**Why did Einstein’s Programme Supersede Abraham’s and Nordström’s ?**

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**Abstract.**

It is exhibited that the dynamics of general relativity (GR) construction was predominately governed by internal tensions between special relativity and Newton’s gravity research traditions. The traditions’ encounter and interpenetration engendered construction of the hybrid domain at first with an irregular set of theoretical models. However, step by step, on revealing and gradual eliminating the contradictions between the models involved, the hybrid set was put into order owing to Einstein’s equivalence principle. A hierarchy of theoretical models starting from the crossbreeds and up to usual hybrids was moulded. With the metric tensor at the top of the edifice Einstein was able to comprise both the knowledge on gravitation and inertia represented by classical mechanics and the knowledge on the structure of space and time embodied by special relativity. The basic claim to put forward is that Einstein’s unification design could be successfully implemented since his programme embraced the premises of the Nordström’s research programme, as well as the presuppositions of the programme of Max Abraham. By and large Einstein’s victory over his rivals became possible because the core of his research strategy was formed by the equivalence principle comprehended in the light of Kantian epistemology. It is stated that the theories of Nordström and Abraham contrived before November 25, 1915, were not merely the scaffolds of GR basic model construction. They were and still are the necessary parts of the whole GR theoretical structure indispensable for its common use. Notwithstanding Einstein’s stupendous impact , the contributions of Nordström, Abraham, Grossmann, Hilbert, Lorentz, Poincaré, Besso, Fokker and others should be taken into account.

**Key words:** Einstein, Nordström, Abraham, nonmetric relativistic theories of gravitation, general relativity.

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**Introduction.**

It is commonly held that Albert Einstein’s strenuous efforts to create the General Relativity (GR) were accompanied by its rival versions concocted by Gunnar Nordström, Max Abraham, Gustav Mie et al. It is a platitude that the underdogs’s papers are still considered as a kind of peculiar delusions that had been capable at best to stir up problem situations and to incite critical discussions around GR highlighting all its splendour. More than in the case of any other theory of modern physics, GR is usually seen as the work of one man, Albert Einstein. However, some current history-of-science data[[1]](#footnote-1) allow one to take these (shallow and scornful) views with a large grain of sault. For instance, the Einstein- Nordström correspondence underscores that it was Albert Einstein himself who , before the November 1915, and even *after* the creation of GR preliminary version – the ‘Entwurf” (1913) – took active part in creation of Nordström’s scalar relativistic theories of gravitation. Einstein was in continued contact with Nordström during the period in which the Nordström theory was developed. The theory actually evolved through a continued exchange between Einstein and Nordström, with Einstein often supplying ideas decisive to the development of the theory. Thus the theory might more accurately be called the “Einstein- Nordström theory”. The next blatant example is A. Einstein’s and A. Fokker’s paper published in early 1914 that aimed “ application of new mathematical methods , used in Einstein’s and Grossmann’s paper, to Nordström’s theory”[[2]](#footnote-2). Moreover, in the same paper in early 1914 the significant connec tions between Nordström’s theory and conformally flat spacetimes were disclosed. It therefore comes as no surprise that it was within Nordström’s 1912 theory where the gravitational field equation R= ϗ T was first derived , where R is fully contracted Riemann-Christoffel tensor and T the trace of the stress-energy tensor ( *ϗ* = const), in the case of an unstressed, static matter distribution .The field equation is an apparent harbinger of Einstein’s illustrious equations promulgated at Preussiche Akademie der Wissenschaften on November 25, 1915[[3]](#footnote-3). In September 1913 presentation of the ‘Entwurf’ theory to the 85th Congress of the German Natural Scientists and Physicians Einstein made clear his preference for Nordström’s theory over other gravitation theories. His single critical remark consisted in that the theory was incompatible with Mach’s principle – a vice that could appear as a virtue to any “Naturforscher” biased against metaphysical principles. Later Wolfgang Pauli called Nordström’s theory an ‘empirical blunder’ since it had not predicted any deflection of a light ray by a gravitational field and had not explain the anomalous motion of Mercury. Yet in 1913 there had been no eclipse expeditions and Einstein’s own ‘Entwurf’ theory also did not explain the anomalous motion of Mercury. On the other hand, for a number of important cases in certain approximations the ‘Entwurf’ and the GR consequences coincide with the consequences from the theories of Nordström and Abraham. For instance, the ‘Entwurf’ reduced in suitable weak -field approximation to a theory with a four-vector field potential that was formally analogous to maxwellian electrodynamics. Furthermore, special relativity appears to be an intermediary step in the transition from GR to Newton’s theory[[4]](#footnote-4) . But the transition is based on the supposition, for weak and stationary gravitational fields, that the gravitational field is described by a scalar in flat (Minkowski) spacetime, i.e. on the reduction to scalar Nordström’s theory[[5]](#footnote-5). Similarly, the so-called “linear approximation” in GR, still in common use to account for gravitational waves[[6]](#footnote-6) , presupposes the transition to such a theory of gravitation in which the gravitational wave , in full analogy with classical electrodynamics, is described by a vector in flat spacetime, i.e. the transition to vector theory of Abraham[[7]](#footnote-7). It was not accidental that only *after* the first publication by Abraham did Einstein also turn to the problem of gravitation after a period of 1908-1911. All these features of GR functioning, the common practice of its implementation bolsters the tenet that the relations between GR and its rivals in 1907-1915 were far more complicated than it may seem from the notorious “truth-falsity” dilemma. Gradually a tenet suggests itself that *Einstein’s GR was better than its inimical rivals if only for the reason that it encompassed them all.* On the other hand, the current philosophy of science investigations allowed to elucidate our views on the structure and functioning of scientific theories, – on the one hand, - and to construct sufficiently sweeping and exact scientific revolutions epistemological models, – on the other. On my view, one of the examples of the advancement of the epistemological purview is the epistemological model that I try to amend [[8]](#footnote-8). According to the model, a scientific revolution is engendered by encounters of some entrenched “old” paradigms, scientific research programmes or research traditions that cannot be reconciled in a common way – by reducing of one of them to another. The way out of the predicament is the establishment of such a global theory that encompasses all the theories in significantly modified forms. The global theory is aimed at “suing” the hiatuses , eliminating the tensions, smoothing away dissensions between different paradigms involved. In the process of the global theory creation an important preliminary stage consists in the construction of a series of hybrid theories. The hybrid theories are persistently set up to the point when such a hybrid model is constructed that is able to point out the fruitful way of the global model creation through the generalization of models that belong to the lower level of mature theories . According to the epistemological model, *radical breakthroughs in science were not due to invention of new paradigms or the creation of new ideas ex nihilo, but rather to the long-term processes of the reconciliation and interpenetration of ‘old’ research traditions preceding such brakes.* It is no wonder that no adequate epistemological model of scientific revolutions can be established without preliminary elucidation the structure of mature scientific theories. What I want to stress is that a mature theory of XIX and XX centuries physics encompasses not a single model or a bundle of models. It embraces a *bundle of groups of models* that are related to one another in rather complicated ways. A mature theory is so organized that the host of its models is disseminated over three main levels : (1) the level of basic model (or fundamental theoretical scheme), (2) the level of partial theoretical schemes constructed from the fundamental ones according to certain rules and (3) the level of empirical schemes that can be approached through the level of partial theoretical schemes[[9]](#footnote-9).

Due to mature scientific theory complicated organization the global theory creation appears to be a slow and consequent transition from the lower levels up to the top ones. Any transition from lower level to the upper one is impossible until the construction of all the lower-level models is finished. Yet an important remark here is that the lower models that served at scaffolding the upper ones are not eliminated. They can be discovered not only in history-of-science archives. They can be transpired in real practice of theories’ functioning (often in implicit forms). As is punctuated in one of the recent studies,

“ both the peculiar emergence and the remarkable stability of Einstein’s theory of gravitation with regard to the further development of physics and astronomy becomes plausible only if the genesis of general relativity is understood, not as a fortunate anticipation of future observational discoveries, but as a *transformation of pre-existing knowledge*”[[10]](#footnote-10) .

All in all, according to modern researchers the dynamics of the theory of gravity unfolding was largely governed by **internal tensions**, contradictions within the knowledge system rather by new empirical knowledge, which at best played only a minor role[[11]](#footnote-11). The perihelion advance of Mercury remained a commonly used touchstone for gravitational theories for more than a half century before GR. The bending of light in a gravitational field could simply be inferred from the observation that, in an accelerated frame of reference, light rays must be curved as a consequence of the superposition of the motion of the observer and of the light. The red shift experiments were performed only in 1960’s. Hence **the aim** of the present paper is to propose such a reconstruction of the GR genesis that makes it possible to highlight some important hallmarks of the process that are obfuscated by other reconstructions and to arrive at a more comprehensive description of the Einsteinian revolution *intertheoretic context* .Indeed, it seems to me that one should always keep in mind that real creative science is always messier and more complicated than philosophers of science and science educators like to think. In the **first part** of the paper the first stage of GR construction (1907-1912) is considered that consisted in preliminary construction of the hybrid models of relativistic theories of gravity by A. Einstein, G. Nordström and M. Abraham. The climax of the stage was Einstein’s proposal and comprehension of the equivalence principle that became firm GR heuristic foundation. The **second part** of the paper (1912-1913) is dedicated to the ‘Entwurf’ construction. The theory sprung out from the synthesis of Abraham’s and Nordström’s theoretical schemes, as well as from the preliminary theoretical schemes of Einstein. The staple was the metric tensor introduced owing to equivalence principle and Nordström’s and Laue’s results. The basic claim to put forward is that *it was namely the fact that Entwurf’s basic model was constructed due to the unification of Nordström’s, Abraham’s and Einstein’s (obtained before 1913) theoretical results that can explain the reasons for Einstein’s programme victory over its rivals.*  The **third part** is dedicated to the 1913-1915 transition from the ‘Entwurf’ to GR exposed by Einstein in the lecture to Berlin Academy on November 25, 1915.The last part deals with the interpretations of the results obtained by the other (first and foremost by Michel Janssen, Jürgen Renn and John Stachel). Their basic claim that I wholeheartedly support is that they were first and foremost *physical*, and not the mathematical arguments that brought Einstein to the GR fundamental equations .

**Part one. The hybrid models of relativistic gravitational theories and the equivalence principle.**

The advent ofspecial relativity (SR) and the incompatibility between Newton’s theory of gravitation and the SR theory presented Einstein and his contemporaries with the task of constructing a relativistic theory of gravitation. Blatant contradiction between the theories consisted in the fact that according to Newton’s theory the velocity of gravitational interaction was infinite. On the other hand, SR prohibits the signals travelling faster than light. Apparent disparity between the concepts of action at a distance and instantaneous action was revealed just after the maxwellian electrodynamics had been created. It was Maxwell himself who tried to construct the first vector theory of gravity. However, he was forced to leave the efforts soon due to the problem of gravitational wave’s negative energy. SR creation only exacerbated the problem. It therefore comes as no surprise that it was Einstein’s 1907 review “*On the Relativity Principle and the Conclusions Drawn from it*”, published in Johannes Stark’s “*Jahrbuch der Radioaktivität und Elektronik*”, that laid the true conceptual foundations for relativistic theory of gravity.

“The most important result of the fourth part is that concerning the inertial mass of the energy. This result suggests the question whether energy also possesses heavy (gravitational) mass. A further question suggesting itself is whether the principle of relativity is limited to nonaccelerated moving systems. In order not to leave this question totally undiscussed, I added to the present paper a fifth part that contains a novel consideration, based on the principle of relativity, on acceleration and gravitation»[[12]](#footnote-12) .

In the fifth part of 1907 epoch-making paper Einstein formulated first his “**principle of equivalence**”. As he later recalled, when he had prepared his 1907 review article for publication, he had tried to modify Newton’s gravitational theory so as to reconcile it with special theory of relativity. The corresponding attempts had shown that it was possible but Einstein did not like them since they were based on physically inacceptable hypotheses.

“At this point, there occurred to me the happiest thought in my life [der glücklichste Gedanke meines Lebens] . *Just as in the case with the electric field* produced by electromagnetic induction, the gravitational field has similarly only a relative existence. For if one considers an observer in free fall, e.g. from the roof of a house, there exists for him during this fall no gravitational field – at least not in his immediate vicinity. Indeed, if the observer drops some bodies, then these remain relative to him in a state of rest or in uniform motion, independent of their particular chemical or physical nature”[[13]](#footnote-13).

Because of the importance of the equivalence principle for the GR creation and the uninterrupted discussions on its true content we have to resort to all the piece of 1907 paper where the principle had been formulated.

“We consider two systems ∑1 and ∑2 in motion. Let ∑1  be accelerated in the direction of its X-axis, and let γ be the (temporally constant) magnitude of that acceleration. ∑2 shall be at rest, but it shall be located in a homogeneous gravitational field that imparts to all objects an acceleration –γ in the direction of the X - axis. As far as we know, the physical laws with respect to ∑1 do not differ from those with respect to ∑2 ; this is based on the fact that all bodies are equally accelerated in the gravitational field. At our present state of experience we have thus no reason to assume that the systems ∑1 and ∑2 differ from each other in any respect, and in the discussion that follows, we shall therefore ***assume*** the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system. This assumption extends the principle of relativity to the uniformly accelerated translational motion of the reference system. The ***heuristic value*** of this assumption rests on the fact that it permits the replacement of a homogeneous gravitational field by a uniformly accelerated reference system, the latter case being to some extent accessible to theoretical treatment”[[14]](#footnote-14) (my italics – RMN).

An important remark here is that Einstein was first and foremost interested not in the ontological, metaphysical content of his principle that could enable to elevate the principle up to the level of some Absolute Law of Nature. The latter would be valid everywhere with any degree of correctness being contemplated by a Super Reason that tried to grasp the essences of the things and events. (For it is well-known that in 1907 Einstein was unaware of Eotvös’s exact experimental results regarding the equality of inertial and gravitational mass; moreover, Papapetrou showed that in GR a rotating body falls differently, in general, from a non-rotating body[[15]](#footnote-15)). Furthermore, in his reminiscences on the equivalence principle invention Einstein appeals not to, say, metaphysical systems of Plato or Aristotle that encouraged grasping the “essences of things” but to his own experience of SR creating. Thus, both in SR and GR cases he was looking for the *heuristical* components of the principle . In gravity purview he tried to comprehend gravitational and inertial phenomena from a single point of view. In my opinion it was consequent implication of the principle in Kantian spirit (the term “heuristic” was borrowed from Kant’s Critique for SR creation[[16]](#footnote-16) first), that promised to invent a consequence of hybrid models unifying SR and Newton’s theory of gravity. As a result, for Einstein the principle of equivalence was not so much a Law of Nature as a **pattern,** a ‘paradigm’ for theories of gravitation construction. At the same time the equivalence principle did not give rise to requirements which the new theory had to satisfy as a set of fixed axioms. It acted in a more general and diffuse way as heuristic guiding principle and, as such, in different contexts, had a variety of concrete implications. The principle allowed Einstein to relate two separate knowledge areas of physics to each other. In particular, it enabled the investigation of special cases of the gravitational field by means of the study of accelerated motion. So, until 1911 Einstein had committed himself mainly to exploring, by means of the equivalence principle, the effects and conceptual changes characterizing a new theory of gravitation, evidently without seriously attempting its construction. Only in early 1912 was he challenged by the publication of Max Abraham to elaborate such a theory, at least for the special case of a static gravitational field. What I want to stress is that it was the principle of equivalence that can be treated as the most apparent case exposing the influence of Kantian epistemology on Einstein. And the most important Kantian idea used by Einstein in GR construction, as well as in SR, was Kantian Idea of **Systematic Unity of Nature**. It is well-known that Einstein first read Kant at the age of thirteen and again at the age of sixteen[[17]](#footnote-17). Later, being an Eidgenössiche Technische Hochshule (ETH) student in Zurich, he had a good opportunity to continue the acquaintance with Kant’s creativity at the lectures of August Stadler, a neo-Kantian of Marburg school[[18]](#footnote-18). Later on Einstein was immersed in Kant again and again. For instance, in 1918 he wrote to Max Born :

“I am reading Kant’s Prolegomena here, among other things, and am beginning to comprehend the enormous suggestive power that emanated from the fellow and still does”[[19]](#footnote-19) .

Or, much later , reflecting on the main principles of reasoning in theoretical physics, Einstein avowed that

“the theoretical attitude here advocated is distinct from that of Kant only by the fact that we do not conceive of the categories as unalterable…They appear to be a priori only insofar as thinking without the positing of the categories and of concepts in general would be as impossible as breathing in the vacuum”[[20]](#footnote-20).

What did attract Einstein in Kantian epistemology? For Kant our freedom from the world makes science possible. He argued in the *Appendix* to the Dialectic of the first Critique that science must adopt certain ideas of reason as *heuristic*(”as if”) devices to encourage systematic unity .

“The concepts of reason are, as we have said, mere ideas, and of course have no object in any sort of experience, but also do not on that account designate objects that are invented and at the same time thereby assumed to be possible. They are merely thought problematically, in order to ground regulative principles of the systematic use of the understanding in the field of experience in relation to them (as heuristic fictions)”[[21]](#footnote-21) .

Along these lines, Fölsing rightly observes that Einstein probably first learned to think in terms of this “heuristic viewpoint”[[22]](#footnote-22) from his early reading of Kant. Einstein’s heuristic method was to state, or perhaps invent, an assertion from which familiar facts could then be deduced. It’s no wonder that Einstein’s path-breaking 1905a paper was entitled “*Uber eine die Erzeugung und verwandlung des Lichtes betreffenden* ***hewristischen*** *Lesictpunkt*” (“On a *Heuristic* Point of View Concerning the Production and Transformation of Light”[[23]](#footnote-23)). Respectively, I contend that the *paramount* notion for understanding Einstein’s epistemological framework is Kant’s idea of the systematic Unity of Nature[[24]](#footnote-24). This unity, for Kant, is not an ontological principle at all. It is meaningless to ask whether Mother Nature in fact possesses such a unity or not. On the contrary, the idea of unity has *epistemological* importance: “ such concepts of reason are not created by nature, rather we question nature according to these ideas, and we take our cognition to be defective as long as it is not adequate to them”[[25]](#footnote-25). Systematic unity of nature provides a *benchmark of validity for scientific hypothesis*, that complements the empirical idea of confirmation. From the host of different uniformities only those can be regarded as having law-like necessity that can be fitted into a unified, systematized general system.

“The hypothetical use of reason is therefore directed at the systematic unity of the understanding’s cognition, which, however, is the touchstone of truth for its rules”[[26]](#footnote-26).

Correspondingly,

“ A system has truth-content according to the certainty and completeness of its coordination-possibility to the totality of experience. A correct proposition borrows its ‘truth’ from the truth-content of a system to which it belongs”[[27]](#footnote-27) .

Yet it was the holistic stand that allowed Einstein as early as in 1906 to disregard the results of Kaufmann’s “crucial” experiments that contradicted the “Lorentz-Einstein theory”. As Einstein had put it, the rival theories (e.g. Abraham’s theory)

“have rather small probability, because their fundamental assumptions (concerning the mass of moving electrons) are not explainable in terms of theoretical systems *which embrace a greater complex of phenomena*”[[28]](#footnote-28).

Furthermore, in September 1913 Einstein presented a lecture at the 85th Congress of the German Natural Scientists and Physicians in Vienna that was published in December issue of Physikalische Zeitschrift under the heading “*On the present state of the problem of gravitation*”. In the lecture Einstein made clear his preference for Nordström’s theory over other gravitation theories, stating that Nordstrom’s later version of his gravitation theory was the only competitor to the ‘Entwurf’ theory satisfying four requirements that could be asked of any reasonable theory of gravitation. 1. Satisfaction of the laws of energy and momentum conservation. 2. The equivalence principle. 3. Validity of SR. 4. The observable laws of nature do not depend on the absolute magnitude of the gravitational potentials. It is hard to exaggerate that Einstein stressed the heuristic value of almost all the requirements admitting that “the postulates 2-4 resemble a ***scientific profession of faith*** *more than a firm foundation*”[[29]](#footnote-29). On the other hand, the second important component of Einstein’s heuristic – “the Lorentz model of a field theory” (Renn, Sauer) – enabled Einstein to conceive Newtonian gravitation and inertia as special cases of a more general interaction. For the case of uniform acceleration he could directly identify inertial effects with a scalar Newtonian gravitational field and he expected that he would be able to do the same for more general cases by generalizing the notion of gravitational field. A model for the generalizations was provided by maxwellian electrodynamics. It was Maxwell who “unified” electricity and magnetism through treating electric field **E** and magnetic field **B** as different facets of one and the same electromagnetic field tensor Fμν. In one of his 1912 papers Einstein even wrote on the “equality of essence”[[30]](#footnote-30) [Wessengleichheit] of inertial and gravitational mass. Between 1907 and 1911 Einstein used the equivalence principle to derive several consequences of his yet to be formulated relativistic theory of gravitation. It is important that in the case considered Einstein follows the paths of SR . Indeed, the new theory creation begins with the crossbred object construction , i.e. with the mass-energy introduction. One of the important SR consequences is the equivalence of mass and energy tenet. But, according to Einstein,

“this result suggests the question whether energy also possesses heavy (gravitational) mass. A further question suggesting itself is whether the principle of relativity is limited to nonaccelerated moving systems”[[31]](#footnote-31).

From the beginning Einstein was aiming at such a theory of gravitation that was to comprise both the knowledge on gravitation and inertia represented by classical mechanics and the knowledge on the structure of space and time embodied by SR. However, the crossbred object introduction – the introduction of inertial and simultaneously gravitational mass – leads to invasion of SR methods into Newtonian theory of gravity and to reverse invasion of Newtonian gravity methods into SR. As a result the both theories were “blown up” from within and the corresponding changes in both of them were set up. The changes were epitomized in the peculiar sequences of crossbred models, the “splinters” of the explosion performed. On the one hand, an inevitable consequence of the SR invasion into Newtonian theory of gravity turned out to be Nordström’s and Abraham’s research programmes. On the other hand, no less inevitable, owing to the equivalence principle, was the Newtonian theory invasion into SR that led to the consequence of Einstein’s works on the relativity principle generalization and to spreading the principle not only on inertial systems of reference, but on the various accelerated systems as well. Einstein used the principle of equivalence in order to transform the knowledge not of classical mechanics only but the knowledge embodied in **both**, classical mechanics and SR. His theory of the static gravitational field, as well as his early attempts to generalize it, were nothing but a reinterpretation of the SR with the help of the introduction of accelerated frames of reference. His systematic treatment of such accelerated frames induced him to apply generalized Gaussian coordinates in order to describe the coordinate systems adapted to these frames. It was then a natural step for him to consider the metric tensor . And with the introduction of the metric tensor Einstein constructed a theoretical object that was capable of representing gravitational and inertial theoretical objects on the same footing. By the beginning of 1912, Einstein realized that he would ultimately have to go beyond a scalar theory of gravitation. His strategy was to proceed in a step-by-step manner towards a full dynamical theory. The first step in the programme was to treat the “gravito-static” case, the gravitational analogue of electrostatics. However, he was already thinking about the second step, the “gravito-stationary” case, the gravitational analogue of magnetostatics. His ultimate goal was to advance a theory for time-dependent gravitational fields.

In March 1912 he was able to write to Paul Ehrenfest:

“The investigations of gravitational statics (point mechanics, electromagnetism, gravitostatics) are complete and satisfy me very much. I really believe that I have found a *part of the truth*. Now I am considering the dynamical case, again also proceeding from the more special to the more general case” [[32]](#footnote-32).

As is well-known, in 1908-1911 Einstein had neglected gravitation, possibly because of his preoccupation with the problem of quanta. But this, however, is only part of the explanation. The remaining part consists in that he realized how much work had to be done to arrive at an ultimate global theory able to embrace all the particular results obtained, “parts of the truth” as Einstein called them, transforming them into the details of a great edifice. And, since Einstein himself was delved into the peculiarities of the quanta, the problem of creating the scaffolds for the gravitation global theory had fallen on Abraham’s and Nordström’s broad shoulders. However, one has to keep in mind that even the pathways of their theories’ creation were outlined by Einstein himself, especially in his ground-breaking 1907 paper. Indeed, one of the important SR consequences states that E = mc2..­Since, in a gravitational field, the energy of a particle depends on the value of the gravitational potential at the position of the particle, the equivalence of energy and mass suggests that :

* (1) either the particle’s mass;
* (2) or the speed of light (or both) must also be a function of the potential.

Einstein in 1907 explored both possibilities, and both of the possibilities considered by him, a dependence of the gravitational potential either of the speed of light or of the inertial mass, were later explored by Max Abraham[[33]](#footnote-33) and Gunnar Nordström [[34]](#footnote-34) respectively in their own consequences of. And first of all it became clear that one can easily construct such a lorentz-invariant theory of gravitation in which the inertial and gravitational masses are equal (Nordström, 1912-1914). Nordström’s 1912 paper “*The principle of relativity and gravitation*” starts as follows:

“ Einstein’s hypothesis that the speed of light c depends upon gravitational potential leads to considerable difficulties for the principle of relativity, as the discussion between Einstein and Abraham shows us. Hence, one is lead to ask if it would not be possible to replace Einstein’s hypothesis with a different one, which leaves c constant and still adapts the theory of gravitation to the principle of relativity in such a way that gravitational and inertial mass are equal. I believe that I have found such a hypothesis, and I will present it in the following”[[35]](#footnote-35).

On the other hand, Einstein’s static gravitational theory did not offer even a hint at how the global theory should be constructed. So, only Göttingen theoretician, a master of classical electrodynamics Max Abraham became the first , in February 1912, to propose that the four-dimensional line element, defining the infinitesimal distance between points in Minkowski space in terms of a constant metric, has to be replaced by a variable line element whose functional dependence of the coordinates is determined by a gravitational potential associated with the variable speed of light.

To Abraham’s advancements belong some of the insights that he had achieved in the course of his research, such as the possibility and essential properties of gravitational waves, remaining up to our times a standard for any relativistic theory of gravitation.

“According to our theory, light and gravitation have the same speed of propagation; but whereas light waves are transverse, gravitational waves are longitudinal”[[36]](#footnote-36)

In a lecture presented in October 1912 and published the following year Abraham was the first to discuss the possibility of gravitational waves in relativistic theories of gravitation. Moreover, in 1912 G. Pavani had calculated the perihelion shift of Mercury according to Abraham’s theory, finding a value that was approximately one third of the observed one[[37]](#footnote-37) .Abraham’s theory thus made a more accurate prediction than even the ‘Entwurf’ theory. Thirdly, Abraham in March 1912 was the first to hit upon a singularity in a field theory of gravitation and to calculate what was later called the “Schwarzchild radius”. It was not accidental that Einstein turned to the global gravitational theory construction only *after* the publication of Abraham’s first vector gravitational theory. It should be noted that for static fields Abraham’s theory coincides with Einstein’s. But the most valuable result of the hybrid theories of Nordström and Abraham consisted in that the both theories maintained **very promising hints** on how the global theory could be created[[38]](#footnote-38). At first, by letting the geometry of Minkowski space depend on the gravitational potential (Abraham). At second, by representing the gravitational potential not by a single function but by a ten-component object on a par with the stress-energy tensor and having this tensor as its source (Laue and Nordström). At third, by including an effect of the gravitational potential on the measurement of space and time (Nordström).

**Part two. The genesis of Einstein’s and Grossmann’s ‘Entwurf’.**

Let me start from Nordström’s most important result obtained with a help of M. Laue’s papers. The result draws on the fundamental problem of classical electrodynamics – the problem of electron’s electromagnetic mass that owes so much to Abraham’s works[[39]](#footnote-39). If one computed total momentum and energy of the electromagnetic field of an electron, the result universally accepted at that time was (Total field momentum) = 4/3c2­ (Total field energy) (Electron velocity) Hence, as Poincaré and Einstein revealed, there must be also stresses of a non-electromagnetic character within the electron (“Poincare’s elastics”, as Richard Feynman later called them).So, the puzzle Max von Laue addressed in 1911 was to find very general circumstances under which the dynamic of such an electron would agree with the relativistic dynamics of point mases. While Hermann Minkowski had introduced the four-dimensional stress-energy tensor at the birth of four-dimensional methods in SR, his use of the tensor was restricted to the special case of the electromagnetic field. Laue’s work concentrated on extending the use of this tensor to the most general domain[[40]](#footnote-40). The properties of this tensor and its behavior under Lorentz transformations summarized a great deal of the then current knowledge of the behavior of stressed bodies. As a result, Laue obtained the expression for the stress-energy tensor Tμν (μ,ν = 1,2,3,4) that embraced three main blocs. (1) The first bloc represents the familiar three dimensional tensor pik  (i,k = 1,2,3). (2) The second bloc represents the momentum density **g** (gx, gy, gz). (3) The third bloc represents the energy flux **θ** (θx, θy, θz). And surely the (T44) component of the energy-momentum tensor represents energy. Einstein’s equivalence principle prompted that each stress-tensor bloc should give *its own impact* into the gravitational field potentials, i.e. each bloc is related to the gravitational potentials of its own. Hence there should be many potentials - scalar potentials, vector potentials, etc. and not a single one .That is why the overall gravitational field potential should be a group of several potentials and should in the most general case be described by a matrix, a tensor, since its components are transformed in the coordinate transformations like scalars, vectors, etc. The most pertinent analogy that played an important heuristic part was, of course, maxwellian electrodynamics with 4-dimensional electromagnetic field potential Aμ = (**А**, φ). The latter, in particular static electromagnetic field case, is reduced to static potential φ. This peculiarity was later thoroughly described by Göttingen master of electrodynamics Max Abraham in his 1914 thought-provoking paper “*Recent Theories of Gravitation*”[[41]](#footnote-41) ;the paper contained a special part critically analyzing Einstein’s and Grossmann’s ‘Entwurf’.

“The basic idea of the tensor theory of the gravitational field can be understood as follows. The energy density, which in a static field is determined by the divergence of the gradient of the gravitational potential, plays in the theory of relativity merely the role of one component of the resulting world tensor T; it is joined by nine other tensor components which characterize the energy flux and the stresses. The tensor theory assumes that, like the energy density (Т44) , the remaining nine components Тμν (μ, ν = 1,2,3,4) ***generate gravitational fields*** whose potentials gμν  form a ten-tensor themselves “[[42]](#footnote-42).

The physical sense of the components is explained by Abraham below when he remarks that the integration of ‘Entwurf’s field equations

“is extraordinary difficult. Only the method of successive approximations promises success. In this one will usually take as a first approximation the solution that treats the field as static. Here, ***Einstein’s theory becomes identical with Abraham’s theory*** […] In his Vienna lecture A. Einstein takes the normal values of the gμν  as the first approximation : g11 = g22 =g33 =1; g44 = -c2 , gμν =0 for μν; he considers the deviations g\*μν from these normal values as quantities of first order, and arrives, by neglecting quantities of second order, at the following differential equations: g\*μν = Tm μν . For incoherent motions of masses, the last (Tm44) among the components of the material tensor Tm is the most important; it determines the potential g\*44 = Фg. Then follow the components Tm14, Tm24, Tm34, which are of first order in v/c; these determine the potentials g\*14, g\*24, g\*34, which can be viewed as the components of a space vector – (1/c) Ug. The remaining components of Tm are of second order in v/c. If one neglects quantities of this order, then one only needs to consider those four potentials, and obtains for them the differential equations

⎕ Фg = c2μ (60a)

⎕ Ug = c2μ (v/c) (60b),

Where μ is the mass density.

Here the analogy with electrodynamics catches one’s eye. Except for the sign, the field equations (60 a,b) agree with those that must be satisfied in the theory of electrons by the ‘electromagnetic potentials’, the scalar one (Ф) and the vector one (A). In this approximation, the Einstein-Grossmann tensor theory of the gravitational fields leads to the same results as the vector theory sketched in (IA) [i.e. the theory of Abraham]”[[43]](#footnote-43).

As the correspondence and the papers indicate, Einstein agreed with Nordström’s assessment of the importance of Laue’s work for gravitation theory. Moreover, some pieces of his 1912 and 1913 papers (his proposal to call T ‘Laue’s scalar’, for instance) indicate that he had personal contacts with Laue and discussed the stress-tensor problems with him. Such personal communication is compatible with the fact that both Einstein and Laue were teaching in Zurich, with Einstein at the ETH and Laue at the University of Zurich[[44]](#footnote-44). It should be added that the same year Nordström also came to Zurich where supposedly he had communicated with the both researchers. Yet what the connection between Тμν and gμν should be ? – An important hint is contained in Nordström’s first 1912 paper : R= (k/2) T, where R is the fully contracted Riemann - Christoffel tensor and T the trace of the stress-energy tensor. But if the expression is characteristic of scalar theory, the expression that generalizes it in a most natural and simple way should look like : k Тμν = Гμν, where Гμν is a “contravariant second rank tensor formed by the derivatives of the fundamental tensor gμν”. But these are exactly the gravitational field equations of the first metric theory – the theory of Einstein and Grossmann[[45]](#footnote-45), published in 1913г.! It was immediately understood that in general the ‘Entwurf’ equations are not covariant; they “remain covariant only with respect to linear orthogonal substitutions”. Yet for a long time this peculiarity did not bother the authors; it indicated once more that the ‘Enwurf’ field equations were born not from the covariance principle but as a direct generalization of hybrid theories of Nordström and Abraham with a help of Laue’s results. Just as Einstein commented in his November 1913 letter to Paul Ehrenfest,

“The gravitational affair has been clarified to my *complete satisfaction* (namely the circumstance that the equations of the gr. field are covariant only with respect to linear transformations). For it can be proved that generally covariant equations that determine the field completely from the matter tensor cannot exist at all. Can there be anything more beautiful than this, that the necessary specialization follows from the conservation laws”[[46]](#footnote-46). However, on the other hand, according to a later reminiscences,

“The equivalence principle allows us…to introduce non-linear coordinate transformations in such a [4-dimensional] space [with pseudo-Euclidean metric]; that is, non-Cartesian (“curvilinear’) coordinates. The pseudo-Euclidean metric then takes the general form : ds2= ∑gik dxidxk summed over the indices i and k (from 1 to 4). These gik are then functions of the four coordinates, which according to the equivalence principle describe not only the metric but also the ‘gravitational field’”[[47]](#footnote-47).

Certainly, the question was raised on getting the mathematical apparatus dealing with such mathematical objects; in particular, from the mathematical point of view, the task was to find a differential operator of second order for the metric tensor covariant with respect to the largest possible class of coordinate transformations. In August 1912 Einstein had left Prague, where he had taught for a year and a half, to become a full professor at the Eidgenössiche Technische Hochshule (ETH). With Einstein’s return to Zurich, he began a collaboration with his old friend Marcel Grossman. These collaboration ceased in 1914, when Einstein moved to Berlin to become a salaried member of the Preussiche Akademie der Wissenschaften. Grossmann’s help was needed to solve the problem. Grossmann found that the exquisite mathematical apparatus was contrived at the end of the XIX-beginning of the XX-th century by Riemann, Levi - Civita, Ricci, Christoffel et al. That is why the first part of ‘Entwurf’ containing the gravitational field equations was written by A. Einstein, and only the second one – by Grossmann. Continuing the quotation from the 1955 reminiscences:

“I was made aware of these [works by Ricci, Levi- Civita et al.] by my friend Grossmann in Zurich, when I put to him the problem to investigate generally covariant tensors, whose components depend only on the derivative of the coefficients of the quadratic fundamental invariant. He at once caught fire, although as a mathematician he had a somewhat skeptical stance towards physics… He went through the literature and soon discovered that the indicated mathematical problem had already been solved, in particular by Riemann, Ricci and Levi - Civita. This entire development was connected to the Gaussian theory of curved surfaces, in which for the first time systematic use was made of generalized coordinates”[[48]](#footnote-48).

And finally in September 1913 in Vienna Einstein presented a lecture exposing the physical foundations of ‘Entwurf’ and those general conditions(1-4) which any relativistic theory of gravity should satisfy[[49]](#footnote-49).It is important that from the host of the gravitational theories at hand Einstein marked out Nordström’s scalar theory that satisfied all the requirements for a theory of gravitation that could be imposed on the basis of current experience. As a result, the main achievement of the second streak consisted in the metric tensor invention; the latter appeared to be a crossbred object that unified two different research traditions – physical (scalar and vector theories of Nordström and Abraham) and a mathematical one (geometrical results of Riemann, Christoffel, Levi-Civita et al.). Now gij’s had a dual function: on the one hand they represented the physical gravitational potentials and on the other they were coefficients in the expression of ds2 = ∑ gij dxi dxj. By dint of the crossbred object gij  contrivance the interpenetration of geometry and physics began: physics became geometrized, and geometry was made empirical[[50]](#footnote-50). The interpenetration led to the GR fundamental theoretical scheme construction. The first stage of interpenetration resulted in the gravitational field equations of ‘Entwurf’ : Rμν  = ϗ Tμν  with their ultimately simple premises of gravitational potentials being common partial derivatives of metric. However the further penetration of physics into the geometry led to skillful modification of plain scheme.

**Part three. Transition from 1913 Entwurf to a full-blooded November 1915 theory of gravitation.**

In hindsight, Einstein gave three reasons for his rejection of the Enwurf theory: - it could not explain, as Michele Besso demonstrated, the perihelion shift of Mercury[[51]](#footnote-51); - it did not allow the interpretation of a rotating system as being equivalent to the state of rest, and hence did not satisfy Einstein’s Machian expectations; - the derivation of the ‘Entwurf’ field equations involved an unjustified assumption. In a series of four communications to the Prussian Academy of Science in November 1915 Einstein replaced the ‘Entwurf’ by a full-blooded metric theory of gravitation, solving incidentally the problem of Mercury’s perihelion. Thus, how did the transition from the ‘Entwurf’ to the full-blooded GR (exposed on November 25, 1915 in Berlin Academy of Science) take place? How genuine Einstein’s gravitational field equations Rμν – (R/2) gμν = kTμν were obtained? Modern researchers discern two basic strategies in Einstein’s creativity – a ‘*physical strategy’* and ‘*mathematical strategy’*. Following the physical strategy, one constructs field equations in analogy with Maxwell’s equations, making sure from the start that energy-momentum conservation is satisfied and that the Poisson equation of Newtonian theory is recovered in the case of weak static fields. This is the approach that led Einstein to the ‘Entwurf’ equations. Following the mathematical strategy, one picks candidate field equations based largely on considerations of mathematical elegance and only after investigates whether they make sense from a physical point of view. Inspite of the fact that the question “which strategy dominated in the GR creation” is a subject of discussions my own experience of dwelling into Einstein’s works cries for the physical strategy the strong adherents of which are M. Janssen and J. Renn[[52]](#footnote-52).According to them, what happened in 1915 was that the physical strategy led Einstein back to field equations to which the mathematical strategy had already led him in the Zurich notebook but which he had then been forced to reject since he could not find a satisfactory physical interpretation to them.

In particular, it was not until October 1915 that Einstein had discovered that the ‘Entwurf’ field equations are incompatible with one of the guiding ideas of his research programme – the idea that the inertial forces of rotation can be conceived of as gravitational forces (the Lense - Thirring effect in GR). And, what is more important, Einstein realized that the gravitational field should be represented not by common partial derivatives but by the so-called Cristoffel symbols. Only then the gravitational field Lagrangian should more resemble the Lagrangian of the electromagnetic field in full accord with Einstein’s research programme heuristic. Hence one can discern two stages in Einstein’s gravitational field equations derivation: (1) Einstein’s, Abraham’s and Nordström’s hybrid models’ synthesis that led to the ‘Entwurf’ construction; (2) analogy with Maxwell’s equations pursuance application that provided the transition from the ‘Entwurf’ to a full-blooded metric theory of gravitation. Yet the GR field equations were only the capstone of the edifice of GR. Since that time, much efforts were to be done to construct an ultimate edifice.

**Conclusions.**

To recapitulate , the rational reconstruction of GR genesis proposed enables to highlight the hallmarks of the process obfuscated by the other reconstructions. (i) The basic GR model was constructed due to the unification of the hybrid models of Einstein , Nordström and Abraham constructed within different research programmes. (ii) It is this hallmark that helps to comprehend the true reasons for Einstein’s victory over the rival programmes of Nordström and Abraham. Einstein’s metric theories – ‘Entwurf’ and GR – superseded the theories of Nordström and Abraham because they were more general, i.e. embraced Nordström’s and Abraham’s theories in modified form. (iii) Author’s epistemological standpoint enables to look further and to conceive why it was Einstein that could propose the synthetic approach unifying all the positive achievements of the other approaches. It was because his heuristic contained the equivalence principle interpreted in Kantian, non-ontological, heuristic spirit .

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