Eur. Phys. J. H (2026)51:7
https://doi.org/10.1140/epjh/s13129-026-00119-z

The European Physical Journal H

Regular Article

A forgotten theory of quantum gravity: Suraj N. Gupta and his quantization of general relativity

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Received 16 April 2025 / Accepted 3 March 2026

Abstract Gupta was among the first to attempt the quantization of Einstein's nonlinear theory of gravity. He had an independent program to quantize gravity in a manner akin to electromagnetism, which spanned at least two decades. He adopted the flat-space views of Rosen and Papapetrou and built his theory around these ideas. Although he was well known for his work in quantum electrodynamics, little is known about his work in quantum gravity. For that reason, in this paper, we try to present a historical overview of his research program.

1 Introduction

Bryce DeWitt, a towering figure in the field of quantum gravity (QG), recalled in 1994,

> I had a strong feeling that Einstein's theory was in a sort of limbo, detached from the rest of physics, and that it was a shame that such a beautiful theory should be so ignored. I proposed to drag it forcibly into the then-modern world by redoing Schwinger's QED calculations with the gravitational field added. I was very naive in those days. (See, e.g., [1], pp. 29–31.)

It was a daring attempt by DeWitt. Leave aside the quantization of general relativity (GR); back then, GR itself was not a mainstream research field in the USA. Despite this, Julian Schwinger,[1] DeWitt's PhD advisor at Harvard, allowed him to perform Rosenfeld's earlier calculations [2] on the gravitational self-energy of a photon in the lowest order of perturbation theory, however, in a manifestly covariant way. He completed his thesis in 1949, entitled "I: The Theory of Gravitational Interactions. II: The Interaction of Gravitation with Light." Therein he introduced the concept of fixed "background space," thereby permitting the treatment of nonlinearities of GR perturbatively in a Lorentz covariant fashion. It marked the birth of the covariant (perturbative) quantization program of quantum gravity.[2] That same year, another approach to quantum gravity emerged with the works of Bergmann, Dirac, Pirani, and Schild. They followed a different, more traditional Hamiltonian ("canonical") quantization path to quantize GR, thus preserving its main feature of "background independence."[3] This lack of *a priori* geometry is what separates both approaches. The canonical program was initiated by the classification of the gauge constraints that were present in the theory. This is best reflected in the "primary" and "secondary" constraints of Bergmann vs. the "first" and "second" class constraints of Dirac. (see, e.g., [4]) This trend would follow throughout.

The ensuing decade was therefore very crucial for the development of QG as a research field. In fact, it was not until the 1950 s that it emerged as an independent field in its own right. To make it clear, contrary to the present scenario,[4] the word "quantum gravity" was still tied exclusively to the problem of quantizing GR. Around the same time, GR re-established itself as a main stream of research in the physics community. Therefore, this period is often called the Renaissance of GR in the historiography of physics, accounting for the fact that in the preceding

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[1] Schwinger himself did not become interested in general relativity until the 1950 s.

[2] A few scattered works recognizing the need of reconciling gravity with quantum had already begun to appear much earlier. (See, e.g., [3] for a detailed review of these preliminary efforts in the first half of the 20th century.)

[3] The term "background independence" here is used in a rather modern context.

[4] E.g., quantum gravity could refer to any quantum theory that reduces to GR in an appropriate classical limit.

decades, GR was stagnant as a field of theoretical research and was studied mainly by mathematicians.[5] Several members of the canonical camp would also go on to contribute to this revival (See e.g., [6], pp. 612–618.).

By the late 1950 s, the Hamiltonian structure of the classical GR was fully elucidated; however, the quantum theory would have to wait since the program faced major conceptual difficulties, notably "the problem of observables" and "the problem of time" (see, e.g., [4,7]). The latter is due to the vanishing of the canonical Hamiltonian in GR, rendering the associated time evolution $e^{-i\hat{H}t}$ trivial in quantized theory. The covariant camp on the other side had made significant progress already at the beginning of the decade. A concise theory of covariant quantum GR has been put forward by an Indian-born quantum field theorist, Suraj N. Gupta, on the other side of the Atlantic. Gupta just completed his PhD from Cambridge. The program started by DeWitt a few years ago seemed (almost) complete. Richard Feynman, who just became interested in the subject, joined the camp; however, it was not until the late 1950 s that he started thinking more seriously about it. He brought attention back to the program by including, for the first time, nonlinear terms in the calculations. His findings hinted toward the possible non-renormalizability of gravity at higher orders. By this time, Gupta was also convinced that "the renormalization theory completely breaks down" for gravitational interactions. In the following decades, further evidence was found supporting this claim, culminating in a widely accepted belief that GR is perturbatively non-renormalizable. To this end, the covariant program was called "dead" [8].

Thus, DeWitt, Feynman, and Gupta were arguably the three main actors of the covariant program in the 1950 s. DeWitt started the program in the late 1940 s; Gupta outlined a framework (though qualitatively different from that of DeWitt and Feynman, as we shall see later) in the early 1950 s and studied it until the end of the decade; and Feynman explored it to an end in the early 1960 s, where it is still stuck to this day. Gupta is certainly an atypical entry here, or perhaps in the entire list of quantum gravity researchers of the era. In the mid-1950 s, a new tradition of international GR conferences began. Both DeWitt and Feynman actively participated in these early conferences and were therefore certainly aware of each other's progress. These conferences played a key role in the Renaissance of GR. Gupta, however, did not become part of this emerging community. By the time the first such conference was organized in Bern, Switzerland, in 1955, he was mainly focusing, though with very limited horizons, on the conceptual aspects of his theory. For him, the quantization problem of GR was already solved, and therefore, his interest in the subject gradually declined in the following years. Besides, to the best of our knowledge, he never crossed paths with either DeWitt or Feynman, which is surprising given the fact that he was already in the USA by that time.

Gupta's contribution is largely unknown, especially in present times. Though a few authors[6] have tried to address his work, these are still very limited in their treatment. Besides, as it appears from his writings, he was a straightforward physicist who, despite spending a significant amount of time on theoretical aspects of the problem, rarely made detailed remarks. This *to-the-point* description often leads to a misrepresentation of his ideas and beliefs to the readers. The present work attempts to fill these gaps by outlining his research program more clearly and how it came to be. Gupta's scientific career is chronicled along the way.

2 DIAS and the unification agenda

Before moving to the main story, it is necessary to take a detour to Gupta's theory of quantum electrodynamics (QED), as the tools he designed there facilitated a smooth transition to quantum GR. Moreover, this early phase of his research career reveals the extrinsic factors that shaped his broader perspective in achieving the goal.

In 1946, when the whole world was seeing the aftermath of World War II, Gupta received his master's degree from St. Stephen's College, Delhi; however, in India, the chaos would not settle until the next few years since it was also the peak of India's independence movement, which would eventually lead to its independence in 1947 from the British Empire. During the course of these major events, Gupta, along with Ramesh Chandra Majumdar[7][10], then newly appointed professor at Delhi University, published his first article in March 1947 on the self-energy of an electron in motion. Such "self-energy" problems had been investigated by several physicists by that time, and the emphasis was put on taming the infinities occurring in these calculations. However, a coherent quantization scheme for the free electromagnetic field (in terms of electromagnetic gauge field A_μ) was not yet available, let alone QED, and the success of the earlier methods relied on separating the longitudinal part of the A_μ from the transverse part and replacing it with the static Coulomb potential, which is left unquantized, thus destroying the *Lorentz* covariance and symmetry of the theory. This led to unnecessary complications in the practical calculations. Gupta

5 For more details, see, e.g., [5].

6 See, e.g., "Covered with Deep Mist: The Development of Quantum Gravity (1916–1956)" by Dean Rickles [9] for another nice (more philosophical) account of the development of quantum gravity research between 1916 and 1956, including a brief overview of Gupta's program.

7 R. C. Majumdar was a renowned Indian theoretical physicist who made significant contributions to ionospheric physics. A brief biography of him can be found at https://insaindia.res.in/BM/BM21_9907.pdf.

and Majumdar noticed in their analysis that if the longitudinal and transverse degrees of freedom of A_μ are treated equally, it could simplify the computation of the self-energy of an electron. This requirement of symmetry was also observed by Feynman, Schwinger, and Tomonaga in their QED calculations. The scalar photon (the timelike component of A_μ), however, demanded the use of *indefinite*[8] metric due to the opposite sign in its (covariant)[9] commutation relations[10]

$$[A_\mu(x), A_\nu(x')] = \frac{i}{2}\eta_{\mu\nu} D\,(x - x') \tag{1}$$

compared to other photons. This spoiled the physical interpretation of the theory since, upon quantization, some states occur with negative probabilities. Dirac [11] proposed an interesting solution by changing the roles of the creation and annihilation operators for scalar photons. However, the trick did not work since it was later shown by S.T. Ma [12] that the *physical*[11] states are not normalizable. So by the late 1940 s, it was clear that the symmetric quantization of the A_μ field was indeed achievable; however, a final bit was missing. In 1950, Gupta [13] completed the framework by modifying the gauge conditions, restoring the usual interpretation of the creation and annihilation operators. He introduced a weaker version of the (quantum) Lorentz[12] gauge conditions[13]

$$\left[\frac{\partial A_\mu}{\partial x_\mu}\right]^+ \phi = 0. \tag{2}$$

This changes the definition of physical states ϕ in the theory, however, in a fully consistent manner.

The requirement for such gauge conditions was due to the fact that the scalar part of A_μ has a vanishing conjugate momentum and is therefore nondynamical, thereby making it impossible to implement the canonical commutation relations (CCR). To overcome this, Fermi in 1932 [15] proposed adding an additional gauge symmetry breaking term to the Maxwell Lagrangian in order to modify the dynamics of the scalar part; however, to maintain consistency, this extra term is implemented as a quantum mechanical gauge condition. For the Lorentz gauge

$$\frac{\partial A_\mu}{\partial x_\mu} = 0, \tag{3}$$

such modification would lead to wave equations

$$\Box^2 A_\mu = 0 \tag{4}$$

for the gauge field A_μ as equations of motion with $\Box^2 \equiv \nabla^2 - (1/c^2)\partial^2/\partial t^2$. The usual quantization procedure can then be carried out, and the resulting theory contains four types of photons. Though only two transverse photons are physically observable, the remaining scalar and longitudinal photons are to be eliminated by the quantum mechanical gauge conditions $< \partial^\mu A_\mu >= 0$. However, as mentioned earlier, the usual Lorentz conditions demanded several ad hoc fixes to the theory.

In contrast, Gupta's splitting of Lorentz conditions into positive and negative frequencies[14] turned out to be entirely consistent. The indefinite metric and the normalizability of physical states fit together perfectly. This formalism was further developed later that same year by Konrad Bleuler [16] to also include the interactions of

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[8] In general, an indefinite metric space is a vector space where norms are not necessarily positive. In the context of quantum theory, given a (normalized) state Ψ in a Hilbert space $\mathcal{H}$, the state norm (probabilities!) is defined as $\|\Psi\| := \Psi^*\Psi = 1$. The introduction of indefinite metric η means the norm is defined as $\|\Psi\| := \Psi^*\eta\Psi$, which can be $\|\Psi\| < 0$. The latter is, however, not compatible with the probability interpretation of (normalized) state norms in quantum theory.

[9] Note that these are different (though related via simple time derivative on both sides with $[\partial D/\partial t]_{t=t'} = -\delta^{(3)}(\mathbf{x} - \mathbf{x}'))$ from the standard (canonical) commutation relations, which read$[A_\mu(\mathbf{x}, t), \pi_\nu(\mathbf{x}', t)] = -i\eta_{\mu\nu}\delta^{(3)}\,(\mathbf{x} - \mathbf{x}')$, where $\pi_\mu(\mathbf{x}, t) = \frac{\partial A_\mu(\mathbf{x},t)}{\partial t}$ are the canonical conjugate momenta to A_μ. These canonical relations are also known as equal time commutation relations, as they single out specific time t, thus destroying the Lorentz covariance. The latter can, of course, be shown to hold after the quantization procedure; however, it can be tricky. Due to this, covariant commutation relations are superior to canonical ones, as they preserve manifest Lorentz covariance throughout the quantization procedure.

[10] Please note that we avoid using the usual hat symbol, which distinguishes quantum mechanical operators from their classical counterparts; however, the context should make the differences clear.

[11] I.e., the states ϕ satisfying the gauge conditions $[\partial^\mu A_\mu]\,\phi = 0$.

[12] Often called "Lorenz gauge" in honor of its original founder, Ludwig V. Lorenz (see, e.g., [14]).

[13] The plus sign here refers to the positive frequency part in the mode expansion of $\partial^\mu A_\mu$.

[14] The gauge conditions (2), together with their conjugate, imply the full (quantum) Lorentz gauge conditions $< \partial^\mu A_\mu >= 0$.

electromagnetic fields with electrons (QED!) and is therefore now widely known as the "Gupta–Bleuler formalism" of QED in literature. He also proved in his paper by means of canonical transformation that their theory was exactly identical to the orthodox theory described at the beginning of the section, maintaining all of the latter's physical outcomes.

After his graduation in 1946, Gupta moved to Ireland, where he was at the Dublin Institute for Advanced Studies (DIAS) during 1948–1949. There he likely worked with Walter Heitler[15], a German physicist who was an expert in QED. DIAS was established in the late 1930 s, based on the Institute for Advanced Study (IAS) in Princeton, USA. It was the first of its kind in Europe and the second in the entire world after the IAS. Far from mainland Europe, it became "an oasis of peace"[16] for European researchers in exile. It accommodated many distinguished physicists of the time, which quickly led it to become a flagship center for theoretical research. The school of theoretical physics placed strong emphasis on areas like unified field theory and general relativity, in stark contrast to the scenario in the USA. Therefore, Gupta was just at the right place at the right time. Exactly at what point he became concerned about the quantization of gravity, and for what reason, is unclear at the moment. But it seems these ongoing developments at the DIAS likely played a major role in shifting his focus toward the quantization of the gravitational field as soon as he finished working on QED. In particular, unification became the guiding principle in his quest for quantum GR, as we shall see later.

3 QG: the Gupta–Bleuler way

Gupta left Dublin in 1949 to pursue his PhD in England. He continued working on QED. Two years later, in 1951, he completed his doctoral studies (the thesis entitled "Some Contributions to Classical and Quantum Electrodynamics") at Cambridge. He maintained his focus on QED for the upcoming few years and addressed the subject once in a while (see e.g., [17,18]). However, already in 1951, he began applying the machinery of Gupta–Bleuler formalism to gravity.

Gupta applied for the I.C.I. (Imperial Chemical Industries) fellowship to continue his research after his PhD. The selection of institutes included Edinburgh and Manchester. He received an earlier call from Edinburgh and, therefore, accepted it.[17] However, it meant that he would not get to work with Léon Rosenfeld, who was in Manchester at the time. He was disappointed. Léon Rosenfeld was one of the pioneers to work toward the quantization of the gravitational field. In fact, he worked at the foundations of both the covariant and canonical approaches as early as 1930 [2,19]. He introduced the theory of constrained Hamiltonian dynamics, the identity of the canonical approach, which predates by two decades the rediscovery of it by Dirac and Bergmann (see, e.g., [20]). Manchester was therefore pretty obvious, and Gupta knew that. Fortunately, he was later able to transfer to Manchester with Rosenfeld's request to the physicist Max Born, as evident from his letter to Rosenfeld.[18] By this time, Gupta had finished working on the problem of quantizing gravity as he attached the manuscripts for Rosenfeld's commentary.[19] He soon published his results in the Proceedings of the Physical Society. The theory was presented in two parts. The first paper [21] deals with the quantization of linearized GR, whereas the second [22] deals with full nonlinear GR, and the way he achieves the latter is remarkable.

3.1 Linear approximation

A few years after the debut of his general theory of relativity, Einstein presented a paper to the Prussian Academy of Sciences in 1918 [23] concerning the solutions to the linearized field equations of GR. These can be obtained by splitting the metric tensor as $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$ with $\eta_{\mu\nu}$ being the usual flat Minkowski metric, and $|h_{\mu\nu}| \ll 1$ is a small perturbation around this flat space. κ is the gravitational constant with $\kappa^2 = 16\pi G/c^4$. This led to the prediction of gravitational waves. To arrive at this conclusion, Einstein employed various approximations, which soon raised doubts about the existence of these waves in the full theory. Einstein himself was not very optimistic. The debate, however, would not settle until the next few decades. (See e.g., [24]) Despite this, linearized equations occupied the center stage of quantum gravity research in the following decades. In the late 1930 s, Fierz and Pauli [25] observed that an arbitrary free massless field of spin-2, as represented by a symmetrical rank two tensor, obeys identical equations to Einstein's linearized GR. This revelation ignited the hope of constructing an

[15] Heitler, who fled to England in 1933 due to his Jewish ancestry, was a pioneer in applying the then newly developed quantum mechanics to chemistry problems as early as 1927. By the time Gupta arrived in Dublin, he was a director there, succeeding Erwin Schrödinger. A brief biography of him is available at https://royalsocietypublishing.org/doi/pdf/10.1098/rsbm.1982.0007.

[16] https://royalsocietypublishing.org/doi/pdf/10.1098/rsbm.1982.0007, p. 144.

[17] Gupta to Rosenfeld, July 17, 1951. Ref. Léon Rosenfeld Papers at the Niels Bohr Archive in Copenhagen.

[18] Gupta to Rosenfeld, August 8, 1951. Ref. Léon Rosenfeld Papers at the Niels Bohr Archive in Copenhagen.

[19] Unfortunately, it is not known what Rosenfeld thought of Gupta's approach, as his letters to Gupta are not available.

interacting quantum (field) theory of gravity without any direct reference to GR. The expectation was that by adding consistent nonlinear terms allowed by QFT principles to this linearized theory, one could recover GR [26]. Since the theory built this way is necessarily a Lorentz covariant one, the geometrical interpretation would become an emergent phenomenon. This laid the foundation of the *constructive* spin-2 approach to covariant quantum gravity. Gupta did not embrace this view and instead stuck to the original equations of Einstein and Rosenfeld.

The (free) linearized field $\gamma_{\mu\nu}$[20] satisfies the wave equation

$$\Box^2 \gamma_{\mu\nu} = 0. \tag{5}$$

In addition, it also obeys the coordinate conditions, a requirement due to the diffeomorphism invariance of GR. Einstein chose

$$\frac{\partial \gamma_{\mu\nu}}{\partial x_\mu} = 0 \tag{6}$$

for this purpose.

One can immediately notice that the setup resembles that of electromagnetism by comparing (5) and (6) with (4) and (3), respectively. Once again, the use of the indefinite metric was indispensable. These allowed Gupta to easily morph linearized GR into his quantization framework. The quantum mechanical coordinate conditions

$$\left[\frac{\partial \gamma_{\mu\nu}}{\partial x_\mu}\right]^+ \psi = 0 \tag{7}$$

that he introduced further add to the analogy of the approach. Furthermore, these conditions eliminate the eight unphysical gravitons from the theory, leaving the two kinds of gravitons observable.[21]

Note that in this original version, Gupta was treating $\gamma := \gamma_{\alpha\alpha}$ as an independent degree of freedom for the ease of calculation. This means that the theory in principle contained a total of *eleven* gravitons, ten coming from the independent components of $\gamma_{\mu\nu}$ and a scalar graviton due to γ. Therefore, he had to further introduce the following *ad hoc* coordinate condition: $\left[\gamma_{\mu\mu} - \gamma\right]^+ \psi = 0$ to make this pseudo-scalar graviton unobservable.[22]

Thus, Gupta showed that it is possible to extend his framework to linearized GR as well, except for the fact the theory is free and therefore trivial. Interesting physics unfolds when we study the interactions of quantum fields. At the same time, however, such theories suffer from many subtleties and bear no exact description. Nonetheless, it is possible to study interactions perturbatively. At the time, perturbation theory was heavily used in studying the interactions of light with matter (QED!). This is done by adding the interaction term $\sim j^\mu A_\mu$ to the Lagrangian of the free electromagnetic gauge field and then calculating the contributions coming from the interaction term step by step up to the desired order in the coupling constant. In the presence of this source term, (4) becomes $\Box^2 A_\mu = -(1/c) j_\mu$.

Analogously for the gravitational field, the prescription at the time was to add roughly[23] the interaction term $\sim T^{\mu\nu}\gamma_{\mu\nu}$, $T_{\mu\nu}$ being the stress-energy tensor of the matter field, to the Lagrangian of the free linearized GR, leading to the modification of (5); $\Box^2\gamma_{\mu\nu} = \kappa T_{\mu\nu}$. It shows that from the very beginning the perturbative quantum gravity primarily dealt with the interactions with matter only, excluding the nonlinear self-interactions of the gravitational field with itself. Gupta, however, regards this interacting theory of gravity and matter "as an approximation to a more involved theory." ([22], p.163) This was due to the fact "that the supplementary conditions [$\partial^\mu\gamma_{\mu\nu} = 0$] are compatible with the field eqn. [$\Box^2\gamma_{\mu\nu} = \kappa T_{\mu\nu}$] only in an approximate sense." ([22], p.163) He does not provide an explanation for this; a closer look at his earlier paper on QED and other papers he published later may give some insights:

When studying the interactions perturbatively in QFT, one deals with the asymptotic ingoing and outgoing states that are taken to be physical and free of interactions. Thus, supplementary conditions are imposed on the asymptotic ingoing states to eliminate the redundant particles. However, as soon as the interactions are turned on, redundant (unobservable) particles may appear in the intermediate virtual states and continue to exist in asymptotically outgoing states even when the interactions are turned off. To take care of that, the supplementary

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[20] $\gamma_{\mu\nu}$ is related to $h_{\mu\nu}$ via $h_{\mu\nu} = \gamma_{\mu\nu} - \frac{1}{2}\delta_{\mu\nu}\gamma$, where $\gamma = \gamma_{\alpha\alpha}$.

[21] The quantized theory has, in general, ten gravitons coming from the ten independent components of the metric tensor. However, as for electromagnetic radiation, gravitational radiation has only two independent polarizations; therefore, the physical states of the theory can contain only two types of gravitons.

[22] It was later shown by K. Just [27] that this condition is redundant since the scalar gravitons already do not contribute anything to the physical observables of the theory; hence, no additional efforts are needed.

[23] ignoring the coupling of the scalar graviton with the trace of the stress-energy tensor for the time being.

conditions should remain effective after the interactions. In other words, the supplementary conditions should be conserved throughout. The latter follows—intuitively speaking—from the compatibility of the supplementary conditions with the modified equations of motion in the presence of interactions. In QED, this condition held on account of the conservation of current density, i.e., $\partial_\mu j^\mu = 0$. Consequently, (3) satisfies the free wave equations in the presence of j^μ, which in turn allows for the implementation of (2) consistently in the interacting theory. The situation, however, is different in the context of gravity since in GR matter fields can interact with the gravitational field and radiate away energy in the form of gravitational waves, and because $T_{\mu\nu}$ only represents the energy distribution of the matter fields, it is not a conserved quantity in an exact sense. As a result, (7) no longer remains consistent in the interacting case.

It is, however, important to note that the gravitational waves were not yet observed at the time. Thus, one could still work with this (linear) interacting theory of gravity and matter by taking $T_{\mu\nu}$ to be a conserved quantity. Nevertheless, for Gupta, the nonexistence of the gravitational waves would have implied the breakdown of the analogy between gravity and electromagnetism. That eventually led him to drop the linear theory.

3.2 General treatment

Although GR stands today as one of the most successful scientific theories, its preliminary assumption that the physical space is Riemannian and not Euclidean faced many difficulties from its very beginning. The issue is that in Riemannian settings, many familiar concepts of physics, like conservation of energy or momentum, become ill-defined. This motivated some in the community to develop a flat-space theory of gravity in the 1930 s.

In this direction, Nathan Rosen [28,29] made pioneering efforts. He showed that, without any modifications to the field equations, Einstein's general relativity itself could be regarded as a theory of gravitation in flat space. The trick was to introduce a fictitious Euclidean metric, $\eta^{\mu\nu}$, in addition to the usual Riemannian metric, $g^{\mu\nu}$. This (g, η)-bimetric theory was initially perceived as a pure mathematical construct; however, the existence of both metrics side by side allowed to assign tensorial character to quantities that, in Riemannian settings, do not possess it, e.g., the energy momentum pseudo-tensor of GR. This possibility increases the number of physical quantities in the current formalism, which in turn allows for the adoption of an alternative interpretation for what was initially proposed as a mathematical trick. Distinct views are possible; however, the most plausible, as already proposed by Rosen himself, would be to think of $\eta^{\mu\nu}$ as representing a fixed background, which here is taken to be flat, and $g^{\mu\nu}$ as representing the gravitational potential. However, at this point, it is important to note that to maintain this view, it becomes inevitable to introduce additional coordinate conditions for $g^{\mu\nu}$. It is due to the fact that in GR, the $g^{\mu\nu}$ is uniquely determined only up to coordinate transformations, and without the coordinate conditions, this could lead to a scenario where a single physical solution may represent infinitely many distinct systems when passing over to the flat-space description.

Building on Rosen's work, Achilles Papapetrou [30] in 1948 derived a flat-space version of Einstein's field equations. Papapetrou himself was working on the flat-space formulation of GR; however, his meditations on the subject were interrupted due to the war, and therefore, he could only return to the topic after the end of the war. His interests were primarily guided by the question "whether the conservation law of angular momentum could be formulated in general relativity" ([30], p.12). This led him to propose a new energy momentum tensor for the whole system using the η-metric that consisted of the usual energy momentum tensor of the matter fields, the (symmetrized) pseudo-energy momentum tensor of the gravitational field, and an additional term representing the angular (or spin) energy tensor density of gravity. The tensor was fully symmetric and conserved. This then allowed him to rewrite Einstein's field equations in the following form:

$$\kappa^2 \Theta^{\mu\nu} = \frac{\partial^2}{\partial x^\alpha \partial x^\beta} \left(\mathfrak{g}^{\mu\nu} \eta^{\alpha\beta} - \mathfrak{g}^{\mu\alpha} \eta^{\nu\beta} + \mathfrak{g}^{\alpha\beta} \eta^{\mu\nu} - \mathfrak{g}^{\alpha\nu} \eta^{\mu\beta} \right), \tag{8}$$

where $\mathfrak{g}^{\mu\nu} := \sqrt{-g} g^{\mu\nu}$ is called the metric tensor density and $\Theta^{\mu\nu}$ is the total energy momentum tensor just mentioned. Papapetrou noticed that by imposing the De Donder coordinate conditions[24]

$$\frac{\partial \mathfrak{g}^{\mu\nu}}{\partial x^\nu} = 0, \tag{9}$$

[24] As it was first proposed by De Donder [31] and has since been adopted by many as a standard choice. In particular, Vladimir Fock [32] conjectured that the conditions determine the coordinate frames uniquely up to Lorentz transformations. Furthermore, he was so highly influenced by the advantage of these conditions over others that he even called for a reinterpretation of general relativity based on them. See e.g., [33] for more details (I am thankful to Jean-Philippe Martinez, who kindly provided a copy of this paper).

it is possible to reduce these equations to an even simpler form, viz.,

$$\eta^{\alpha\beta}\frac{\partial^2 \mathfrak{g}^{\mu\nu}}{\partial x^\alpha \partial x^\beta} = \kappa^2 \Theta^{\mu\nu}. \tag{10}$$

This is certainly a very elegant representation of Einstein's (nonlinear) field equations, especially when one notices the fact that they take a similar form to Einstein's linearized field equations discussed in the previous section, except for $T_{\mu\nu}$, which is now replaced by a more general conserved energy momentum tensor $\Theta_{\mu\nu}$. Papapetrou was aware of these fascinating aspects of his equations; however, he missed noting yet another intriguing aspect of them that was only recognized by Gupta. Gupta, coming from the QED background, immediately noticed that Papapetrou equations share striking analogies to the inhomogeneous Maxwell's equations, i.e., with the source term. Besides, they solved the issue of incompatibility of coordinate conditions with the equations of motion due to the conserved nature of $\Theta^{\mu\nu}$. Furthermore, to extend the analogies between the nonlinear and linearized fields, Gupta proposed the following decomposition of $\mathfrak{g}^{\mu\nu}$:

$$\mathfrak{g}^{\mu\nu} = \eta^{\mu\nu} - \kappa\gamma^{\mu\nu}. \tag{11}$$

This complements the metric split $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$ of the linearized case, and substituting it into (9) and (10) produces equations similar to those in the linearized case. It is, however, important to observe that the metric split (11) (henceforth called "Gupta split") is nonperturbative in contrast to the perturbative split of the linearized case; therefore, despite the parallels, the γ-field here is fundamentally distinct from that of the linearized case. Thus,

> [...] the choice of the linear field [i.e., $\Theta^{\mu\nu} = 0$] as the free gravitational field simply means that we are putting the interaction of the gravitational field with its own energy momentum pseudo-tensor on the same footing as its interaction with the energy momentum tensor of the matter field. ([22], p.610)

It is interesting to note that Papapetrou was at the DIAS when he carried out this work; however, around 1948, he left (and Gupta joined) the institute to work at the University of Manchester until 1952, where he was a colleague of Léon Rosenfeld. Coincidentally, at this time, Gupta was also working with Rosenfeld; therefore, it appears that this Gupta–Papapetrou–Rosenfeld connection was very foundational in shaping Gupta's approach to quantum GR, with Rosenfeld serving as a bridge between a field theorist and a general relativist. This can further be attested to by the fact that in his August 8, 1951, letter to Rosenfeld (fn. 17), Gupta also asked him about Papapetrou's views on his treatment of the nonlinearity of GR. However, in [22], Gupta only acknowledges Rosenfeld. This whole episode again highlights the central role of DIAS as an institution and Rosenfeld as a key figure in the earliest developments of quantum gravity. Though it is noteworthy that after his initial take on quantum gravity in 1930, Rosenfeld turned against the subject in the subsequent years and perhaps maintained the stance at least until the arrival of Gupta's program. Moreover, surprisingly, in the years following the reception of Gupta's papers, he again went on to take a completely opposite stance on the subject in the 1960 s and began arguing against "the program of formal quantization of gravitation." (For details, see e.g., [34].) For us here, due to the insufficiency of archival material, it is unfortunately not possible to comment on how it fits with Gupta's case. Therefore, it remains to understand this curious intermediate shift he made around 1950.

Papapetrou's equations provided Gupta with the exact ingredients he was looking for. This allowed him to put his approximate theory on firm ground. Thus, the Gupta–Bleuler framework was generalized to GR. Furthermore, to make practical calculations, he proposed an expansion scheme[25] using (11) that allowed him to write down quantities in Riemannian space as an infinite series in the coupling constant κ over flat space. The lowest order terms of such series resemble the expressions of linearized GR; hence, the higher-order nonlinear terms may be quantized perturbatively. For example, expanding the Lagrangian density of GR with Gupta's procedure yields an infinite series of the terms containing mixtures of $\gamma_{\mu\nu}$, $\gamma_{\alpha\alpha}$, and their derivatives. The linear part is identical to the Lagrangian of the linearized field, and therefore, the nonlinear terms are regarded as the direct interaction between gravitons. Interaction terms with the other fields can be expanded identically to study such interactions perturbatively.

[25] However, the GR Lagrangian that Gupta used was not very suitable for obtaining higher-order terms for $\gamma^{\mu\nu}$. To circumvent this, Léopold Halpern [35] in 1963 formulated the Lagrangian density of GR as a polynomial in $\mathfrak{g}^{\mu\nu}$, its inverse, and derivatives, which allowed for an efficient way of calculating these terms.

4 Later years: the shifting paradigms

For Gupta, the quantization problem of gravity was thus completely solved, and the unifying picture of electromagnetism and gravity that he presented contributes strongly to his belief that he made the right path. Although Gupta never uttered the former explicitly, our discussion in this and the following section attests clearly to this belief. He therefore shifted his attention away from gravity, except for the two papers [36,37] that he wrote in 1954 and 1957. In these papers, Gupta attempts to resolve some of the conceptual issues that went unaddressed in his earlier papers of 1952. These papers are therefore less technical and more *philosophical* in nature. The discussion revolves around the concern of an infinite number of terms in the Lagrangian density of GR over the flat space that he proposed. Gupta argues that it is a natural consequence of the gravitational field's spin-2 characteristics. Out of these emerges one of the first ever proofs relating the two different schools of thought of covariant quantum gravity, i.e., the bottom-up view of the constructive approach and the Gupta's own approach, which was necessarily a top-down one. He sketched a method for generating nonlinear terms in the Lagrangian of Pauli and Fierz via successive approximations. Besides, it was found this iterative process never stops and leads to infinite terms in the Lagrangian density. Gupta, however, did not show explicitly that the (Lorentz covariant) nonlinear theory obtained in such a way would converge exactly to GR in the infinite limit.[26] This might be due to the fact that his primary interest was just in showing that any *reasonable* Lorentz covariant spin-2 theory of gravity would necessarily contain an infinite number of terms in its Lagrangian, thereby defending his own theory.

Gupta did a major part of this research during his time at Purdue University in the USA. In 1953, his I.C.I. fellowship had expired, and he was looking for a better position. Since he had already made significant progress in his scientific career by that time, he was very optimistic. He wanted to return to India and applied for a position under the physicist Homi J. Bhabha and at Allahabad University. However, after hearing that Bhabha would only offer a readership position at his institute and that Allahabad University was not very responsive, he seemed disappointed.[27]About that time, Gupta received a letter from physicist Karl Lark-Horovitz, then the head of the physics department at Purdue University, about the possibility of arranging a visiting professorship for Gupta at his department.[28] Initially, he was hesitant about moving to the USA, but amid the uncertainties, he accepted the offer. Though it turned out to be a nice decision for him, he later found a comfortable fit in the country and decided to stay for the rest of his life.

In regard to his 1954 and 1957 papers, Gupta had correspondence with Peter G. Bergmann and John A. Wheeler for their suggestions on the manuscripts. A brief record of their communication is known.[29] It is also evident from the papers where Gupta explicitly acknowledged both. Bergmann was one of the trailblazers of the canonical approach, and Wheeler was another giant in the field of quantum gravity who played a vital role in the development of another well-known approach to quantum gravity that emerged around that time, i.e., path-integral quantization ("sum-over histories") of GR. Yet there is virtually no sign of Gupta taking an interest in any cross comparisons in his letters, which is quite surprising. Though he showed some interest in Wheeler's "geons,"[30][39] as evident from the following[31]:

> I have looked through your paper in the January 15th issue of the Physical Review, which contains very interesting ideas on a fundamental problem. I am planning to study this paper in detail in the near future.

Gupta's interest in QG was clearly diminishing. On the other hand, these years turned out to be landmarks for the field of GR and for the birth of QG as a research field in its own right. A new research community emerged in 1955 at a conference called the *Jubilee of Relativity Theory*, organized in Bern, Switzerland.[32] The conference, now also known as GR0[33], started the series of notable international GR conferences[34] that played a prominent role in re-establishing interest in GR research. Before this, during the so-called "low-watermark period" (1925–1955), the

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[26] It was Kraichnan [38] who (independently) gave a more complete account of such derivation in 1955. Kraichnan, however, impressively discussed the issue first as early as 1947 in his unpublished bachelor thesis at MIT.

[27] Gupta to Rosenfeld, January 16, 1953. Ref. Léon Rosenfeld Papers at the Niels Bohr Archive in Copenhagen.

[28] Gupta to Rosenfeld, 4 August 1953. Ref. Léon Rosenfeld Papers at the Niels Bohr Archive in Copenhagen.

[29] Peter G. Bergmann Papers, University Archives, Syracuse University Libraries, Syracuse, Correspondence-subject files, Box 3, Gupta, Suraj 1954. John Archibald Wheeler Papers, American Philosophical Society, Philadelphia, Box 11, Suraj N. Gupta - Correspondence, 1955–1970.

[30] A type of electromagnetic wave confined under gravitational forces of its own field energy.

[31] Gupta to Wheeler, 22 February 1955. Ref. John Wheeler Papers at the American Philosophical Society Library in Philadelphia.

[32] Proceedings: Jubilee of Relativity Theory, ed. A. Mercier and M. Kervaire. Helvetica Physica Acta, Supplementum IV, pp. 286, Birkhauser Verlag, Basel (1956).

[33] The GRn nomenclature, where -n refers to the number of the conference organized by the International Society on General Relativity and Gravitation, was adopted much later.

[34] A tradition that lasts to this date.

relativity community was very isolated, and research on GR was very limited as everyone was pursuing independent research projects of their own, mainly centered around the search for a unified field theory and the quantization of GR in a marginal sense. The GR0 brought these individuals together and fostered new collaborations that put GR back at the center of discussion. Within this Renaissance of GR, individuals like Bryce DeWitt would also try to push QG as a central issue of importance[35]; however, without major success despite the significant attention QG received at the next GR conference, GR1–*Conference on the Role of Gravitation in Physics*,[36] organized at the University of North Carolina, Chapel Hill, in 1957. Nonetheless, various emerging lines of approaches to QG were formally recognized, several other conceptual issues of QG were identified, and QG surfaced as an independent field in its own right around this time. It is noteworthy that GR1 was attended by many of Gupta's peers and mentors, e.g., Belinfante, Bergmann, Rosenfeld, and Wheeler. The list also includes people like Deser, DeWitt, Feynman, and Misner, who would dominate the field in the following decade, among others. Yet Gupta did not take part. Nevertheless, Gupta's approach did find a brief mention at the conference, surprisingly[37] by a Japanese physicist, Ryōyū Uchiyama (or Utiyama).

It is therefore evident that all three actors of the covariant approach to QG—DeWitt, Feynman, and Gupta—were part of the forays of the Renaissance. However, ultimately they were unable to fully integrate themselves—and thus the covariant approach—into the Renaissance community. Gupta's disengagement is particularly surprising given that his perspective was clearly shaped by places and individuals who made substantial contributions to the Renaissance, whether through his stints at the DIAS or the line of works he followed, i.e., Rosen-Papapetrou. Perhaps his background in QFT would have made it challenging for him to become part of the new relativity community despite his apparent interest in gravity research around this time. On the other hand, Feynman, another field theorist, who—unlike Gupta—attended GR1 and several subsequent GR conferences, eventually started losing interest in gravity research altogether[38] and thus remained only an asymptotic observer of the community. The sole exception was DeWitt, who was able to maintain a long-term place within the community, but even he had to retrain himself as a relativist to do so.[39]

At the GR1, DeWitt raised an interesting point concerning the expansion variables in the (perturbative) covariant quantum GR:

> [T]here is an ambiguity in the choice of field variables in terms of which one may make an expansion about the Minkowski metric $\eta_{\mu\nu}$. For example, one might use either $\psi_{\mu\nu}$ or $\varphi_{\mu\nu}$ where $g_{\mu\nu} = \eta_{\mu\nu} + \psi_{\mu\nu}$, $\mathfrak{g}_{\mu\nu} = \eta_{\mu\nu} + \varphi_{\mu\nu}$. To be consistent in a self-energy calculation, one should expand out to the second order, and the difference in choice leads to a difference in the trace of the nongravitational (or matter) stress tensor. ([41], p.247)

The remark particularly concerns the (perturbative) covariant quantum GR and not the full covariant quantum GR because at the nonperturbative level one is necessarily quantizing the full GR and hence expects to have similar results for any of these splits. However, at the perturbative level,[40] it is not at all obvious that the standard split $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$ (or "DeWitt–Feynman split") and the "Gupta split" $\mathfrak{g}^{\mu\nu} = \eta^{\mu\nu} - \kappa\gamma^{\mu\nu}$ lead to identical results for finite-order nonlinear interactions. This subtle difference is often overlooked and taken for granted in the discussions. It clearly shows how Gupta's approach of (perturbative) covariant quantum GR was fundamentally different from the DeWitt–Feynman approach.

This ambivalent nature becomes even clearer in the path-integral quantization of GR. Consider, for example, a similar remark concerning the choice of appropriate integration variables made earlier in 1956 by B. E. Laurent [42] when he applied Feynman's path-integral formulation to calculate the propagator for two Dirac particles interacting via a gravitational field:

> How are the integration variables to be chosen? Shall we integrate with respect to $g_{\mu\nu}$, $[\mathfrak{g}_{\mu\nu}]$, $\Gamma^{\alpha}_{\beta\gamma}$, or some other variables? The question is important because the relations between the different sets of variables are nonlinear, and one can consequently not neglect the transformation determinant when going from one set to another. The transformation determinant can, of course, be included in the action, which then gets a new imaginary term that is of no importance for the classical limit. The above question may accordingly also be formulated thus: How is the action function to be chosen for a certain set of variables? ([42], pp.1451-1452)

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35 See e.g., [26], p. 117 and the references therein.
36 Proceedings: Rev. Mod. Phys. 29, 351-546 (1957).
37 again, given the fact that Gupta's mentor and (American) colleagues who were aware of his work were also present at the conference.
38 His growing frustration with the subject and the community is quite visible from the letter ([40], p. 91) he wrote to his wife while attending GR3.
39 See e.g., [3], p. 461, for the discussion on why he diverged toward the canonical approach after his 1949 PhD thesis on the covariant approach.
40 I.e., restricting the infinite series of the expanded GR Lagrangian (in terms of $g_{\mu\nu}$ or $\mathfrak{g}_{\mu\nu}$) to some finite order.

Laurent chose $\mathfrak{g}_{\mu\nu}$ arbitrarily and expands the Lagrangian using "Gupta split" (11) for his calculations. However, in a note added at the end, he mentions Wheeler had suggested that "the most natural choice of integration variables, according to a work done by Dr. C. Misner, seems to be the 16-field $S_{\alpha\beta}$, which fulfills $g_{\mu\nu} = [S_{\mu\alpha}\eta^{\alpha\beta}S_{\beta\nu}]$" ([42], p.1459).

These show that from the onset, the most practical approaches to quantum GR, viz., (perturbative) covariant and path-integral quantization, suffer from "the problem of fundamental variables," and as it seems, it might not be possible (owing to the infinite number of nonlinear terms) to argue in favor of or against a particular choice of variables for perturbative covariant quantum GR on a purely theoretical basis,[41] and one has to resort to empirical inputs[42] to identify[43] the *true* fundamental field for the (perturbative) covariant quantum GR. However, such a test would require going beyond linear orders, thus rendering it an enormously difficult task for the moment, as already the detection of free gravitons is beyond reach!

At Purdue, Gupta would share the department with the physicist Frederik J. Belinfante. Belinfante had a research program of his own for the flat-space quantization of the gravitational field. The focus was not restricted to the quantization of GR only, and various alternative theories of gravity were explored. The emphasis was put on an interacting theory of gravity and matter from the beginning, and a linear theory was sought with the intention of avoiding quantization difficulties posed by the nonlinear theories of gravity. Belinfante [43–45], together with his student J. C. Swihart, published in a series of papers a "phenomenological" linear theory of gravitation. The papers were partly based on Swihart's PhD thesis [46]. Their Lagrangian for the pure gravitational field reads

$$L_g = -(c^4/16\pi G)\eta^{\alpha\beta}\eta^{\lambda\mu}\eta^{\rho\sigma}\big[a(\partial_\alpha h_{\lambda\rho})(\partial_\beta h_{\mu\sigma}) + b(\partial_\lambda h_{\alpha\mu})(\partial_\rho h_{\sigma\beta}) + f(\partial_\alpha h_{\lambda\mu})(\partial_\beta h_{\rho\sigma}) + q(\partial_\alpha h_{\lambda\mu})(\partial_\rho h_{\beta\sigma})\big], \tag{12}$$

where $\eta^{\alpha\beta}$ is the flat-space metric and $h_{\mu\nu}$ represents the gravitational field. The a, b, f, and q are numerical constants that are to be chosen in order to match the predictions of the theory with the experimental data. It is important to note that although the field h is defined over the flat space η, it is not to be confused with the metric perturbation of Einstein's linearized GR. The h exists in its own right, and therefore, "the combination $(\eta_{\mu\nu} + h_{\mu\nu})$ has no fundamental meaning whatsoever." ([43], p.172) This theory, due to its linear nature, was easily quantizable; however, the interpretative fixes it demanded were rather messy. For example, the Lorentz covariant auxiliary conditions that were imposed to eliminate the redundant gravitons go as $\left[\partial_\mu(h^{\mu\nu} + \mathrm{R}_1\eta^{\mu\nu}h^\lambda_\lambda)\right]^{(+)}\psi_H = 0$ with R_1 a constant. This shares similarities to the conditions (7) of Gupta; however, the operator $[\partial_\mu(...)]^{(+)}$ here is in the interaction representation, whereas the state it is acting on is in the Heisenberg representation, as opposed to Gupta's complete Heisenberg representation. Writing them down in either of the representations would make the expression rather complicated.

On the GR side, an interesting problem that was studied by Belinfante and his later PhD student John C. Garrison concerns "the problem of defining an interaction picture for a quantized version of the Einstein theory of gravitation." ([47], p.1424) Garrison [47] was able to show that for the spacetime geometries restricted by the conditions (9), it was possible to define an interaction representation under further assumptions. In these accounts, the Belinfante group criticizes Gupta for taking the interaction representation for granted[44] without showing that the integrability condition is satisfied.

5 Renormalization and the fate of the covariant program

The covariant approaches of the 1950 s treated GR as a (quantum) field theory. This field view had the immediate advantage of being more practical than the canonical approach, as the framework of QFT was deemed complete by 1950. However, this also meant that it would inherit all of the latter's limitations, most notably the divergence

[41] Though if one considers other possibilities, e.g., the beauty criterion, then Gupta's choice of taking $\mathfrak{g}_{\mu\nu}$ as fundamental variables and thus his approach would have been more justifiable owing to its analogies to (quantum) electrodynamics, especially given the fact that the starting point of his approach was full GR in contrast to the $g_{\mu\nu}$-based approach built on linearized GR (or Pauli–Fierz), where there was a clear doubt about its convergence to full GR. Despite that, the use of $g_{\mu\nu}$ became dominant due to the fact that all attempts at quantizing GR perturbatively, starting from e.g., Rosenfeld, DeWitt, and later Feynman, were all based on this choice, and Gupta's was the only account that existed on the other side.

[42] If (perturbative) covariant quantum GR is indeed a physically realizable theory (which one might naturally expect it to be given the small value of gravitational coupling) in the sense that finite-order nonlinear interactions are testable.

[43] given that the differences in the choice of fundamental variables lead to different predictions for finite-order nonlinear interactions.

[44] In [22], Gupta used the interaction representation to calculate the gravitational self-energy of the photon and the electron without explicitly proving the existence of such a representation for the gravitational case.

difficulties, i.e., the occurrence of infinities in the calculations. These infinities would have to be taken care of systematically with the renormalization and regularization procedures. Although in present times these techniques have become an integral part of QFT calculations and go more or less as a universal concept under the framework of QFT, these were still new, and the only successful case of them was QED by the time Gupta presented his theory. Gupta, in his second paper of 1952, utilized these techniques to calculate the gravitational self-energy of the electron. However, he encountered serious issues. He found that the inclusion of gravity leads to more divergences than a similar problem in QED. Moreover, these interactions were not renormalizable. Today, this lack of renormalizability of gravitational interactions is widely cited as a prime suspect for the failure of the (perturbative) covariant approach. Gupta, however, did not see this as a limitation of his theory but rather the opposite. He was indeed testing the renormalization theory against the quantum GR, not the vice versa; however, at this stage he was more cautious, as in his calculations he only used the linearized gravitational field and wanted to investigate the effects of nonlinear terms before making any strong claims against the renormalization theory, as can be understood by the following:

> [...] It must be noted that in our calculations we have not taken into account the contributions of the nonlinear terms to the self-energy graphs. In order to see whether the renormalization theory really breaks down for the gravitational field, it would be necessary to carry out more involved calculations by including the nonlinear terms. This problem will be fully discussed in a subsequent paper. (Ref. [22], p. 619)

Apparently, that paper never appeared. Perhaps he became less interested in the problem due to the complex nature of those calculations, as this was certainly not his style. For example, when asked about his view on lamb shift calculations during the discussion session of the summer lectures that he delivered at the Argonne national laboratory in 1958, he remarked:

> But these are extremely tedious calculations, and I try to keep away from such calculations. [...] In most cases, one has to make many crude assumptions and approximations, which are often justified but are still not very pleasant for a theoretical physicist. So when I have nothing else to do and no fundamental problem to think about, I might start doing that kind of calculation. At the moment, there are many fundamental problems that have to be investigated. (Ref. [48] pp. 29, 30)

This was in fact his general attitude during the mid-1950 s, as discussed in the previous section. For this reason, he abstained from making any practical application of his theory.

It also took others a while to follow up on Gupta's theory. One of the significant results to back up his approach came from Ernesto Corinaldesi [49,50] in 1955. At the time, Corinaldesi was at DIAS. He applied the linear approximation of Gupta's theory to calculate the induced gravitational potential between two spin-0 particles through the exchange of a single graviton. That way, he presented a quantum field theoretic derivation of a well-known two-body problem in general relativity (the EIH equations) as first obtained by Einstein, Infeld, and Hoffmann in 1939 [51]. Corinaldesi reported these findings at GR0.

In the fall of 1956, Gupta transferred to Wayne State University in Michigan. There he was appointed a full professor of physics.[45] At this stage, it was possible that Gupta had to return to India as the government was taking an interest in him to work on its nuclear program.[46] However, he declined and remained at Wayne State until his retirement.

At Wayne State, he subsequently trained PhD students. The first five students were Robert L. Anderson, John Huschilt, Richard D. Haracz, James Kaskas, and Bruce M. Barker, of whom the first four wrote their theses on the study of nuclear forces and graduated in 1963–64.[47] Barker was the only one to work toward Gupta's theory of quantum gravity. He finished his PhD in 1965 with the thesis entitled "Gravitational interaction of elementary particles" [52]. Already in the beginning of the thesis, a compelling remark was made summarizing the collective thinking of his and Gupta on the status of the problem of quantum GR by that time:

> Gupta was the first to quantize the gravitational field (1952). This major achievement was due to his recognizing that quantization could only he achieved in flat space, not in the Riemannian space. By using flat space, Gupta has also unified gravitation with the rest of physics. Thus, the problem is completely solved, but in a different manner than earlier expected. (Ref. [52], p. 1)

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[45] Gupta to Rosenfeld, April 19, 1956. Ref. Léon Rosenfeld Papers at the Niels Bohr Archive in Copenhagen.

[46] For the original discussion, please refer to the Lok Sabha (also known as the House of the People, the lower house of India's bicameral Parliament) debates of July 24, 1957, pp. 4935–4954: https://eparlib.nic.in/bitstream/123456789/1489/1/lsd_02_02_24-07-1957.pdf.

[47] Robert Leonard Anderson: "Theory of Multiply Charged Mesons and Baryons" (1963), John Huschilt: "Effect of Pion-Pion Interaction on Nuclear Forces" (1963), Richard Daniel Haracz: "Meson Resonances and Nuclear Forces" (1964), James Kaskas: "Pion Theory of Relativistic Nucleon-Nucleon Interaction" (1964). I am thankful to Sarah Lebovitz, University Archivist at Wayne State University, who kindly provided the list.

In his thesis, Barker worked out exact relativistic calculations for single graviton exchange processes between particles of various spins using Gupta's theory. In addition, he also included various approximations, e.g., non-relativistic, extreme relativistic, and large mass/distance limits. He found that in all such cases, gravitational potentials (in the center of the mass frame) admit the following form:

$$\mathrm{U(r)} = \frac{-Gm_1m_2}{r}\left[1+\left(4+\frac{m_1}{m_2}+\frac{m_1}{m_2}\right)\frac{p^2}{m_1m_2c^2}+\frac{p^4}{m_1^2m_2^2c^4}\right] + \text{spin-dependent term,} \tag{13}$$

where p is the momentum of particles in the center of the mass frame, and m_1 and m_2 are the relativistic masses of the particles, which are related to their rest mass M_1 and M_2 via

$$m_{1,2} = \sqrt{M_{1,2}^2 + p^2/c^2}. \tag{14}$$

Notably, (13) already reproduces known results under various approximations, e.g., (i) It returns Newton's law in the nonrelativistic limit ($p \ll mc$) as it should be. (ii) It gives the correct factor of 2 for the case of the bending of light around a heavy stationary object ($M_2 = 0, m_1 \gg m_2$). The spin-independent part may be viewed as the post-Newtonian/Minkowskian corrections, while the spin-dependent[48] part is purely quantum.

It is therefore evident that by the late 1950 s, Gupta's interest in perturbative calculations was reignited. However, he left all the details to his PhD student. What made him return to such considerations is unknown. Maybe the evolving dynamics of the field at the time had influenced him to revisit the subject.

Barker's thesis, despite being one of the most comprehensive accounts of leading order calculations at the time, did not address the influence of nonlinear terms. Even if it did, it came a little late, as the effects of nonlinear terms had already been explored a few years ago by none other than Feynman himself, who strongly became interested in the quantization of gravity around the late fifties. His efforts revealed the true nature, albeit shortcomings, of the perturbative covariant approach. He showed that going beyond the tree-level would spoil the game; such interactions, e.g., violate the unitarity condition and are non-renormalizable. Feynman reported these at the international conference GR3 organized in Warszawa and Jablonna, Poland, in July 1962 (later published as a regular paper [53]). It is often perceived historically that Feynman was largely unaware of Gupta's work despite apparent similarities in their approach and attitude toward covariant quantum GR. (see, e.g., [54]) This consensus is due to the fact that Feynman never cited Gupta explicitly in this context.[49] However, it might not be entirely true, as can be seen from the fact that Feynman attended the GR1 conference where there was a mention of Gupta's approach by Utiyama and the observation that a 1958 reference letter for Gupta found in Wheeler's collection bears his name.[50] Moreover, Feynman clearly took over from where Gupta left, i.e., the inclusion of nonlinear terms. This rather suggests that Feynman's work can even be seen as the direct continuation of Gupta's program. The latter also resonates with DeWitt's remarks on p. 183 in [55]. In conclusion, it is safe to say that while Feynman did not cite Gupta explicitly, his colleagues[51] clearly saw his approach as a continuation of Gupta's.

By 1962, Gupta was already convinced of the breakdown of the renormalization theory for quantum GR, and according to him, it needed to be replaced as far as the practicality of the covariant approach was concerned:

> [...] There are so many other divergencies involved in the interaction diagrams that the renormalization theory completely breaks down in the case of gravitational interactions. This seems to show that the renormalization theory succeeds in some cases simply because the divergencies involved happen to be particularly mild and that it cannot be regarded as the final solution to the divergence difficulties in the interaction of elementary particles. (Ref. [56], p. 257)

It also explains why he never went beyond leading order with Barker. Though he firmly believed that gravity would play a major role in this direction:

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48 It indicates a clear violation of the weak equivalence principle at the quantum level. Moreover, this breakdown already occurs at a length scale comparable to the Compton wavelengths of the particles under consideration. However, the spin dependence rapidly decreases with the separation distance and no longer remains significant; thus, in the classical limit, we recover the equivalence principle.

49 Which is not that surprising given that Feynman did not publish anything proper on quantum gravity at the time, and our understanding of his views on the subject predominantly stems from his remarks and discussions at the GR conferences.

50 Suraj N. Gupta–Correspondence, 1955-1970, Ref. 1955–1970, John Archibald Wheeler Papers, 1880–2008, at the American Philosophical Society Library. The document is dated April 17, 1958, and seems like a reference letter for Gupta's funding proposal. It includes Freeman Dyson's and Richard Feynman's names, whose roles are unclear at the moment but show that they were somehow linked to Gupta's proposal.

51 For example, consider also an earlier remark made by Murray Gell-Mann already in 1959, where he regards the constructive spin-2 approach to GR as the "Gupta-Feynman" view. ([26], p. 110)

> [...] It is obvious that in the ultimate solution to the divergence difficulties, the gravitational field is bound to play an important role. That is, when ultimately our knowledge becomes clearer about the structure of elementary particles and what happens at high energies, the gravitational field certainly cannot be ignored. (Ref. [48], p. 42)

Later, it was shown that the unitarity could indeed be achieved at arbitrarily many loops. A one-loop solution to this problem was already devised by Feynman himself. The idea was to introduce a fictitious quanta (now known as "ghost") to restore unitarity and gauge invariance. The generalization of this procedure to arbitrarily many loops was later developed by DeWitt[52] and presented in his celebrated *trilogy* of 1967 [57–59]. To this point, DeWitt introduced an "adjustable c-number background metric" instead of a flat background metric to deal with (in a restricted sense) the *general* covariance of GR in a covariant manner [58, 59]. Gravitons are thus excitations relative to this variable background. This was a clear departure from the original covariant approaches of the 1950 s that relied on the use of the flat metric as background. The latter was the hallmark of Gupta's approach; unlike others who viewed the flat background as merely a mathematical trick, Gupta saw it as a representation of physical reality:

> [...] we have shown that the gravitational field can be quantized in a straightforward way by reducing the curved space to the flat space by a Lorentz covariant expansion of the field quantities, while all attempts to quantize the gravitational field in the curved space have failed so far. This strongly suggests that the space is flat and not curved. (Ref. [56], p. 258)

At this stage, however, it is really not possible to comment precisely on how Gupta's overall attitude changed toward quantum GR in view of these later developments on both the canonical [57] and covariant [58, 59] sides introduced by DeWitt and in general. But it can be speculated from [61] that he never abandoned his fixation on the flat-spacetime view and the *standard* QFT picture as was introduced by him.

The problem of non-renormalizability, on the other hand, found no cure. The pursuit eventually led in the mid-1970 s to the branching of the covariant approach into disparate approaches. However, none of them has led to any convincing results to date. The other two major approaches to quantum GR, i.e., canonical and sum-over histories, faced a more or less similar fate.

Final remarks

Gupta's program was a landmark on the road to quantum gravity, in particular (perturbative) covariant quantum GR, and testimony to Rosenfeld's central role in this quest. It was the first true and unique attempt at the quantization of GR and more or less a complete one; Gupta was able to identify a coherent framework for explicitly generating nonlinear terms for perturbative quantum gravity starting with the Lagrangian of GR. Furthermore, it revealed many important aspects and subtleties associated with it even before the emergence of quantum gravity as a proper research field. Despite that, its unorthodox roots and early appearance are precisely what contributed to its detachment from the mainstream developments of that time, and it remained widely unrecognized and largely misunderstood in the quantum gravity community to date. In present times, it is often recalled, if at all, under the umbrella of the more popular DeWitt–Feynman approach to (perturbative) covariant quantum GR. Such oversights in general may result in a failure to recognize fundamental issues (here, e.g., "the problem of fundamental variables") associated with the problem in question and its far-reaching consequences. It therefore becomes crucial to identify and avoid such mistakes if one is dealing with problems as involved as quantum gravity. The present work was initiated with this spirit, and besides its primary subject matter—Gupta and his quantization of Einstein's GR—it is certainly an invitation for the quantum gravity community to introspect on the historical developments of this ever-evolving field of research to assess its progress!

Acknowledgements I am indebted to Alexander Blum for drawing my attention to this topic and his unwavering support and guidance during the course of the project. The discussions I have had with him have been an enlightening experience for me. In addition, I am thankful to Stefano Furlan for a brief yet fruitful correspondence and to Ajoy Ghatak, Donald Salisbury, Dean Rickles, and N. Panchapakesan, with whom I corresponded at the earliest stages of the project. I would also like to extend my thanks to library staff at Purdue and Wayne State Universities for providing some useful information on Gupta and to two anonymous referees for their valuable comments and remarks on the earlier version of the manuscript that helped improve the quality of the paper. The major part of this research was done while I was a guest of the research group "Historical Epistemology of the Final Theory Program" of Alexander Blum at the Max Planck Institute for the History of Science. I would like to thank the latter for the administrative support. Open access is funded by Helsinki University Library.

[52] and in the path-integral formulation by Ludvig D. Faddeev and Viktor N. Popov [60].

Funding Information Open Access funding provided by University of Helsinki (including Helsinki University Central Hospital).

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