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The renaissance of General Relativity: How and why it happened

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After an initial burst of excitement about its extraordinary implications for our concept of space and time, the theory of general relativity underwent a thirty-year period of stagnation, during which only a few specialists worked on it, achieving little progress. In the aftermath of World War II, however, general relativity gradually re-entered the mainstream of physics, attracting an increasing number of practitioners and becoming the basis for the current standard theory of gravitation and cosmology-a process Clifford Will baptized the Renaissance of General Relativity. The recent detection of gravitational radiation by the LIGO experiment can be seen as one of the most outstanding achievements in this long-lasting historical process. In the paper, we present a new multifaceted historical perspective on the causes and characteristics of the Renaissance of General Relativity, focusing in particular on the case of gravitational radiation in order to illustrate this complex and far-reaching process.

The year 2015 marked the centenary of Einstein's final formulation of the gravitational equation that bears his name, the cornerstone of the general theory of relativity. Almost exactly one hundred years after the theory's inception, the direct detection of gravitational waves through a large-scale experiment operated by the multinational LIGO Collaboration has confirmed one of its most elusive predictions. With this momentous achievement, general relativity has once again strengthened its position as the standard theory of gravitational phenomena and the basis of cosmological models, in spite of the still unresolved difficulties in reconciling Einstein's theory with quantum mechanics.

The central position the theory continues to hold in our description of the physical world might not seem all that surprising, given its immediate spectacular confirmation (Eddington's solar eclipse expedition of 1919) and Einstein's subsequent rise to scientific superstardom. However, historical investigations have revealed that matters appeared quite different after the initial hype and before the current age of spectacular experimental and observational confirmations. In the early years after its formulation, the epistemic status of general relativity theory was highly uncertain in many respects, from the understanding of its physical implications to the interpretation of the impact of a choice of coordinate system on the result obtained. A perfect example of the uncertainty concerning the epistemic status of the theory is the early debate on the nature and existence of gravitational waves within the framework of general relativity. The 1916 correspondence between Einstein and the astronomers Karl Schwarzschild and Willem de Sitter reveals how confused the connections between the theory and its physical consequences were in the months following the formulation of the theory. Thanks to these epistolary exchanges, Einstein passed from believing that his gravitational theory implied the non-existence of gravitational waves to demonstrating that gravitational wave solutions of the linearized approximation of general relativity exist and carry energy [1]. The formula of gravitational radiation Einstein derived in 1916 was incorrect, though. It permitted the radiation of energy from monopole sources. It was only after reviewing calculations made by the Finnish physicist Gunnar Nördström that Einstein discovered an error in his 1916 derivation of the gravitational radiation and was able to derive the correct quadrupole formula of gravitational radiation in 1918 (apart from a factor of two) [2].

Moreover, only a few years after Eddington's observations of the bending of light general relativity underwent

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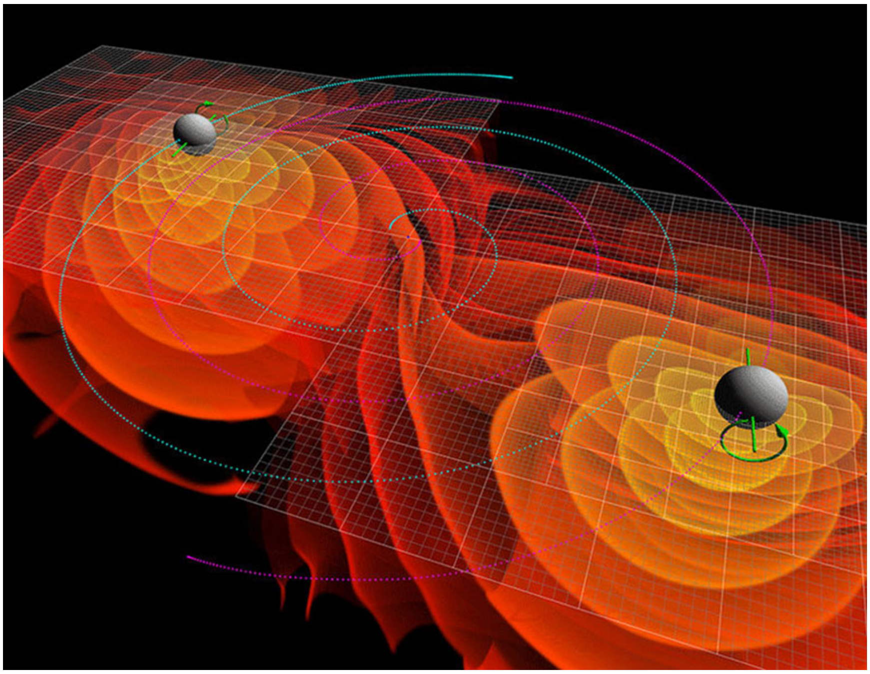

Figure 1 Numerical simulations of the gravitational waves emitted by the inspiral and merger of two black holes. The colored contours around each black hole represent the amplitude of the gravitational radiation; the blue lines represent the orbits of the black holes and the green arrows represent their spins.

(Image: NASA/Ames Research Center/C. Henze)

a period of marginalization within the field of physics—labeled by Jean Eisenstaedt the "low-water-mark" period of general relativity—that lasted roughly from the mid-1920s to the mid-1950s. During this period most physicists considered general relativity as a highly formalistic theory providing only small corrections to the Newtonian picture. The comprehension of the most subtle physical consequences of the theory remained limited as most scholars employed what Eisenstaedt called a neo-Newtonian interpretation, where general relativity only provides small corrections to a gravitational interaction otherwise conceptualized in terms of Newton's theory [3]. From a social perspective, only a small number of theoretical physicists worked on the theory, as the majority focused on the development of quantum theory, which had far stronger links with both experimental activities and possible technological applications. Theoretical research on gravitational waves played no significant role during the "low-water-mark" period; those few works that tackled the subject added nothing new to the existence debate. Einstein himself came to doubt the existence of gravitational waves and, in 1936, even wrote a paper (with his collaborator Nathan Rosen) purporting to demonstrate the point. But a referee spotted a mistake in their argument and the paper ended up being published in a different journal, with a modified conclusion that left the original question entirely open. Although the published paper thus did not add anything of substance to the question of the existence of gravitational waves, Einstein's wavering on this point did have a sociological effect and was probably responsible for the attitude of some of his closest collaborators, Leopold Infeld and Nathan Rosen, who for a long time continued to be skeptical about the possibility that gravitational radiation could carry away energy from binary systems [4].

In our recent historical investigation on the causes underlying the status of the research field of general relativity in the so-called "low-water-mark" period, we focused on the way in which general relativity retained its singular position, despite manifold attempts to modify and replace it with more encompassing theories. A closer look at the main research projects of the period related to the general theory of relativity shows that they were mostly aimed at going beyond general relativity from different perspectives: through the search for unified field theories of gravitation and electromagnetism (pursued most notably by Einstein himself); through the attempts to incorporate general relativity into the framework of quantum theory; and by developing a theory of physical cosmology [5].

The first research stream was dominated by a purely mathematical strategy, which aimed at mimicking and repeating Einstein's successful strategy of constructing a new physical theory by introducing modified notions of space and time. While these attempts at doing physics by generalizing geometry did in a sense follow Einstein's methodology, what they lacked was the input of actual spatio-temporal experiences and thought experiments that had guided Einstein toward his new space-time framework in the first place [6].

The second path for going beyond general relativity was to quantize, i.e., to construct a quantum theory that would have the same relation to general relativity, as, e.g., quantum electrodynamics had to Maxwell's theory. While, during the low-water-mark period, some formal progress was made in the quantization of general relativity by studying formal analogies and disanalogies with quantum electrodynamics, these studies never amounted to the formulation of a full, workable theory of quantum gravity; much less did it shed any light on the novel implications for our notions of space and time that such a theory might have.

In both the abovementioned research agendas pursued during the "low-water-mark" period, physicists 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 as well as of his heuristics and methodology. The physicists who pursued these developments mostly did so, however, not to explore general relativity for its own sake; instead they aimed at integrating specific, attractive elements of general relativity into some sort of universal successor theory, be it a unified field theory or a quantum field theory, encompassing both electrodynamics and gravitation. They believed that the fundamental insights to be taken from Einstein's revolutionary theory were not be sought in the empirical domain, but rather in its theoretical structure, expecting general relativity to act as a blueprint for a future theory of everything.

The only empirical domain where general relativity was believed to have some impact beyond small corrections to the Newtonian picture was cosmology. Cosmological research was pursued by a small group of scientists, mostly mathematicians and astronomers with strong mathematical training. They were interested in the specific application of general relativity to cosmological problems, which encompassed not only the empirical structure of understanding cosmic dynamics with the help of Einstein's theory, but also the intricate theoretical problem of interpreting cosmological solutions to the Einstein equations, in particular separating time (which determined the evolution of the universe) from space (to which a simplified assumption concerning the structure of the universe, such as homogeneity and isotropy, was to be applied). After the general implications of general relativity for cosmology (e.g., the description of cosmic dynamics in terms of a dynamical space-time metric) had been established, the cosmological debate was separate enough from the full theory of general relativity to open a field of discussion in which these implications could be modified and challenged within the cosmological sector, without implying any modification of Einstein's theory proper. So, even in the case of cosmology, we observe the same development identified in our discussion of the purely theoretical developments: certain aspects of the general relativity were considered useful in specific contexts, but were not viewed as forming the hard core of a research program in relativity.

This kind of epistemic eclecticism was accompanied by social dispersion. A number of important insights were actually reached within the research branches related to general relativity just described, but these advances had no further impact on the strongly dispersed network of practitioners, divided, as it was, by disciplinary and national boundaries. Research on general relativity suffered from not being perceived as a (sub-)disciplinary domain in its own right, and the diverse group of mathematicians, physicists and astronomers, who were interested in the theory did not share a common knowledge foundation, which could have enabled interdisciplinary collaborations and conversations. Besides the difficulty of sharing knowledge and novel insights through disciplinary boundaries, national divides also hindered cooperation and transfer of knowledge. The result was that the few scientists who worked on the theory of general relativity did so in isolation or in small groups bound to specific institutions. In addition, 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 such matters were published in highly diverse publication venues with different disciplinary affiliations, such as *Monthly Notices of the Royal Astronomical Society*, *Annals of Mathematics*, and *Physical Review*. There were, it almost goes without saying, also no conferences specifically dedicated to general relativity. In brief the scientific field called general relativity, which we take for granted today, with entire research institutes devoted to the subject, did not exist at all in the low-water-mark period.

The research traditions focusing respectively on unified field theories, quantum gravity and cosmology did, however, keep interest in general relativity alive and, for all their shortcomings, formed the basis for what is known as the "Renaissance of general relativity," as the physicist Clifford Will designated the process of general relativity's return to the mainstream of physics and its emergence as a scientific field in its own right under the more favorable societal conditions of the postwar period [7].

Despite their dispersion, the research agendas pursued during the "low-water-mark" period acted as a conduit for the transmission of general relativity to the next generation. And the fact that the aim of these research projects had chiefly been that of going beyond general relativity meant that there was a wide array of approaches to general relativity, a dispersed potential as it were, which was then activated under the new conditions of affluence for physics in the postwar period. How exactly, now, did this activation occur?

Because of the fundamental role of physics in World War II and its continuing relevance in the global arms race during the Cold War, substantial funding and talent flowed into the field of theoretical physics in general. Around 1955, a number of research centers focusing on the abovementioned research projects related to general relativity were active in different parts of the globe. These research centers were characterized by the presence of one principal investigator with a stable position who had the opportunity to pursue one specific project and to build a small group with younger researchers working on topics related to the principal research project. Relevant examples of these kinds of centers were: Syracuse University with Peter Bergmann; Princeton University with John A. Wheeler; the Paris groups led by André Lichnerowicz and Marie-Antoinette Tonnelat, respectively; King's College in London with Hermann Bondi; the University of Warsaw with Leopold Infeld; the University of Hamburg with Pascual Jordan; the Institute for Pure Mathematics of the German Academy of Sciences at Berlin, GDR, under Achilles Papapetrou; and the Institute of Field Physics at the University of North Carolina directed by Bryce DeWitt and Cécile DeWitt-Morette.

The majority of these research centers, focusing on specific research agendas related to general relativity, profited from the boom that was transforming the landscape of theoretical physics in the postwar period. The increase of both the funding for and the social status of theoretical physics, as well as the enormous increase in the number of new PhDs, in turn increased the scientific production of these centers, as well. This quantitative increase in productivity would not, by itself, have been sufficient to overcome the lack of communication that had prevented the evolution of commonly shared knowledge in general relativity in the decades before. One crucial element in the dynamics of the "renaissance" of general relativity was the establishment of a stable tradition of a long post-doctoral education. The growing number of young PhDs in theoretical physics could not easily and quickly be absorbed by the academic system. It therefore became customary to spend two or three years—in some cases many more—in various institutes as a post-doc. The mobility of these young researchers—the "postdoc cascade," as David Kaiser has called it—improved and strengthened the communication between scientists working on issues related to general relativity, and allowed for the transfer of theoretical tools, concepts, and problems among individual research centers, and even from one research tradition to another [8].

These were all general trends and similar stories could be told for many sub-disciplines of physics, although the qualitative changes brought about by these developments were naturally greater in a small and previously marginal, if not non-existent, field, such as general relativity. Another essential factor in the renaissance, particular to general relativity was the *explicit* attempts at building a scientific community where, initially, there was only a set of very diverse research agendas, loosely connected by the fact that knowledge of general relativity and specific theoretical tools were required. These attempts began in 1955 with the Bern conference, held to celebrate the fiftieth anniversary of special relativity, but concerned almost exclusively with topics and problems connected to general relativity [9]. The Bern conference was the first occasion in which some of the historical actors could recognize that there were various active research agendas related to general relativity and that these agendas could be jointly promoted by means of well-directed social action. This recognition led to the organization of further, equally, if not more, successful international conferences (like the Chapel Hill conference in 1957 and the Royaumont conference in 1959, and the Warsaw/Jablonna conference in 1962) [10]—which soon led to a stable tradition of GR conferences, continuing to this day—and to the creation of an international institution called the International Committee on General Relativity and Gravitation in 1959. With the establishment of an institutional body also came the social identification of a research field that from that year onward was commonly known as General Relativity and Gravitation, or GRG for short [11].

The new possibilities for scientific interactions had a tremendous impact on the way in which the theory of general relativity and its relation to the wider field of physics were perceived. Those members of the newly established GRG community who were closer to physics, as a discipline and a larger scientific community, recognized that there were fundamental unanswered questions concerning the theory of general relativity proper, which were of relevance for all the different research agendas related to the theory. Some of widely recognized leaders of the newly emerging field of General Relativity and Gravitation explicitly formulated a research program aimed at a better understanding of general relativity proper and its physical implications, in order to establish a common basis for pursuing the different research projects. One of the most important open questions, and one of the first to be tackled by the newly emerging community as a whole, was the question of the existence and the physical properties of gravitational waves. In the mid-1950s there was an enormous amount of confusion surrounding the existence of gravitational waves and their properties. Some of the scholars who were at the time establishing new research centers now even decided to make this topic the main investigatory focus at their centers. This is, e.g., the case for the work pursued at King's College in London under the leadership of Bondi. A few months after Bondi decided to make gravitational waves the main topic of his research center one of his collaborators, Felix Pirani, obtained a fundamental result that deeply influenced the theoretical developments in gravitational wave research in the following years [12]. The renewed interest in gravitational radiation had immediate ramifications for experimental activities, when Joseph Weber of the University of Maryland began pursuing a long-lasting project aimed at the direct detection of gravitational waves using an instrument he himself devised: the Weber bar [13].

This shift of the research agendas toward more conservative topics, which focused on general relativity proper and were sometimes even physically relevant enough to spark new experimental undertakings, is the central epistemic factor in the "renaissance" of general relativity [14]. The turn towards more physical (rather than philosophico-mathematical) questions anticipated, and was in turn re-enforced by, the new astrophysical discoveries of the 1960s. When new astrophysical objects, soon to be dubbed quasars, were discovered in 1963, the community of relativists was well prepared, both with regard to theoretical developments and with regard to community building: not only were they able to quickly provide a heuristic physical model explaining the observed properties of quasars, as the Kerr solution of the Einstein equations, describing a rotating black hole, was developed in that same year, 1963, independent of all astrophysical considerations; they also, within just a few months, inaugurated a new series of large conferences explicitly dedicated to the exploration of the connections between the novel astrophysical discoveries and their theoretical explanation in the context of general relativity [15]. Even if general relativity was not immediately used to give a realistic physical description of the detailed dynamics involved in the quasars, it was quickly and widely accepted that the general physical mechanisms at work had been identified and that their further study would have to rely on the rapidly developing theoretical toolbox of general relativity, implying the formation of an entirely new field: relativistic astrophysics. The speed with which this process occurred would have been unthinkable without the strong community and the new theoretical approach that relativists had built in the course of the preceding decade.

As we have tried to show, our investigation provides an interpretation of the renaissance of general relativity as the product of the interplay of what we call internal and environmental factors. The internal factors refer to the resilient theoretical framework provided by general relativity to physicists working in diverse and dispersed fields; the external factors relate to the changing working conditions of physicists in the post-war period that include—beside the rapid technological development—the novel possibilities for the mobility of young researchers, for the transfer of knowledge in a growing international community, and for the self-organization of that community in international institutional bodies.

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 a coherent and communal investigation of the theoretical core of general relativity for its own sake and for the creation of a community specifically dedicated to this investigation. During the period of the "renaissance," general relativity was turned by these dynamics from a theoretical framework into a field of research in its own right.

The theoretical physicist Kip S. Thorne—one of the major proponents of the LIGO experiment—has described the period immediately following the renaissance, the years from 1963 to 1974, as the "Golden Age of general relativity" [16]. During this period the theory of general relativity produced deep conceptual transformations resulting in a clear understanding of the most exciting physical implications of the theory of general relativity such as black holes and gravitational waves. With the recent observation of the gravitational radiation emitted by two giant black holes that merged more than a billion years ago, the LIGO experiment has thereby produced direct evidence of two of the most novel and historically contested predictions of the theory of general relativity. Thanks to this result, the connection between theoretical research in general relativity and its empirical applications is being radically transformed, with gravitational waves no longer appearing just as the object of theoretical and experimental inquiry, but rather as a novel tool for observing the universe in what has been called gravitational-wave astronomy. This transformation might perhaps signal that general relativity is on the verge of entering a new historical phase, an age in which hard-won scientific insights are finally applied, akin to the industrial revolution, as new instrumentation is being built to observe astrophysical phenomena through a new window, opened not just by Einstein's theory, but also by the theoretical and conceptual innovations of the renaissance of general relativity.

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