically nontrivial solutions of the Einstein-Maxwell field

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[26] The standard text on the genesis of QED is Silvan S. Schweber, *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga* (Princeton, N.J.: Princeton Univ. Press, 1994).

[27] Roger Penrose, "Angular Momentum: An Approach to Combinatorial Space-time," in *Quantum Theory and Beyond*, ed. T. Bastin (Cambridge: Cambridge Univ. Press, 1971), pp. 151–180. On string theory's shift from a theory of the strong nuclear interaction to a theory of quantum gravity see Dean Rickles, *A Brief History of String Theory* (Dordrecht: Springer, 2014), Ch. 7.

[28] Albert Einstein, Leopold Infeld, and Banesh Hoffmann, "The Gravitational Equations and the Problems of Motion," *Annals of Mathematics*, 1938, 39:65–100.

[29] In his programmatic 1954 Richtmeyer Memorial Lecture, "Fields and Particles," Wheeler formulated one of his research questions thus: "In which points of principle, if any, do the disturbances [geons] of smallest mass differ from elementary particles?" The lecture manuscript can be found in the John Archibald Wheeler Papers, American Philosophical Society, Philadelphia, Box 182.

[30] In Bergmann and Brunings, "Non-Linear Field Theories, II" (cit. n. 25), p. 480, the authors state: "The motion of field singularities is determined by the field outside the singularities. . . . To this extent, this type of theory is the most nearly self-consistent classical field theory yet devised. . . . The purpose of our present program is to attempt the quantization of such a field theory and to see to what extent the usual divergences of quantum field theory can be avoided."

equations. Similarly, the issue of star collapse was originally meant to provide input on the question of nuclear dynamics and meson decay.[31]

Further examples are Hamiltonian reformulations of general relativity, which were initially undertaken only to allow for the application of canonical quantization techniques; gravitational waves, whose study was also relevant to the quantization program because it allowed the identification of the degrees of freedom to be quantized;[32] and, finally, the initial value problem, motivated in part also by the study of wormholes.[33]

We thus see in the 1950s the hope that the insights into the structure of space-time offered by general relativity might solve some of the open questions of particle physics. However, this was not connected to the promise of a more fundamental space-time theory in quantum gravity. In this sense, quantum gravity traditions stemming from general relativity are closely related to the contemporaneous nongeometric attempts at quantizing a massless spin-2 field in the framework established by Wolfgang Pauli and Markus Fierz and first used for quantizing gravity in Bryce DeWitt's 1950 thesis. Both are mainly concerned with things other than space-time, even where they aim for a final, unified theory.[34] In this regard, the different approaches to quantum gravity pursued in the 1950s and 1960s are more closely related to each other than they are to their respective successors: loop quantum gravity and string theory.

In summary, physicists in the decades after the genesis of general relativity stuck to Einstein's method but not to his theory. The theoretical developments involving general relativity in the period prior to the renaissance made use of central principles of Einstein's theory and of his heuristics and methodology; the physicists who pursued these developments mostly did so, however, not to explore general relativity for its own sake but, rather, from an ulterior motive—the construction of some sort of successor theory. This goal they did not achieve. They did not consider general relativity itself to be a theory fundamental enough to warrant detailed theoretical study, nor did they believe that it held much empirical potential beyond what was already known. There was one central exception to this latter belief, and that is cosmology.

A Contender in the Emerging Field of Physical Cosmology

In the beginning, the establishment of first ties between general relativity and astronomy was a tedious exercise involving only a small number of bridge builders, most notably Freundlich, Karl Schwarzschild, Willem de Sitter, Arthur Eddington, Georges Lemaître, and Edwin Hubble.

From these beginnings, two rather separate research agendas emerged—separate not just from each other, but also from the theoretical developments outlined above. On the one hand, we have investigations of what were to become the three classical tests, envisaged by

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[31] A second research question formulated in Wheeler's "Fields and Particles" lecture (cit. n. 29): "What are the distinctions of principle, if any, between the final stages of collapse of the star, and the steps . . . in the decay of a meson?"

[32] This connection was made as early as 1938 by Jacques Solomon, who pointed out that the field quantization procedure used in electrodynamics would not work for general relativity owing to the (supposed) absence of plane gravitational wave solutions. See Jacques Solomon, "Gravitation et quanta," *Journal de Physique et le Radium*, 1938, 9:479–485.

[33] Charles W. Misner, "Wormhole Initial Conditions," *Physical Review*, 1960, *118*:1110–1111.

[34] Markus Fierz and Wolfgang Pauli, "On Relativistic Wave Equations for Particles of Arbitrary Spin in an Electromagnetic Field," *Proceedings of the Royal Society of London* A, 1939, *173*:211–232; and Carl Bryce Seligman, "I: The Theory of Gravitational Interactions; II: The Interaction of Gravitation with Light" (Ph.D. diss., Harvard Univ., 1949). Carl Bryce Seligman changed his surname to DeWitt in the 1950s. For a discussion of the history of the study of field theories for arbitrary spin and its origins in meson theory see Alexander Blum, "From the Necessary to the Possible: The Genesis of the Spin-Statistics Theorem," *European Physical Journal H*, 2014, 39:543–574.

Einstein as early as 1907.[35] On the other hand, we have investigations of cosmological issues, whose only observational basis was the redshift observations. Of the classical tests, both the bending of light and the gravitational redshift remained controversial matters until the renaissance, since research focused on the development of better measurement techniques and higher precision. This research agenda involved a small number of astronomers interested in a broader spectrum of research activities, not necessarily focused on general relativity.[36] The cosmological research involved a separate group, consisting mostly of mathematicians like Howard Robertson and Cornelius Lanczos and astronomers with strong mathematical training such as Eddington, Lemaître, George McVittie, and William McCrea.[37] They were mainly interested in how to apply general relativity to cosmological problems, which involved not only understanding cosmic dynamics but also solving the intricate problem of interpreting cosmological solutions to the Einstein equations, in particular separating time (which determined the evolution of the universe) from space (to which simplified assumptions concerning the structure of the universe, such as homogeneity and isotropy, were to be applied).[38]

Once the framework for a relativistic cosmic dynamics was established, it was separate enough from the full theory of general relativity to open an arena of cosmological debate in which the framework could be challenged and modified with consequences affecting only the cosmological sector. In the early 1930s, starting from purely philosophical considerations about the construction of a theory so far removed from experimental evidence, Edward Milne held that cosmology should be a purely deductive field of research. He constructed a cosmology starting from special relativity and the cosmological principle—that is, the principle that there is no privileged point of observation in the universe. Milne's theory engen-

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[35] Einstein publicly discussed the light-bending effect and the gravitational redshift in Albert Einstein, "Über das Relativitätsprinzip und die aus demselben gezogen Folgerungen," *Jahrbuch der Radioaktivität und Elektronik*, 1907, 4:411–462, rpt. in *The Collected Papers of Albert Einstein*, Vol. 2: *The Swiss Years: Writings, 1900–1909*, ed. John Stachel, David C. Cassidy, Jürgen Renn, and Robert Schulmann (Princeton, N.J.: Princeton Univ. Press, 1989), pp. 432–488. A reference to the Mercury perihelion is in Einstein to Conrad Habicht, 24 Dec. 1907, in *The Collected Papers of Albert Einstein*, Vol. 5: *The Swiss Years: Correspondence, 1902–1914*, ed. Martin J. Klein, A. J. Kox, and Schulmann (Princeton, N.J.: Princeton Univ. Press, 1993), p. 82.

[36] For the history of the controversy surrounding the astronomical tests of general relativity up to 1930 see Jeffrey Crelinsten, *Einstein's Jury: The Race to Test Relativity* (Princeton, N.J.: Princeton Univ. Press, 2006). That the issue was unsettled at the outset of the renaissance is demonstrated by the different opinions held by two experts who discussed the observational status of general relativity at the "jubilee" conference in Bern in 1955. While Robert J. Trumpler stated that evidence appeared not to contradict the theoretical predictions of general relativity, Erwin Freundlich voiced some doubts on the reliability of the evidence summarized by Trumpler. See Robert Trumpler, "Observational Results on the Light Deflection and on Red-shift in Star Spectra," in *Fünfzig Jahre Relativitätstheorie: Jubilee of Relativity Theory, Helvetica Physica Acta, Supplementum IV*, ed. André Mercier and Michel Kervaire (Basel: Birkhäuser, 1956), pp. 106–133.

[37] A notable exception is the American physical chemist Richard C. Tolman, who made important contributions to relativistic cosmology and who also wrote the first textbook on the subject: Richard C. Tolman, *Relativity, Thermodynamics, and Cosmology* (Oxford: Clarendon, 1934). The impact of works on cosmological issues concerning the interpretation of the Schwarzschild solution is addressed in Eisenstaedt, "Trajectoires et impasses de la solution de Schwarzschild" (cit. n. 2).

[38] The relevance of these kinds of issues in the genesis of relativistic cosmology has been discussed in Pierre Kerszberg, *The Invented Universe: The Einstein–De Sitter Controversy (1916–1917) and the Rise of Relativistic Cosmology* (Oxford: Clarendon, 1989). A thorough analysis is in Janssen, "'No Success Like Failure . . .'" (cit. n. 1). See also Christopher Smeenk, "Einstein's Role in the Creation of Relativistic Cosmology," in *Cambridge Companion to Einstein*, ed. Janssen and Lehner (cit. n. 1), pp. 228–269. For comprehensive historical accounts of twentieth-century cosmology see John D. North, *The Measure of the Universe: A History of Modern Cosmology* (Oxford: Oxford Univ. Press, 1965); Jacques Merleau-Ponty, *Cosmologie du XXe siècle: Étude épistémologique et historique des théories de la cosmologie contemporaine* (Paris: Gollimard, 1965); Helge Kragh, *Cosmology and Controversy: The Historical Development of Two Theories of the Universe* (Princeton, N.J.: Princeton Univ. Press, 1996); and Malcolm Longair, *The Cosmic Century: A History of Astrophysics and Cosmology* (Cambridge: Cambridge Univ. Press, 2006).

dered a controversy that lasted until the 1940s and as a side effect suggested the formulation of the Robertson-Walker metric.[39]

In 1948, similar philosophical considerations led Hermann Bondi, Thomas Gold, and Fred Hoyle to propose another alternative to relativistic cosmology, christened the "steady-state" theory. It extended the cosmological principle, claiming that there is no privileged time, either, and thus implying a constant matter density. To reconcile this with expansion, it was necessary to postulate the continuous creation of matter. Proponents of the steady-state theory ridiculed the notion of a universe originating in an initial singularity as a "big bang," which to them seemed a physically unacceptable extrapolation of relativistic cosmology. Big bang cosmology actually had some initial success at this point, in particular with the explanation of the frequency of elements through George Gamow's 1946 work on primordial nucleosynthesis. But the need to trust extrapolations of general relativity all the way back to times far removed from the present (and even all the way back to the initial singularity) made such early-universe cosmology highly doubtful, and thus steady-state theory was long considered a preferred theory of the universe.[40]

Again, it needs to be stressed that the antirelativistic stance of steady-state theory was limited to the cosmological arena and did not constitute a disavowal of the basic space-time notions of general relativity itself. Remarkably, this separation from the foundations of general relativity holds true on both sides: Gamow's original note on nucleosynthesis does not mention the word "relativity" at all but refers only to "the general theory of [the] expanding universe."[41]

In summary, the cosmological application of general relativity was shaped by disciplinary divides and by controversies related to questions that were largely philosophical and methodological.

Apart from the case of cosmology, applications of general relativity beyond the three classical tests were on even shakier ground. Gravitational waves remained a controversial issue until the renaissance in the 1950s, when they were tackled with the help of new techniques and concepts such as the Bondi news function. The study of collapsing stars had been pursued since the pioneering work of Subrahmanyan Chandrasekhar on white dwarves in the early 1930s. The first to use general relativity in treating a collapsing star were J. Robert Oppenheimer and Hartland Snyder, who generalized Schwarzschild's result to allow for a nonstationary eternal collapse. Little emphasis was placed on the various singularities occurring in these calculations, and in any case this work received very little attention from the physics community at the time, with notable exceptions such as Lev Landau. Like early-universe cosmology, their approach was regarded as an unwarranted extrapolation of general relativity,

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[39] Edward A. Milne, *Relativity, Gravitation, and World-structure* (Oxford: Clarendon, 1935); Howard P. Robertson, "Kinematics and World Structure," *Astrophysical Journal*, 1935, 82:284–301; and Arthur G. Walker, "On Milne's Theory of World Structure," *Proceedings of the London Mathematical Society*, 1936, Ser. 2, 42:9–127. An analysis of the debate, its philosophical implications, and its influence on the formulation of the steady-state theory is given in George Gale and John Urani, "Milne, Bondi, and the 'Second Way' to Cosmology," in *Expanding Worlds of General Relativity*, ed. Goenner *et al.* (cit. n. 1), pp. 343–375. See also Gale, "Cosmology: Methodological Debates in the 1930s and 1940s," in *The Stanford Encyclopedia of Philosophy*, Spring 2014 ed., ed. Edward N. Zalta, http://plato.stanford.edu/archives/spr2014/entries/cosmology-30s/.

[40] For the origin of the name and its reception within the communities of physicists and astronomers see Helge Kragh, "Naming the Big Bang," *Hist. Stud. Nat. Sci.*, 2014, 44:3–36. For the historical reconstruction of the controversy between steady-state and big bang cosmologies see esp. Kragh, *Cosmology and Controversy* (cit. n. 38).

[41] George Gamow, "Expanding Universe and the Origin of Elements," *Phys. Rev.*, 1946, 70:572–573, on p. 573.

which had a clearly delimited empirical domain, originally confined to the small effects observable in the solar system.[42]

Cosmological and astrophysical applications did not significantly change the situation we observed in discussing theoretical developments. Certain aspects of the theory were considered useful in specific contexts, but not as belonging to an overarching research agenda in relativity. Moreover, the means of communication employed by scientists working on problems related to general relativity did not favor a smooth and rapid transmission of knowledge. Papers on these matters could be found in highly diverse publications in disciplines such as mathematics, astrophysics, and physics. There were no conferences specifically dedicated to exploring all aspects of general relativity. In short, it was not possible easily to identify a coherent community of its practitioners.

III. REINVENTING RELATIVITY IN THE RENAISSANCE

Within a few years all of this changed. General relativity became the uncontested theory of space and time, trusted all the way down to the Planck length.[43] It became the physical basis of astrophysics and observational cosmology. An international society devoted to general relativity and gravitation was established, with frequent meetings and its own journal, and leaders in the field, such as Stephen Hawking and Roger Penrose, came to be counted among the most renowned scientists in the world.

The beginnings of the renaissance that would place general relativity at the forefront of physics in the 1960s were rather unspectacular. A handful of physicists planned a conference to honor the fiftieth birthday of special relativity at its birthplace in Bern. In his role as president of the conference, Pauli wrote to Jordan: “In spring 1955, we want to hold a congress on relativity theory and cosmology in Bern. Because of the fiftieth anniversary of Einstein’s first work in Bern, there is actually a chance of getting money for this.”[44]

At the time, building on the significant role of physics in World War II and its continuing importance in the global arms race during the Cold War, substantial funding and talent were flowing into the field of theoretical physics in general. In addition, the global connectivity of the field had increased, with international conferences and meetings being held on various

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[42] For the history of gravitational waves, including the introduction of the Bondi news function, see Kennefick, *Traveling at the Speed of Thought* (cit. n. 5). The history of the Schwarzschild singularity and its neo-Newtonian interpretation is thoroughly analyzed in Jean Eisenstaedt, “Histoire et singularités de la solution de Schwarzschild (1915–1923),” *Arch. Hist. Exact Sci.*, 1982, 27:157–198; and Eisenstaedt, “Trajectoires et impasses de la solution de Schwarzschild” (cit. n. 2). As Eisenstaedt rightly stresses, Oppenheimer and Snyder built on the work on the transformation of coordinates previously accomplished by Lemaître and Lewis Tolman: Eisenstaedt, “Lemaître and Schwarzschild Solution,” in *Attraction of Gravitation*, ed. Earman *et al.* (cit. n. 1), pp. 353–389. However, Oppenheimer and Snyder seem to have been the first to apply general relativity to the properties of a concrete stellar object. For Landau’s reaction to the Oppenheimer-Snyder paper see Thorne, *Black Holes and Time Warps* (cit. n. 3), p. 219.

[43] First timid statements to this effect can be found as early as 1963 in John Archibald Wheeler, “Geometrodynamics and the Issue of the Final State,” in *Relativity, Groups, and Topology*, ed. DeWitt and DeWitt (cit. n. 21), pp. 317–520, on p. 506: “These estimates . . . rest on the idea that present theory makes sense down to 10^{-33} cm. . . . For Einstein’s equations to be of any use at this level of analysis, they must apply not merely down to 10^{-13} cm but down through twenty further orders of smallness. One has as little—and as much—justification to expect this range of predictive power out of general relativity as he did from the inverse square law in electricity.”

[44] “Im Frühjahr 1955 wollen wir einen Kongreß über Relativitätstheorie und Kosmologie in Bern machen. Anläßlich des 50jährigen Jubiläums der Abfassung von Einsteins erster Arbeit in Bern besteht nämlich die Aussicht, dafür Geld zu bekommen.” Wolfgang Pauli to Pascual Jordan, 3 Feb. 1954, in *Wolfgang Pauli: Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.*, Vol. 4, Pt. 2: *1953–1954*, ed. Karl von Meyenn (Heidelberg: Springer, 1999), pp. 442–443, on p. 443 (our translation).

specialized subjects, many of them supported by the International Union of Pure and Applied Physics. Nevertheless, Pauli—despite the fact that he was a recent Nobel laureate—felt that he had best make the most of the opportunity the anniversary offered to obtain funds for a conference on relativity. Given the state of the field, as described above, this is hardly surprising.

But, as we have shown in the preceding pages, there was what one might call a hidden and dispersed potential embedded in a variety of research traditions touching on general relativity. It was this potential that was now activated under the new conditions of affluence for physics. Nonetheless—considering, for example, that the funding for the Bern conference was obtained mainly for celebratory rather than scientific reasons—this activation can hardly be considered inevitable: it was entirely likely that money would flow instead into fields with a more coherent community and a greater relevance to practical applications. As our historical research has evidenced, the renaissance of general relativity can also be understood as a feat of the emerging community itself, and so, in this sense, the beginning of this historical process might be moved back to the mid 1950s, when early attempts at community building took place.

It is striking that the year of the first conference dedicated entirely to issues related to relativity coincided with the death of its creator. Einstein's death was announced while final preparations for the conference were being made. Some have claimed that this somehow liberated the physics community from the spell of unified field theory.[45] To us, it seems rather to have been a wake-up call—Pauli referred to it as "alarming news"—reminding a dispersed community that if general relativity was to be pursued and kept alive, its fate was now in their hands.[46]

But how exactly was the existing potential for further development now being activated? In 1955, several of the research centers that would shortly become hubs of the new relativity community were already active in all the various fields that had kept the tradition of general relativity alive (see Table 1).[47] To name only the most influential sites: Syracuse University with Bergmann; Princeton with Wheeler; the Paris groups around the figures of André Lichnerowicz and Marie-Antoinette Tonnelat; London with Bondi; and Warsaw with Infeld. That very same year a younger generation of theoretical physicists, some of them interested in quantum gravity, established other stable centers of research in the United States, such as Bryce DeWitt and Cécile DeWitt-Morette at the University of North Carolina.

This multitude of smaller local centers, rather than hindering the coordination of the research, was turned into an asset. The growth in the number of physicists had led to a transformation of the curriculum: the tradition of a long and mobile postdoctoral education was established. Although still rather small when compared to other research fields in physics, its former incoherence provided the general relativity community with a large variety and a significant geographical spread of temporary "homes" for the increasing number of young

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[45] So, e.g., suggests Bernard Schutz, "Thoughts about a Conceptual Framework for Relativistic Gravity," in *Einstein and the Changing Worldviews of Physics*, ed. Lehner *et al.* (cit. n. 1), pp. 259–269.

[46] Wolfgang Pauli, "Opening Talk," in *Fünfzig Jahre Relativitätstheorie*, ed. Mercier and Kervaire (cit. n. 36), p. 27.

[47] In this section we refer to the qualitative concepts of network analysis as employed in sociology, such as networks, hubs, and connectivity. See, e.g., Stanley Wasserman and Katherine Faust, *Social Network Analysis: Methods and Applications* (Cambridge: Cambridge Univ. Press, 1994); and Duncan Watts, *Six Degrees: The Science of a Connected Age* (New York: Norton, 2003). For a pioneering attempt at applying network theory to historical processes see Irad Malkin, *A Small Greek World: Networks in the Ancient Mediterranean* (Oxford: Oxford Univ. Press, 2011).

Table 1. Research Centers on Topics Related to General Relativity in 1955

Institutions	Leader(s)	Major Research Interests	Starting Year
Cambridge University (UK)	Fred Hoyle	Cosmology	1948
Collège de France (France)	André Lichnerowicz	Unified field theories—mathematical methods	1952
Copenhagen University (Denmark)	Christian Møller	General relativity proper	1952
Dublin Institute for Advanced Study (Ireland)	John L. Synge	General relativity proper	1948
Hamburg Observatory (West Germany)	Otto Heckmann	Cosmology	
King's College, University of London (UK)	Hermann Bondi	Gravitational waves	1954
Institut für reine Mathematik der Deutschen Akademie der Wissenschaften zu Berlin (East Germany)	Achille Papapetrou	General relativity proper	1952
Institut für Theoretische Physik der Universität Bern (Switzerland)	André Mercier	Philosophical problems of general relativity	1948
Institut für Theoretische Physik—Hamburg University (West Germany)	Pascual Jordan	Unified field theory	1951
Institute of Field Physics—University of North Carolina (USA)	Bryce DeWitt, Cécile DeWitt-Morette	Quantum gravity	1955
Leningrad University (USSR)	Vladimir Fock	Noncovariant approach to general relativity	ca. 1952
Princeton University (USA)	John A. Wheeler	Geometrodynamics	1952
Purdue University (USA)	Frederick Belinfante	Quantum gravity	1955
Research Institute for Advanced Study, Baltimore (USA)	Louis Witten	Theories of gravitation	1955
Stevens Institute of Technology (USA)	James Anderson		1952
Stockholm University (Sweden)	Oskar Klein	Unified field theories	
Syracuse University (USA)	Peter Bergmann	Quantum gravity	1947
Technion—Israel Institute of Technology (Israel)	Nathan Rosen	General relativity proper—bimetric theories	1953
Université Libre de Bruxelles (Belgium)	Jules Géhéniau, Robert Debever	Mathematical methods	1955
Warsaw Institute of Theoretical Physics (Poland)	Leopold Infeld	General relativity proper	1950

Note.—This table is not intended as a comprehensive list of all scientists working on general relativity and related subjects in 1955 but, rather, represents in alphabetical order those stable research centers that would become relevant in the establishment of the interinstitutional network between 1955 and 1962. The stability of these research centers was guaranteed, in turn, by the permanence of (at least) one leader pursuing his or her research agenda related to the field of general relativity and gravitation, as well as by the availability of funds. The starting dates are approximate and were calculated on the basis of the recollections or the biographies of the scientists and the list of articles related to general relativity and gravitation published in the *Bulletin on General Relativity and Gravitation* between 1962 and 1969. When no date is indicated it means that the center was active since before the end of World War II.

Ph.D.'s who had recently finished their graduate studies. Many of these young researchers worked in three or four of the above-mentioned centers at one time or another, contributing their own knowledge reserves and at the same time coming into contact with different perspectives and different research agendas.[48]

To give just one example: the British theoretical physicist Felix Pirani earned a Ph.D. doing work on quantum gravity with Alfred Schild at the Carnegie Institute of Technology in Pittsburgh in 1951. He decided to continue his studies, focusing on different problems, in the United Kingdom under Bondi and then, before earning a second Ph.D. in 1955, spent a year at the Dublin Institute for Advanced Studies with Synge in 1954–1955. He later worked at Warsaw University in the group headed by Infeld, at the Institute of Field Physics with the DeWitts, and, between 1958 and 1959, at the Research Institute for Advanced Study with Louis Witten—all before obtaining a more permanent position as lecturer in mathematics at King's College, London.[49]

From the mid 1950s on, this structure of stable centers and highly mobile and well-trained specialists greatly increased the connectivity of the network of scholars working on general relativity–related problems at the interinstitutional and international level. But merely establishing contact between the various centers was not enough, especially since their leaders still followed widely divergent research agendas. The heterogeneous character of the research in the field of general relativity became evident at the Bern conference. The various commentators attempting to summarize the results reported at the meeting were unable to find a common way of categorizing the topics that had been dealt with.[50]

Nonetheless, it was thanks to the Bern conference and later follow-up events that scholars were able to recognize for the first time that important progress was being made in general relativity proper—for instance, on issues such as the Cauchy problem. They were also able to identify important common questions that were essential for different research agendas, such as the existence and properties of gravitational waves.[51] The emerging community was thus

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[48] The relevance of the postdoc cascade in the transmission of new knowledge products in the post–World War II period has been emphasized in David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: Univ. Chicago Press, 2005), esp. pp. 60–111. For the enormous growth of physics manpower in the United States from the postwar period up to 1970 see Kaiser, "Booms, Busts, and the World of Ideas: Enrollment Pressures and the Challenge of Specialization," *Osiris*, 2012, N.S., 27:276–302. Information about the establishment of research centers and the role of the Air Force in providing economic support for theoretical activities concerning the field of general relativity and gravitation can be found in Rickles, "Chapel Hill Conference in Context" (cit. n. 4); Goldberg, "U.S. Air Force Support of General Relativity" (cit. n. 4); Goldberg, "Syracuse" (cit. n. 25); Ezra T. Newman, "A Biased and Personal Description of GR at Syracuse University, 1951–1961," in *Universe of General Relativity*, ed. Eisenstaedt and Kox (cit. n. 1), pp. 373–383; and various recollections and interviews of the physicists working in the 1950s and early 1960s, including, e.g., John Archibald Wheeler, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York: Norton, 1998), and Roger Penrose, "The Rediscovery of Gravity: The Einstein Equation of General Relativity," in *It Must Be Beautiful: Great Equations of Modern Sciences*, ed. Graham Farmelo (London: Granta, 2002), pp. 47–79.

[49] Dean Rickles, interview of Felix Pirani, 23 June 2011, Niels Bohr Library and Archives, American Institute of Physics, College Park, Maryland, http://www.aip.org/history/ohilist/34463.html.

[50] See the different categorizations employed by Pauli, McCrea, and Bergmann in Wolfgang Pauli, "Schlußwort den Präsidenten der Konferenz," in *Fünfzig Jahre Relativitätstheorie*, ed. Mercier and Kervaire (cit. n. 36), pp. 261–267; William McCrea, "Jubilee of Relativity Theory: Conference at Berne," *Nature*, 1955, *176*:330–331; and Peter Bergmann, "Fifty Years of Relativity," *Science*, 1956, *123*:487–494. The difficulty of finding a shared way to categorize the different activities that were related to the field of general relativity and gravitation persisted in the following conferences. See esp. the difference between the categories listed in André Lichnerowicz and Marie-Antoinette Tonnelat, "Introduction," in *Les théories relativistes de la gravitation*, ed. Lichnerowicz and Tonnelat (Paris: Centre National de la Recherche Scientifique, 1962), p. 13; and those employed in Bergmann, "Allocution de cloture," *ibid.*, pp. 463–475.

[51] For studies on the Cauchy problem in general relativity in a previous period see John Stachel, "The Cauchy Problem in General Relativity—The Early Years," in *Studies in the History of General Relativity*, ed. Eisenstaedt and Kox (cit. n. 1), pp. 407–418.

Figure 1. John L. Synge's lecture at the international conference held in Warsaw and Jablonna in July 1962. This conference was the fourth international conference dedicated to topics related to general relativity. It was later referred to as GR3, whereas relativists christened the Bern conference "GR0" to imply that it was a starting point for a stable tradition of international conferences that continues to this day. In the first row, left to right: Leopold Infeld, Vladimir Fock, James L. Anderson, Ezra Ted Newman, Roger Penrose, Banesh Hoffmann. At the far right: Roza Michalska-Trautman. From Leopold Infeld, ed., *Relativistic Theories of Gravitation: Proceedings of a Conference Held in Warsaw and Jablonna, July 1962* (Oxford: Pergamon, 1964), p. xvii.

able to build a core of knowledge around which it could formulate a transformed research agenda that focused increasingly on general relativity proper, whose challenging mathematical structure was ever more explored.[52] (See Figure 1.)

This convergence created a new dynamics of intellectual exchange and innovation in general relativity. Gravitational waves, for instance, which had been a marginal subject subordinated to other research agendas, became a central issue within general relativity proper. New information now traveled much more effectively, not only from one geographical

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[52] After the Bern conference, Bergmann stated: "The very fact that interest in general relativity has recently increased throughout the world is indicative of the fact that its implications have not *yet* been fully worked out and exploited for our understanding of the physical universe as an organic whole." Peter Bergmann, "Fifty Years of Relativity" (cit. n. 50), p. 494. Wheeler expressed a similar judgment two years later. Focusing on the initial value problem, he maintained that "this is one of the most important problems of relativity theory, and one may well believe that it must be solved before further progress with quantization of the theory can be made." John Wheeler, "The Present Position of Classical Relativity Theory and Some of Its Problems," in *Role of Gravitation in Physics*, ed. DeWitt and Rickles (cit. n. 4), pp. 43–60, on p. 45.

location to another but also among subfields of general relativity. A striking example is the Petrov classification, today also known as the Petrov-Pirani-Penrose classification. This was developed in the rather marginal University of Kazan (in the USSR), was subsequently taken up by Pirani to treat gravitational waves, and went on to become an essential tool used by Roy Kerr in the construction of his solution of Einstein's field equations.[53]

Alongside the new practice of long postdoctoral training, other changes in the transmission of knowledge enhanced the effectiveness of communication among researchers and the institutionalization of their practices. In 1959, during the third international conference, held at the Royaumont Abbey near Paris, the leaders of the field decided to establish an international committee to stabilize the tradition of these international conferences and improve communication among researchers working in different geographical areas as well as on different research agendas. To achieve this goal, the new International Committee on General Relativity and Gravitation published a periodical, the *Bulletin on General Relativity and Gravitation*, to transmit important pieces of information; it ran from 1962 until 1970, when it was absorbed by the journal *General Relativity and Gravitation*—the first journal entirely devoted to the field.

The *Bulletin* published a list of scientists actively working on, or interested in, general relativity and gravitation, along with their affiliations and research interests. The initial list, containing 223 scientists, was the first official document recognizing the members of the recently established relativity community (or, better, the general relativity and gravitation community, as it would come to be called) as a group.[54] Including the names of interested researchers served to create new connections between scholars working on similar topics. Moreover, the *Bulletin* listed papers on subjects related to general relativity and gravitation published in the last few years. Given that publications in the field were still widely dispersed in the early 1960s, establishing the *Bulletin* was a momentous step in the construction of the community.[55] The importance of such a step cannot be overestimated, because it was a way actively to create a connection between scientists still working within defined disciplinary and national boundaries. According to André Mercier—who was the secretary of the International Committee from its establishment until its transformation into the International Society on

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[53] Aleksei Z. Petrov, "Klassifikacya prostranstv opredelyayushchikh polya tyagoteniya," *Uchenye Zapiski Kazanskogo Universiteta: Seriya Fiziko–Matematicheskie Nauki*, 1954, *114*:55–69 (English translation in Petrov, "Classification of Spaces Defined by Gravitational Fields," *Gen. Relativ. Gravitation*, 2000, 32:1665–1685); Felix Pirani, "Invariant Formulation of Gravitational Radiation Theory," *Phys. Rev.*, 1957, *105*:1089–1099; and Roy Kerr, "Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics," *Physical Review Letters*, 1963, *11*:237–238. For personal recollections concerning the transmission of this tool see Rickles, interview of Pirani (cit. n. 49); and Kerr, "Discovering the Kerr and Kerr-Schild Metric," in *The Kerr Spacetime: Rotating Black Holes in General Relativity*, ed. David L. Wiltshire, Matt Visser, and Susan S. Scott (Cambridge: Cambridge Univ. Press, 2009), pp. 38–72.

[54] "Names and Addresses of Scientists Working in the Field of GRG," *Bulletin on General Relativity and Gravitation*, 1962, *1*:3–38.

[55] A preliminary study of the publication venues of papers on general relativity and gravitation listed in the twenty-one volumes of the *Bulletin on General Relativity and Gravitation* shows that such articles were widely dispersed in journals devoted to physics, mathematics, and astronomy/astrophysics and in general scientific journals, especially those connected to national or local scientific societies. Between 1948 and 1962, about 1,400 papers in the field of general relativity and gravitation were published in more than two hundred journals, in at least six different languages. Moreover, the politics of publication still followed very local dynamics. Before 1960, Bergmann, e.g., published almost exclusively in *Physical Review* and other journals of the American Physical Society. The *Physical Review*, in turn, published almost exclusively papers written by American physicists or physicists who were working in American institutions at that time. Lichnerowicz and Tonnelat published their papers in French journals; Infeld's preferred publication venues were Polish journals such as *Acta Physica Polonica* and the *Bulletin of the Polish Academy of Science*; and so forth.

General Relativity and Gravitation in 1974 —the success of the *Bulletin* was enormous in this regard. It became an essential instrument in community building and in spreading information among interested scientists on a regular basis.[56]

IV. CONCLUSION AND OUTLOOK

The historiographical framework we have proposed indicates that the historical process that has been dubbed the "renaissance of general relativity" can be understood as resulting from the confluence of several factors closely interacting with each other. One was the untapped potential of general relativity as a physical theory, which could be explored with the help of new mathematical tools but also using experimental techniques. Once the proper conditions for the emergence of a new perspective were in place, general relativity was turned from a framework for treating a set of diverse problems into a field of study in its own right. One of these conditions was the creation of a powerful and flexible institutional structure, a process that began in the mid 1950s. This institutional structure allowed practitioners of general relativity to overcome both disciplinary and national divides and to develop a perspective on general relativity as an integrated field. This autocatalytic process, driven by the interaction of internal and external factors, explains why the emerging relativity community was capable of reacting so quickly and so effectively to the challenges raised by the new astrophysical discoveries of the 1960s: they were able to make use of both their newly developed theoretical tools and their experience in active community building. Even if general relativity was not immediately used to give a realistic physical description of the dynamics involved in the newly discovered astrophysical objects, it was accepted that it would be able to do so and that the general physical mechanisms it proposed to describe—for example, the formation of quasars—were correct.

In the four decades following the creation of general relativity, people had been inspired by and tried to mimic Einstein's methodology rather than sticking to the theory of general relativity, which they tried to supersede. The renaissance turned this around: general relativity now became central to research and the research community and attracted a wealth of new, post-Einsteinian tools and methodologies. It was, in short, reinvented as a subdiscipline of physics.[57]

As a consequence of the breakthroughs that took place during the renaissance, trust in general relativity greatly increased. It now became the basis of an emerging standard model of the evolution of the universe and the theoretical framework for a wealth of astrophysical phenomena. The search for gravitational waves was transformed into a potential new window on the universe rather than simply representing a test for general relativity.

This assessment of general relativity has changed little over the last half century: in our current understanding, the description of space-time by general relativity has a wide domain of applicability. As we hope to have shown, this promise was by no means clear from the outset. While the research programs that tried to modify space and time failed, those that did not touch on space and time succeeded. With the great success of general relativity, it might

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[56] On the publication of the *Bulletin on General Relativity and Gravitation* and Mercier's role in the institutionalization of the GRG community see André Mercier, "Editorial," *Gen. Relativ. Gravitation*, 1970, *1*:1–7; Mercier, "General Relativity at the Turning Point of Its Renewal," in *Studies in the History of General Relativity*, ed. Eisenstaedt and Kox (cit. n. 1), pp. 109–121; and Alan Held, Heinrich Leutwyler, and Peter Bergmann, "To André Mercier on the Occasion of His Retirement," *Gen. Relativ. Gravitation*, 1978, 9:759–762.

[57] An interesting historical project would be to investigate the parallels with the emergence of the foundations of quantum mechanics as a subdiscipline in its own right in the late twentieth century.

have been hoped that its concept of space and time would even prove to be final. This finality might have manifested itself in two ways.

On the one hand, beginning in the 1950s, some physicists argued for the peaceful coexistence of a classical field theory of gravity alongside a quantum field theory of microscopic interactions.[58] In such a scenario, all the attempts at unification and quantization would have been entirely misguided. But this assumption could be shown to lead to inconsistencies, and a widespread consensus emerged that any field that was able to couple to a quantum system—as gravitation necessarily does—must itself be quantized.[59] Thus it was clear that here—in dealing with questions that would not be accessible to experiments in the foreseeable future—lurked the unavoidable borderline problem of microscopic gravitational interaction.

The other option was that the space-time concept of general relativity might be carried over to the microscopic domain of quantum theory rather straightforwardly through some process of quantization. It was clear that quantization would not leave the space-time picture of general relativity entirely unchanged, but it would then be merely a question of interpreting the implications of a quantum theory of gravity *after* its establishment. This hope was nourished by the great success of renormalized quantum field theory (quantum field theory having gone through several low-water-mark periods of its own) and the establishment of the standard model of particle physics in the early 1970s.[60]

But almost immediately it was shown that the techniques that had led to successful quantum field theories of the nuclear interactions would not be applicable to gravity, which turned out to be perturbatively nonrenormalizable.[61] Only now did gravity emerge as the lone classical field theory to resist quantization, and quantum gravity begin to look like what we see it as today: the central unsolved problem of fundamental theoretical physics.

It became clear that new foundational assumptions were needed to construct a theory of quantum gravity and that fundamentally new ideas concerning the microscopic structure of space-time were necessary. The lack of empirical borderline problems at the intersection between quantum theory and gravity was met by a new approach: instead of hoping to obtain

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[58] A main proponent of this view was Léon Rosenfeld. See, e.g., his extended comments in *Relativistic Theories of Gravitation: Proceedings of a Conference Held in Warsaw and Jablonna, July 1962*, ed. Leopold Infeld (Oxford: Pergamon, 1964), pp. 219–222.

[59] See Claus Kiefer, *Quantum Gravity*, 2nd ed. (Oxford: Oxford Univ. Press, 2007), pp. 15–22, for an extensive discussion of the various arguments brought against such a semiclassical theory, along with references to the original literature.

[60] The first low-water-mark period of quantum field theory—the crisis of infinities—came immediately after its creation. See, e.g., Alexander Rueger, "Attitudes towards Infinities: Responses to Anomalies in Quantum Electrodynamics, 1927–1947," *Historical Studies in the Physical and Biological Sciences*, 1992, 22:309–337. A second low-water-mark period followed in the 1960s, when the methods developed for quantum electrodynamics did not appear to be transferable to the nuclear interactions and S-matrix theory was poised to replace quantum field theory, as discussed in James T. Cushing, *Theory Construction and Selection in Modern Physics: The S-Matrix* (Cambridge: Cambridge Univ. Press, 1990). A synthetic account of the creation of the standard model of particle physics remains to be written, but an overview can be found in Lillian Hoddeson, Laurie Brown, Michael Riordan, and Max Dresden, eds., *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s* (Cambridge: Cambridge Univ. Press, 1997).

[61] The first proof of the perturbative nonrenormalizability of general relativity was in fact provided by the same physicists who had just proved the renormalizability of the electroweak gauge theories of the emerging standard model of particle physics: Gerardus 't Hooft and Martin Veltman, "One-Loop Divergences in the Theory of Gravitation," *Annales de l'Institut Henri Poincaré, Section* A, 1974, 20:69–94. Owing to the great complexity of the question, many other articles could also be cited, for 't Hooft and Veltman concede at the end of their paper: "We do not feel that this is the last word on this subject, because the situation . . . is so complicated that we feel less than sure that there is no way out. A certain exhaustion however prevents us from further investigation, for the time being" (p. 94).

fundamental insights into the nature of space and time by welding together quantum theory and general relativity,[62] physicists had now convinced themselves that it was necessary to start from fundamentally new ideas concerning the structure of space-time in order to construct a quantum theory of gravity. The most notable instance of this approach is string theory, which came up as early as the mid 1970s as a potential basis for a quantum theory of gravity. Loop quantum gravity followed in the 1980s, and nowadays a fair number of other approaches to a quantum theory of gravity are being pursued by smaller research groups and communities, all with decidedly different ideas about the fundamental structure and even the existence of space-time.[63]

The tension between quantum theory and gravity now manifested itself not in empirical borderline problems but, rather, in the difficulties encountered in extracting from an elaborate and radically new fundamental structure a mathematically consistent theory of microscopic gravity that is consistent with the low-energy theories of general relativity and quantum theory. These difficulties— one might mention the additional dimensions needed for a self-consistent string theory— can be viewed as manifestations of the tensions at the borderline of general relativity and quantum theory. They might remind us, as historians, of the consistency issues encountered when trying to bridge the borderline between the classical theories of electromagnetism and mechanics through the overarching ether structure, such as the difficulty of assigning consistent mechanical properties to the ether. Einstein realized that the problem could be simplified by thinking instead in terms of the structure of space and time itself. Quantum gravity, on the other hand, might not be about space and time after all.

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[62] This was still the standard view of quantum gravity as late as 1970. See Bryce DeWitt, "Quantum Theories of Gravity," *Gen. Relativ. Gravitation*, 1970, *1*:181–189, on p. 181, where he writes: "It is now clear that no obstacles of principle exist which prevent the unification of the quantum theory and general relativity. Several formalisms providing such unification are very much alive and kicking. These formalisms invoke no new axioms of physics; rather they provide us with new insights into what we already have and what we can yet do with quantum field theory."

[63] On string theory see Rickles, *Brief History of String Theory* (cit. n. 27). For an overview of the history of loop quantum gravity (and quantum gravity in general) see Carlo Rovelli, "Notes for a Brief History of Quantum Gravity," arXiv:gr-qc/0006061 (2000). On some of the less widely used approaches see also Daniele Oriti, ed., *Approaches to Quantum Gravity: Toward a New Understanding of Space, Time, and Matter* (Cambridge: Cambridge Univ. Press, 2009).