Coordination, Geometrization, Unification. An Overview of the Reichenbach–Einstein Debate on the Unified Field Theory Program

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Keywords: Reichenbach • Einstein • Weyl • Unified Field Theory • General Relativity • Geometrization • Unification • Coordination

Introduction

Most of Einstein's published work from 1919 till his death in 1955 (Einstein and Kaufman, 1955)[1] is dominated by the search of a unified field theory, which would combine both gravitational field and electromagnetic field into a single mathematical structure and at the same time integrate the field with its sources. The history of Einstein's engagement with such program has been rightly described as a rapid succession of hopes and disappointments[2] (Vizgin, 1994, 187). Einstein was aware that, without an analogon of the equivalence principle, the choice of the basic field structure to represent the combined electromagnetic/gravitational field could not be empirically motivated from the outset as in case of his theory of gravitation. One had to proceed tentatively to search the right field quantities that would allow to derive, usually from a variational principle, the desired set field equations—that is to recover Maxwell and Einstein field equations in first approximation. In Einstein's view the principle of general covariance considerably reduced the number of possible sets of field equations. However, it not determine the field-equations uniquely. Einstein seemed to have progressively came to accept that only mathematical simplicity which is of course quite arbitrary. Since, in most cases, the basic field quantities did not have a physical interpretation, the theory could be compared with experience only indirectly, by integrating

[1]For an overview of Einstein's work on unified field theory-project, see Sauer (2014); for the philosophical background of Einstein's search for a unified field theory see Dongen (2010); on Einstein's philosophy of science Ryckman (2017).

[2]During his Berlin years, after using a trace-free equation (Einstein, 1919b), Einstein explored the so called conformal theory, returned to Kaluza's (1921) theory, (**Einstein1921?**) and then moved to (Eddington, 1921a)'s purely affine approach (Einstein, 1923b,c,d) in late 1922. By 1925 Einstein proposed his first original approach, the so-called metric-affine theory (Einstein, 1925a), which he soon abandoned returning to the trace-free equations after a correspondence with G. Y. Rainich (Einstein, 1927a), and then, inspired by the work of O. Klein, moved to the five-dimensional approach (Einstein, 1927b,c). The decade closed with *Fernparallelismus*-field theory that he abandoned in favor of the semi-vector theory before leaving for the United States in 1933. During his Princeton years Einstein, by then in near complete isolation, returned to the five-dimensional approach, and after the interlude the bi-vector theory, pursed again the metric-affine approach until his death in 1955.

the field equations in the hope of finding static spherically symmetric solutions representing electron and proton and their law of motion.

It has not been fully appreciated that Hans Reichenbach was probably the only philosopher who, alongside his more well-known work on relativity theory (Reichenbach, 1920b, 1924, 1928a), possessed the technical skills to make head or tail of the variety of the unification attempts. Indeed, Reichenbach could follow the historical development of unified field theory-project closer than almost all others. In the late 1910s, he witnessed as a student the rise of the program when he attended the Berlin lectures and was confronted with Einstein's skeptical reaction to Hermann Weyl's (1918b) early attempt. When he returned to Berlin as a professor nearly a decade later (see Hecht and Hoffmann, 1982), he observed the beginning of the unified field theory-project's decline, observing closely the development Einstein's *Fernparallelismus* field theory. Thereby, Reichenbach did not only observed closely the technical development of the field-theoretical approach to physics, but he was a privileged witness of the progressive transformation in Einstein's philosophical outlook, from the moderate empiricism of his youth, to the extreme rationalism of his later years.

The goal of this paper is to revisit the Einstein-Reichenbach relations not from the point of view of his capacity as staunch *defender* of relativity theory Hentschel, 1982, but from the perspective of his less well-know role of indefatigable *critic* of the unified field theory-project. Most of Reichenbach's critical remarks on the unified field theory-project appeared in published writings. However, the personal and philosophical motivations of his mistrust toward the unification program emerges more straightforwardly, in his private correspondence. For a general overview, it is useful to organize Reichenbach's reflections on the unified field theory-project around three correspondences, which roughly seem to revolve around three different conceptual issues:

Coordination: The Reichenbach-Weyl correspondence (1920-1922). In his 1920 habilitation, Reichenbach, although rather in passing, accused Weyl of attempting to deduce physics from geometry, by reducing physical reality to 'geometrical necessity' (Reichenbach, 1920b, 73). On the contrary, the greatest achievement of general relativity, Reichenbach claimed, was to have shifted the question of the truth of geometry from mathematics to physics (Reichenbach, 1920b, 73). Reichenbach insisted in what he thought was the central of Einstein's epistemology: abstract mathematical apparatus of the theory should be coordinated with behavior of physical probes. After a correspondence with Weyl, Reichenbach (1922a, 367–368), Reichenbach accepted Weyl's (1921d)'s defense that he did not meant to derive physics from mathematics. However, Weyl also insisted that spacetime geometry has nothing to do with behavior of rods and clocks, or similar physical devices. However, Reichenbach objected that in this way, the theory becomes overly formal, losing its convincing power (Reichenbach, 1922a, 367).

Geometrization: Reichenbach-Einstein correspondence (1926-1927). Reichenbach observed that Weyl's style of doing physics was prevailing. Einstein's (1923a) started to pursue more aggressively a unified field theory program by the end of 1922, when he pursed Eddington's (1921a) approach. In March 1926, after making some critical remarks on Einstein's newly published metric-affine theory (Einstein, 1925a), Reichenbach sent Einstein a 10-page 'note' (Reichenbach, 1926b). In it, he constructed a toy unification of the gravitational and electricity in a single geometrical framework, thereby showing that the 'geometrization' of a physical field was a mathematical trickery rather physical achievement. After a back and forth Einstein seemed to agree (Lehmkuhl, 2014). The note was later included as section §49 in a long technical Appendix to the *Philosophie der Raum-Zeit-Lehre* (Reichenbach, 1928a, SS46-50) in which general relativity was presented as a 'physicalization of geometry' rather than a '*geometrizaton* of gravitation' (Giovanelli, 2021).

Unification: Reichenbach-Einstein correspondence (1928-1929). A few months after the publication of the *Philosophie der Raum-Zeit-Lehre* (Reichenbach, 1928a), Einstein (1928b,d) launched yet another attempt at a unified field theory, the so-called *Fernparallelismus*-field theory. Reichenbach, now back in Berlin, discussed the new theory in person with Einstein and sent him once again a manuscript with some comments (Reichenbach, 1928c). This exchange of letters marked the cooling of Einstein's and Reichenbach's personal friendship but also the end of their philosophical kinship. In the late 1920s, Reichenbach (1929b,c,d) came to realize that, in Einstein's mind, the actual goal of the unified field theory-project was not the geometrization, but as the *unification* of two different fields, an undertaking for the sake of which Einstein was ready to embrace a strongly speculative approach to physics (Dongen, 2010).

The present paper does not have the ambition to provide new documentary material. The recognition of the importance of **??** has been an important result of the Reichenbach-scholarship of the last decades (Ryckman, 1995, 1996). The last two correspondences has been analyzed in more details more recently elsewhere (**Giovanelli2022**, Giovanelli, 2016a). However, the paper makes the attempt to build a coherent narrative out of these episodes that have been considered only separately and thus hopes to throw new lights of each of them. In particular, the paper argues that Reichenbach's hostile reflection to unification research program were motivated by common thread. The great achievement of general relativity was the separation between mathematics and physics. Mathematics teaches what is physically permissible, but never what is physically true. Reichenbach was disappointed that part relativists started to progressively mathematical simplicity in itself could provide an insight physical reality. In this sense Reichenbach's role of defender of relativity and critic of further unification program complement each other. Reichenbach's attacks the unified field theory-project, including Einstein's contribution to the field in as much it was to have betray the key philosophical achievement of Einstein's theory: "The general theory of relativity by no means turns physics into mathematics. Quite the opposite: it brings about the recognition of a physical problem of geometry"Mit der allgemeinen Relativitätstheorie wird keineswegs die Physik zur Mathe- matik gemacht, sondern das Umgekehrte gilt: es wird ein physikalisches Pro- blem der Geometrie erkannt (Reichenbach, 1929a, 11).

In this manner, Reichenbach, somewhat unwittingly, was able to formulate a sort of 'theory of spacetime-theories' (Lehmkuhl, 2017). He attempted to unravel the key to Einstein's success in formulating a field theory of gravitation by uncovering the reasons for the failure of subsequent unification attempts. Thereby, Reichenbach was responsible for having brought to the debate, often for the first time, some of the central issues of the philosophy of space-time physics: (a) the relation between a theory's abstract geometrical structures (metric, affine connection) and the behavior of physical probes (rods and clocks, free particles, etc.); (b) the question whether such association should be regarded as a geometrization of physics or a physicalization of geometry (c) the interplay between geometrization and unification in the context of a field theory; .

1 Coordination. The Weyl-Reichenbach Correspondence (1920–1921)

After serving in World War I, from 1917 until 1920, Reichenbach worked in Berlin as an engineer specializing in radio technology to support himself after the death of his father. Nevertheless, in his spare time, he managed to attend Einstein's lectures on special and general relativity in winter term 1917–1918 and in summer term 1919. We posses three sets of Reichenbach's undated student notes (HR, 028-01-04, 028-01-03, 028-01-01). One set of notes (HR, 028-01-01) appears to be very similar to Einstein's own lecture notes from 1919 (Einstein, 1919a). In presenting general relativity, Einstein's lectures follow roughly the corresponding sections of his previous published presentations of relativity theory (Einstein, 1916, 1914). The mathematical apparatus of Riemannian geometry is introduced by starting from the metric $g_{\mu\nu}$ as the fundamental concept, that is from the formula to calculate the squared distance $ds^2 = g_{\mu\nu}dx_\mu dx_\nu$ between any two neighboring points x_ν and $x_\nu + dx_\nu$ independently of the coordinate system. From the $g_{\mu\nu}$, one calculate the so-called Christofell symbols $\begin{Bmatrix}\mu\nu \\ \tau\end{Bmatrix}$, which enters in the geodesic equation, and the Riemann tensor $R^\tau_{\mu\nu\sigma}$ which generalized the Gaussian notion of curvature.

However, both Reichenbach's (see fig. 1) and Einstein's notes show that in the lectures May-June 1919, Einstein used for the first time the interpretation of the curvature in terms of the parallel displacement of vectors, which was introduced by Tullio Levi-Civita (1916) and applied to relativity theory by Hermann Weyl (1918b). Both names are mentioned explicitly (HR, 028-01-03, 33). Instead of using the metric as a fundamental concept, it is more convenient to start by introducing a coordinate-independent criterion of parallelism of two vectors at neighboring at points x_ν and $x_\nu + dx_\nu$, that is it is determined whether or not two vectors point into the same direction: $dA^\mu = \Gamma^\tau_{\mu\nu}A^\nu x_\nu$ (HR, 028-01-03, 33).[3] The $\Gamma^\tau_{\mu\nu}$, which is supposed to be symmetrical in the lower indexes, is the so-called affine connection (*Zusammenhang* or displacement (*Verschiebung*).[4] The metric could be introduced at a later stage by defining via the

[3]The notation used by Reichenbach (1928a) which in turn is based on Eddington (1923, 1925) is used throughout the paper..

[4]The affine geometry is the study of parallel lines, Weyl (1918c) hence the expression 'affine connection' (*affiner Zusammenhang*), where 'connection' refers to the possibility comparison of vectors at close points

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. However, because it is a relation of 'sameness' rather than parallelism that is relevant in this context, others, such as Reichenbach, prefer to speak of the operation of 'displacement' (*Verschiebung*), where the latter indicates the small parallelverschiebungDOUB.png

Figure 1: Reichenbach's student notes. Einstein introduces the notion of parallel transport of vectors

notion of scalar product in a manner independent of the choice of the coordinate system. A vector's squared length is the scalar product of this vector with itself: $l^2 = g_{\mu\nu}A^\mu A^\nu$. By imposing the condition that the length of vectors does not change under parallel transport, the coefficients of the $\Gamma^\tau_{\mu\nu}$ happen to have the same numerical values of the Christoffel symbols $-\left\{\begin{matrix}\mu\nu\\ \tau\end{matrix}\right\}$ (up to a sign). The structure of the Einstein-Riemann geometry could be then recovered without any reference to the metric $g_{\mu\nu}$. It differs from the Euclidean structure by the fact that, when a vector is transported along a closed curve, it will acquire a rotation whose amount is determined by Riemann tensor $R^\tau_{\mu\nu\sigma}(g)$. If the latter does not vanish vectors defined at different spacetime points cannot be compared.

This technical innovation in differential geometry played a fundamental role, not only in successive presentations of general relativity (see Einstein, 1921a), but even more prominently in the development of the unified field theory-project. If one starts with a symmetric $g_{\mu\nu}$ the road is, so to speak, marked. The Christoffel symbols are the only possible destination. However, if one defines the displacement $\Gamma^\tau_{\mu\nu}$ independently from the metric $g_{\mu\nu}$, the Riemannian connection $\Gamma^\tau_{\mu\nu} = -\left\{\begin{matrix}\mu\nu\\ \tau\end{matrix}\right\}$ appears only as a special case that has been achieved by introducing a series of conditions, that turned out not be necessary. By dropping some of these conditions, the possibility opens up to introduce additional mathematical degrees of freedom to accommodate the electromagnetic field alongside the gravitational field in a unified 'geometrical' description.

As it is well-known, Weyl (1918a, 1919a) was bothered by a conceptual asymmetry characterizing Riemannian geometry. The comparison of direction of vectors is path-dependent, whereas the comparison of their lengths remains distant-geometrical. To compensate for this 'mathematical injustice' (Afriat, 2009), Weyl introduced a more general affine connection depending not only on the metric/gravitational tensor $g_{\mu\nu}$ but also on the four-vector φ_ν. For formal reason, the latter could be identified with electromagnetic four-potential. Weyl could then conclude that, just like general relativity represented a geometrization of gravitational phenomena, his theory represented a unified geometrization of both gravitational and electromagnetic phenomena, which were, at that time, the only kind known. Weyl did not hesitate to declare that "Descartes' dream of a purely geometrical physics" had be finally fulfilled (Weyl, 1919b, 263).

Einstein had repeatedly criticized Weyl's attempt (Einstein, 1918a). However, by the spring of 1919, after a correspondence with Theodore Kaluza he had started to show increasing interest in the unification program (Wünsch, 2005). The question fell into the background after the success of the eclipse expedition was announced in November 1919 (Dyson, Eddington, and Davidson, 1920). By the end of the year, Einstein was turned into an international celebrity leaving him little time to work (Einstein to Fokker, Dec. 1, 1919; CPAE, Vol. 9, Doc. 187, Einstein to Hopf, Feb. 2, 1920; CPAE, Vol. 9, Doc. 295). Inevitably, the German philosophical community started to show increasing interest in the theory (see Hentschel, 1990, for an overview). The question whether the new theory was compatible with Kant's philosophy

more examples

Kaluza

coordinate difference dx_ν along which the vector is transferred. The word displacement also refers to the vector dx_ν. To avoid confusion the world transfer *Übetragung* was also used.

became particularly pressing. As trained physicists with a doctorate in philosophy Reichenbach, 1916 Reichenbach was in a privileged position to deal with this issue. By following Einstein's lectures, he had acquired a technical knowledge of the new theory that probably had no equal among the philosophers of his time. In February or March 1920, Reichenbach, who has just moved to Stuttgart, decided to write his habilitation on this topic.. In the preceding months, he had further worked on the theory "also according to Weyl" (HR, 044-06-23)—that is probably studying Weyl's textbook *Raum–Zeit–Materie* (Weyl, 1918b). The Kapp-Pusch coup on March of 1920 gave Reichenbach a few days of leave from Huth radio industry were he was employed (HR, 044-06-23). Thus, he could work without interruptions and in ten days he completed an early draft. The manuscript was then typed and shown among others to Einstein. Thanks to the mediation of Arnold Berliner, the influential editor of the *Naturwisseschaften*, Reichenbach obtained a publication agreement with Springer (HR, 044-06-23).

Reichenbach's habilitation has recently attracted renewed attention (Friedman, 2001). Reichenbach borrowed from Schlick (1918) that idea that physical knowledge is ultimately (*Zuordnung*), the process of relating an axiomatically defined mathematical structure to concrete empirical reality (Padovani, 2009). However, Reichenbach attempted to give this insight a 'Kantian' twist. According to Reichenbach, in a physical theory, beside the 'axioms of connections' (*Verknüpfungsaxiome*) encoding the mathematical structure of a theory, one needs special class of physical principles the 'axioms of coordination' (*Zuordnungsaxiome*) to ensure a univocal coordination of that structure to reality. For the young Reichenbach, the latter axioms are *a priori* in the sense that they are 'constitutive' sense of the object of a physical theory. However, they are not apodeictic, or valid for all time. As it is well known, Reichenbach would soon abandon the project of a constitutive but relativized *a priori*. However, he would firmly maintain the separation between the mathematical framework of a theory (the 'defined side') and the way it related to empirical reality (the 'undefined side') (Reichenbach, 1920b, 40; tr. 1969 42) as an essential feature of his philosophy.

1.1 Reichenbach's Habilitation and his critique of Weyl Theory

According to Reichenbach, relativity theory made this division of labor in the realm of geometry inevitable. The possibility of non-Euclidean geometries had already indicated that the Euclidean character of physical space could no longer been taken for granted (Reichenbach, 1920b, 3; tr. 1969 3). Mathematicians were inclined to considered geometry as an empty schema that did not contain any statements about the physical world if not in the form of arbitrary conventions (Reichenbach, 1920b, 3; tr. 1969 3). In comparison to these positions, Reichenbach wrote, "the theory of relativity embodies a completely new idea" (Reichenbach, 1920b, 3; tr. 1969 4). Relativity theory claims that the theorems of Euclidean geometry do not apply to the physical space, that Euclidea geometry si simply *false* (Reichenbach, 1920b, 3; tr. 1969 4). In this way, relativity theory has made necessary to distinguish between pure geometry as an uninterpreted formal system and applied geometry as an empirical theory of physical space (Reichenbach, 1920b, 73; tr. 1969 76). The propositions of pure geometry are neither true nor false. The question of the truth of physiical geometry pertain to physics alone. In order to clarify this point, rather in passing, Reichenbach, indicated Weyl's theory as a glaring example of how easy it was to slip into old habits. Weyl once again believed to have found a certain geometry that, for its intrinsic mathematical appeal, must have been true for physical reality: "In this way the old mistake is repeated" (Reichenbach, 1920b, 73; tr. 1969 76).

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Reichenbach's brief outline of Weyl's theory is sufficient to grasp the gist of his argument. As Reichenbach's put it, "Weyl's generalization of the theory of relativity [...] abandons altogether the concept of a definite length for an infinitesimal measuring rod" (Reichenbach, 1920b, 73; tr. 1969 76). In Euclidean geometry a vector can be shifted parallel to itself along a closed curve so that upon its return to the point of departure it has the same direction and the same length. In the Einstein-Riemannian geometry it has merely the same length, no longer the original direction, after its return. In Weyl's theory it does not even retain the same length. As we have seen, in this way, in addition to the 'metric tensor' $g_{\mu\nu}$, a 'metric vector' φ_ν is introduced that, for formal reasons, could be identified with electromagnetic potential. Reichenbach conceded that Weyl's theory represented a possible generalization of Einstein's conception of spacetime which, "although not yet confirmed physically, is by no means impossible" (Reichenbach, 1920b, 76; tr. 1969 79).

Reichenbach seemed to have been aware of Einstein's main objection to Weyl's proposal (Einstein, 1918a, see). In general relativity, the length ds of the time-like vector dx_ν is measured by a physical clock, e.g., by the crests of waves of radiation were emitted by an atom. If we maintain this interpretation, then Weyl's theories implies that "the frequency of a clock is dependent upon its prehistory"Nach der Weylschen Theorie ist die Frequenz einer Uhr von mrer Vorgeschichte abhängig. (Reichenbach, 1920b, 77; tr. 1969 80). Two atomic clocks at one place, will in general not tick at the same rate when they are separated brought back together. This result appears to be contradicted by a vast amount of spectroscopic data shown that all atoms of the same type have the same systems of stripes in their characteristic spectra independently of their past history. Reichenbach conceded to Weyl that these effects might "compensate each other on the average" daß sich diese Einflüsse im Durchschnitt ausgleichen, (Reichenbach, 1920b, 77; tr. 1969 80). Thus, the fact that "the frequency of a spectral line under otherwise equal conditions is the same on all celestial bodies" could he interpreted as an approximation, rather than being a consequence of the Riemannian nature of space-time (Reichenbach, 1920b, 77; tr. 1969 81). This, remark anticipates to a certain extent Weyl's line of defense. However, Reichenbach considered unacceptable was Weyl's justification for the choice of a more general geometry as the actual geometry of spacetime.

According to Reichenbach, Weyl seems to imply that his non-Riemannian geometry must be true *physically* because it is *mathematically* superior to Riemannian geometry, being the true realization of the principle of locality. As we have seen, in Weyl geometry a vector moving close loop which would same length but different direction in Riemannian geometry, different length and different direction in Weyl's geometry. Thus, Weyl geometry eliminated the last distant-geometrical treatment of Riemannian geometry. Weyl geometry seems to be the most 'general geometry,' a purely infinitesimal geometry. Thus, there would be no reason to assume from the outset than a more special geometry applies to reality. However, Reichenbach had already surmised that this generalization could be continued. In Weyl's geometry lengths can be compared at the same point in different directions, but not at distant points. "The next step in the generalization would be to assume that the vector changes its length upon turning around itself" (Reichenbach, 1920b, 76; tr. 1969 85). Probably, more complicated generalization could be thought of. "Nothing may prevent our grandchildren from being confronted some day by a physics that has made the transition to a line element of the fourth degree" (Reichenbach, 1920b, 76; tr. 1969 79).[5] Thus, there is no "'most general' geometry" that in and by itself must be physically true (Reichenbach, 1920b, 76; tr. 1969 80). No matter one pushes further the level of mathematical abstraction, the "difference between physics and mathematics" (Reichenbach, 1920b, 76; tr. 1969 80) cannot be erased; geometry alone can never be sufficient to establish the reality of physical space (Reichenbach, 1920b, 76; tr. 1969 80).

Thus, Reichenbach accused Weyl of having neglected the main philosophical lesson of general relativity, the unbridgeable difference between physics and mathematics. A mathematical axiom system is indifferent with regard to the applicability and "never leads to principles of an *empirical theory*" (Reichenbach, 1920b, 73; tr. 1969 76). "Only a physical theory could answer the question of the validity" (Reichenbach, 1920b, 73; tr. 1969 76) of a particular geometry for physical space:

> [Thus] it is incorrect to conclude, like Weyl[6] and Haas,[7] that mathematics and physics are but one discipline. The question concerning the *validity* of the axioms for the physical world must be distinguished from that concerning *possible* axiomatic systems. It is the merit of the theory of relativity that it renowned the question of the truth of geometry from mathematics and relegated it to physics. If now, from a general geometry, theorems are derived and asserted to be a necessary foundation of physics, the old mistake is repeated. This objection must be made to Weyl's generalization of the theory of relativity [...] Such a generalization is possible, but whether it is compatible with reality *does not depend on its significance for a general local geometry.* Therefore, Weyl's generalization must be investigated from the viewpoint of a physical theory, and only experience can be used for a critical analysis. Physics is not a 'geometrical necessity'; whoever asserts this returns to the pre-Kantian point of view where it was a necessity given by reason (Reichenbach, 1920b, 73; tr. 1969 76).

. To a certain extent, this objection contains the backbone of Reichenbach's criticism of the unified field theory-project in the following decade. Weyl seems to have misunderstood the fundamental lesson of Einstein's theory. The question of the "*validity* of axioms for the physical world" (Reichenbach, 1920b, 73; tr. 1969 76) must be distinguished from that concerning possible axiomatic systems is happened to be in reality. It is true that it is "a characteristic of modern physics to represent all processes in terms of mathematical equations", and, one might add, progressively more abstract mathematics. Still, "the close connection between the two sciences must not blur their essential difference" impliziten Definitionen. The truth of mathematical propositions depends upon internal relations among their terms; the truth of

[5] $ds^4 = g_{\mu\nu\sigma\tau} dx_\mu dx_\nu dx_\sigma dx_\tau$ instead of $ds^2 = g_{\mu\nu} dx_\mu dx_\nu$ as in Riemannian geometry.

[6] Weyl, 1918b, 227. In the 1919 edition of the *Raum–Zeit–Materie* Weyl included a presentation of his theory. Thus, conclusion was characterized by even more inspired rhetoric: "physics and geometry coincides with each other" (Weyl, 1919b, 263). The tendency of physicalizing geometry that have prevailed leading protagonists of the 19th century from Gauss to Helmholtz seemed to superseded have of geometrizing physics that run from Riemann to Einstein: "geometry has not been physics but physics has become geometry" (Weyl, 1919b, 263).

[7] Haas, 1920.

physical propositions, on the other hand, depends on relations to something external, on a connection with experience. "This distinction is due to the difference in the objects of knowledge of the two sciences" (Reichenbach, 1920b, 33; tr. 1969 34). The mathematical object of knowledge is uniquely determined by the axioms and definitions of mathematics. The definitions indicate how a term is related to that Schlick (1918) had called "implicit definitions" (Reichenbach, 1920b, 33; tr. 1969 36).

As it is well-known, Reichenbach will abandon the Kantian framework in which this distinction was initially presented. However, he never abandoned the idea that the separation between mathematics and physics was of paramount epistemological importance: mathematical necessity must be sharply distinguished form physical reality. This separation was the irreversible conceptual shift that relativity theory had forced upon philosophy. On June 24, 1920, Einstein praised Reichenbach's *Habilitationschrift* in a letter to Schlick (Einstein to Schlick, Apr. 19, 1920; CPAE, Vol. 9, Doc. 378). A few days later, Reichenbach asked Einstein to dedicate the book to him, insisting on the philosophical significance of relativity theory: "very few among tenured philosophers have the faintest idea that your theory performed philosophical act and that your physical conceptions contain more philosophy than all the multivolume works by the epigones of the great Kant" (Reichenbach to Einstein, Jun. 13, 1920; CPAE, Vol. 10, Doc. 57). Einstein conceded, that the theory might have had philosophical relevance: "The value of the th. of rel. for philosophy seems to me to be that it exposed the dubiousness of certain concepts that even in philosophy were recognized as small change [*Scheidemünzen*]" (Einstein to Reichenbach, Jun. 30, 1920; CPAE, Vol. 10, Doc. 66). Alleged *a priori* principles are like those parvenu that are ashamed of their humble origin and try to deny it: "[c]oncepts are simply empty when they stop being firmly linked to experience" (Einstein to Reichenbach, Jun. 30, 1920; CPAE, Vol. 10, Doc. 66).[8] This remark, which Reichenbach would later quote in a published writing (Reichenbach, 1922b, 354), seals a sort of philosophical alliance between Reichenbach and Einstein. Against the Weyl's speculative style doing physics which reduced physical reality to geometrical necessity, relativity theory had has introduced a clear cut separation between between geometrical necessity and physical reality. As we shall see, this philosophical covenant will be broken less then a decade later.

1.2 The Reichenbach-Weyl Correspondence

Reichenbach's book was published a few months later just on that occasion the 86th Assembly of the *Versammlung der Gesellschaft Deutscher Naturforscher und Ärzte* in Bad Nauheim in September 1920. This meeting of fundamental importance for in the history of relativity theory, not least for the famous debate between Einstein and Philipp Lenard (**Dongen2007**). Reichenbach met Weyl there for the first time, where the latter gave a talk on his unified theory (Weyl, 1920a). Reichenbach might have assisted at the debate that followed in which Einstein rehearsed his objections against Weyl,[9] and the same time defended the possibility of a field theory of matter against Pauli's objections.[10] Schlick did not attend

[8]Einstein used a similar wording by commenting on the manuscript of Cassirer's 'Kantian' booklet on relativity. "Conceptual systems appear empty to me, if the manner in which they are to be referred to experience is not established" (Einstein to Cassirer, Jun. 6, 1920; CPAE, Vol. 10, Doc. 44). In particular, "[w]ith the interpretation of the *ds* as a result of measurement, which is obtainable by means of measuring rods and clocks the general theory of relativity as a physical theory stands or falls" (Einstein to Cassirer, Jun. 6, 1920; CPAE, Vol. 10, Doc. 44). The gravitational redshift, can be taken as an empirical confirmation of general relativity only because different atoms of the same substance can be regarded as identically constructed clocks reproducing the identical unit of time. For this reason it is possible to 'normalize' the absolute value of *ds* by counting the wave crests on atom. According, Weyl's theory deprived the *ds* of any physical meaning. However, real rods and clocks behave differently than predicted by Weyl's theory forcing Weyl to assume an inconsistent position. According to Einstein, line general relativity, Weyl's "theory is based on a measuring rods geometry", that is it presupposes the comparability of lengths. However, it entains only "thought measuring rods [*nur gedachte Massstäbe*]" that behave differently from the real ones. "This is repugnant" (Einstein to Besso, Aug. 26, 1920; CPAE, Vol. 10, Doc. 85; m.e.).

[9]Commenting on Weyl's talk, he pointed out once again that the "arrangement of [his] conceptual system," "it has become decisive [*massgebend*] to bring elementary experiences into the language of signs [*Zeichensprache*]" (Einstein et al., 1920, 650). For Einstein, "temporal-spatial intervals are physically defined with the help of measuring rods and clocks", under the assumption that "their equality is empirically independent of their prehistory" (Einstein et al., 1920, 650). Einstein insisted that precisely upon this assumption rests "the possibility of coordinating [*zuzuordnen*] a number *ds* to two neighboring world points"; if this were impossible, general relativity would be robbed of "its most solid empirical support and possibilities of confirmation" (Einstein et al., 1920, 650)..

[10]In is interesting to notice, that Einstein already showed a more flexible attitude replying to Pauli's remarks during the same discussion. Pauli reiterated his objection based on his 'observability' criterion. Just as the field strength in the interior of the electron is meaningless because there is no smaller test particle than the electron, "one could claim something similar concerning spatial measurements, *since there are no infinitely small measuring-rods*" (Einstein et al., 1920, 650). Einstein replied to Pauli that "with the increasing refinement of the system of scientific concepts, the manner and procedure of associating the concepts with experiences becomes increasingly more complicated" (Einstein et al., 1920, 650). In particular, he recognized that in cases such as that of the continuum theories, "one finds that a definite experience cannot be associated any longer with a concept" (Einstein et al., 1920, 650). According to Einstein, there is an alternative: one can abandon 'continuum theories' for the sake of Pauli's observability criterion, or replace such a "system of associating

Bad Nauheim but received Reichenbach's new published book in those days. Writing to Einstein he praised the book, but complained about his critique of conventionalism (Schlick to Einstein, Sep. 23, 1920).

The five letters that Reichenbach exchanged with Schlick between October and November of 1920[11] turned out to be of fundamental importance in his intellectual biography. Reichenbach was confronted with Schlick's objection that his 'axioms of coordination' were nothing but 'conventions.' He initially opposed some resistance. If the coordinating principles are fully arbitrary, he feared, geometry would be empirically meaningless. In Poincaré conventionalism, Reichenbach missed claim that "the arbitrariness of the principles is constrained, if the principles are combined" Reichenbach to Schlick, Nov. 26, 1920; HR, 015-63-22. Einstein's famous lecture on 'geometry and experience' of the end January of 1921 *Geometrie und Erfahrung*[12] seemed to have tipped the scale in Schlick's favor (Reichenbach, 1921b, 5). At the beginning of the lecture, Einstein mentions approvingly Schlick's separation between pure and applied geometry. He provisionally defended a form of geometrical empiricism in which geometry has physical meaning separately from physics if understood as science of the behavior of rigid rods. However, since perfectly rigid rods do not exist in nature geometry seems to lose gain its connection with reality. As a way out, Einstein plead for an holistic reading of Poincaré's conventionalism. Geometry isolated might be arbitrary, but the combination (G)eometry plus (P)hysics has an empirical meaning (Reichenbach, 1921b, 5).[13]

Reichenbach must have sent a copy of his *Relativitätstheorie und Erkenntnis apriori* (Reichenbach, 1920b) also to Weyl despite the rather severe critiques he had expressed in the book. Weyl replied with some delay in February of 1921. He did not appear to be upset by Reichenbach's objections and replied rather amicably to some issues "which concern less the philosophical than the physical" (Weyl to Reichenbach, Feb. 2, 1921; HR, 015-68-04). In particular Weyl denied to have ever claimed that physics has been absorbed into mathematics:

> It is certainly not true, as you say on p. 73, that, for me, mathematics (!!, e.g. theory of the ζ-function?) and physics are growing together into a single discipline. I have claimed only that the *concepts* in *geometry* and field physics have come to coincide [...] As for my extended theory of relativity, so I cannot admit that the epistemological situation is in any way different from that of Einstein. [...] *Experience* is in no way anticipated by the assumption of that general metric; that the laws of nature, to which the propagation of action in the ether is bound, can be of such a nature that they do not allow any curvature. [...] What I stand for is simply this: The integrability of length transfer (if it exists, but I don't think so, because I don't see the slightest dubious reason for it) does not lie in the nature of the metric medium, but can only be based on a special law of action.[14] If the historical development had been different, it seems to me that no one would have thought of considering the Riemannian case from the outset. As far as the notorious 'dependence on previous history' is concerned, I probably expressed my opinion clearly enough in Nauheim (Weyl to Reichenbach, Feb. 2, 1921; HR, 015-68-04).

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concepts [with experiences] with a more complicated one" (Einstein et al., 1920, 650). Einstein's in his contributions to the the discussion which followed Max von Laue's (1920)'s Bad Nauheim paper. Einstein, however, in the very same sentence, did not hesitate to admit that "[it] is a logical shortcoming of the theory of relativity in its present form to be forced to introduce measuring rods and clocks *separately instead of being able to construct them as solutions to differential equations*" (Einstein's reply to Laue, 1920, 662; m.e.).

[11] Schlick to Reichenbach, Sep. 25, 1920; HR, 015-63-23 Schlick to Reichenbach, Nov. 26, 1920; HR, 015-63-22 Schlick to Reichenbach, Dec. 11, 1920; HR, 015-63-19 Reichenbach to Schlick, Nov. 29, 1920 Reichenbach to Schlick, Sep. 10, 1920.

[12] Most readers seems to have neglected that the problem that the lecture was discussing was related to the Bad Nauheim discussion with Weyl and Pauli. On January 14, 1921 Einstein, while in Vienna, released the following declaration: "A theoretical system can only claim completeness if the relationships of the concepts to the facts that can be experienced are clearly established. It is not enough, for example, to base the theory of relativity on a mathematical fundamental invariant [ds]. It must also be clear how this invariant is related to the observable facts as [that](2) [happened] for the fundamental concepts of Maxwell's theory by Heinrich Hertz. If one disregards this point of view, one can only arrive at unrealistic systems" (CPAE, Vol. 7[13], Doc. 50a) A few days later January 27, 1921 Einstein held *Geometrie und Erfahrung* in Berlin. the lecture ultimately meant to address precisely this issue although in a popular form. (a) the invariant ds is measured by ideal rods and clocks, like the electric field strengths are measured by charged test particles (b) ideal rods and clocks do no exist in nature (as pointed out by Poincaré). Conclusion: *sub specie aeterni* geometry cannot be tested separately from the rest of physics (the famous $G + P$ formula). The choice of a particular geometry is ultimately justified by its success of delivering a good physical theory. It is assumed that solutions to the appropriate dynamical equations exist that can serve as rods and clocks. In Weyl's theory, however, real rods and clocks would behave differently differently from the ideal rods and clocks in Weyl geometry. This inconsistency was the point that Einstein found unbearable. Thus, in March 1921 Einstein preferred to suggest a theory in which there were no transportable ideal rods at all and only $ds = 0$ has physical meaning (Einstein, 1921b).

[13] Reichenbach (1922b) seems to have ultimately turned the Einstein's $G + P$ formula into his $G + F$ formula, where F is a 'metric force' affecting all bodies in the same way. By setting $F = 0$ geometry becomes empirically testable. Reichenbach could embrace conventionalism, without having to accept that the proposition of geometry are empirical meaningless.

[14] That is on the field equations of the theory which in turned can be derived from an 'action principle'.

In Bad Nauheim, Weyl outlined a now well-known speculative explanation for the discrepancy between the behavior of 'ideal' and 'real' rods. Roughly, Weyl suggested that the atoms we use as clocks might not *preserve* their size if transported, but *adjust* it every time to some constant field quantity, which he could identify with the constant radius of the spherical curvature of every three-dimensional slice of the world (Weyl, 1920b). The geometry read off from the behavior of material bodies would appear different from the actual geometry of spacetime, because of the 'distortion' due to the mechanism of the adjustment. In 1921, the 'pivotal year' for unified field theories (Vizgin, 1994, ch. 4), Weyl (followed to some extent by Eddington, 1921a,b) reacted by expanding his strategy of 'doubling the geometry,' the real 'aether geometry' and the 'body geometry' distorted by the mechanism of adjustment,[15] in three papers intended for different audiences, February (Weyl, 1921f), May (Weyl, 1921c) and July (Weyl, 1921e). In the July paper, Weyl also addresses Reichenbach's criticism publicly:

> From different sides[16] it has been argued against my theory that it would attempt to demonstrate in a purely speculative way something *a priori* about matters on which only experience can actually decide. This is a misunderstanding. Of course from the epistemological principle [*aus dem erkenntnistheoretischen Prinzip*] of the relativity of magnitude does not follow that the 'tract' displacement [*Streckenübertragung*] through 'congruent displacement' [*durch kongruente Verpflanzung*] is not integrable; from that principle that no *fact* can be derived. The principle only teaches that the integrability *per se* must not be retained, but, if it is realized, it must be understood as the *outflow [Ausfluß] of a law of nature* (Weyl, 1921b, 475; last emphasis mine).

As Weyl explains in this passage, he never claimed that his geometry entails in its mathematical structure alone the *a priori* justification of its physical truth. On the very contrary, he questioned the alleged *a priori* status of the assumption that the comparison of lengths is path-independent. For this reason Weyl did not deny the well-established empirical fact that two atoms of the same chemical substance placed identically in the same conditions, is independent of their prehistory. However, he insists that the physical behavior of atoms does not have nothing to do with the abstract notion of parallel transport of vectors.[17] Einstein simply assumed as empirical fact the ratio of the wave lengths of two spectral lines is a physical constant that can be used to normalize the ds. Weyl, on the contrary, claims that the wave lengths of two spectral lines are always multiple of a certain field quantity of dimension of a length that can be used to normalize the ds. Nevertheless, the constancy of emerged from a theory in which only the ration of ds at a point is physically meaningful.

1.3 The Weyl-Reichenbach Appeasement

Weyl's paper referencing Reichenbach appeared at beginning of September (Weyl, 1921e). A few weeks later, Reichenbach and Weyl met again in Jena on occasion of the first *Deutsche Physiker- und Mathematikertag*, the first national scientific meeting held independently from the meetings of the *Gesellschaft Deutscher Naturforscher und Ärzte*. Weyl gave a talk in which he tried to provide a mathematical justification for the quadratic or Pythagorean nature of the metric (Weyl, 1921a).[18] Reichenbach presented a report of his work on the axiomatization of relativity (Reichenbach, 1921a). This report is the first written testimony of the development of Reichenbach's philosophy after the Schlick-correspondence. Reichenbach suggested that in a physical theory one should distinguish the *axioms* as empirical proposition about light rays, rods and clocks , etc. and the *definitions* that establish the conceptual framework of the theory (Reichenbach to Einstein, Dec. 5, 1921; CPAE, Vol. 12, Doc. 266). After the paper came out by the end of year (Reichenbach, 1921a), Reichenbach must have sent a copy to Weyl in a lost letter of January 8, 1922. The possibly including a personal retraction of his criticisms. The latter is no longer

[15]A different variation of this strategy of doubling the geometry was suggested by Eddington at about the same time. He considered non-Riemannian geometries as mere 'graphical representation' that might serve to organize different theories into a common mathematical framework. The "natural geometry" remains exactly Riemannian (Eddington, 1921a).

[16]The reference is to Reichenbach, 1920b and Freundlich, 1920 who, however, refers to Haas, 1920.

[17]In September 1921, Pauli's encyclopedia article on relativity theory was published, as part of the fifth volume of the *Enzyklopädie der Mathematischen Wissenschaften*, and later as a book with an introduction by Pauli's mentor, Arnold Sommerfeld (Pauli, 1921). In the chapter dedicated to Weyl's theory, Pauli suggested that Weyl provided two different versions of the theory. In the first version Weyl's theory sought to make predictions on the behavior of rods and clocks, just like Einstein's theory. From this point of view, the theory is empirically inadequate because of the existence of atoms with sharp spectral lines. Later Weyl renounced this interpretation. The ideal process of the congruent displacement vectors has nothing to do with the real behavior of rods and clocks (Pauli, 1921, 763; tr. 1958, 196). However, in this form the theory furnishes only "formal, and not physical, evidence for a connection between [the] world metric and electricity" (Pauli, 1921, 763; tr. 1958, 196). In this form the theory loess its "convincing power [*Uberzeugunggkraft*]" (Pauli, 1921, 763; tr. 1958, 196).

[18]I assume that this talk would have again bee suspiction since the local is intrinsically mathematical reason. Indeed, in Reuchenbach view there was no reason.

extant and reached Weyl only months later (Weyl to Reichenbach, Mar. 3, 1922; HR, 015-68-03) since he was in Barcelona, where he was giving his Catalonian Lectures (Weyl, 1923).

However, Reichenbach soon issued a public retraction. In those months, he was working on a long review article about philosophical interpretations of relativity, that he finished in Spring 1922. In march Erwin Freundlich sent the proofs of the paper to Einstein (Freundlich to Einstein, Mar. 24, 1922; CPAE, Vol. 13, Doc. 109), who expressed his general agreement with Reichenbach's analysis of the philosophical implications of relativity and praised its clarity (Einstein to Reichenbach, Mar. 27, 1922; CPAE, Vol. 13, Doc. 119). The paper reviews the most significant philosophical interpretation of relativity. However, it also included a last section on Weyl's unified field theory: "One cannot conclude an exposition of relativistic philosophy", Reichenbach wrote "without considering the important expansion that Weyl bestowed on the problem of space three years ago" (Reichenbach, 1922b, 365).

Reichenbach appears to be now fully converted to conventionalism. The choice between Euclidean and non-Euclidean geometries is conventional, that is, it depends on which rods are rigid. (Reichenbach, 1922c, 366). However, both Euclidean and non-Euclidean geometries tacitly presuppose the validity of an axiom based on an empirical fact: rods that are of equal length in one place can be obtained in one place, it will be possible at any other places, no matter how the prehistory of each rod might have been. If this were not the case a different definition of the unit of length would have to be given for every space point. Reichenbach labels this tacit assumption the "axiom of the Riemann class" (Reichenbach, 1922c, 366).

The merit of Weyl is to have shown that this axiom, although quite natural, is not necessary and can be questioned: From this point of view, what Weyl achieved is a purely mathematical discovery; it indicates a more general type of manifold that can be applied to reality when the Riemann class of axioms is not satisfied for natural rods. "Weyl's great discovery is that he uncovered a more general type of manifold, of which Riemann's space is only a special case" (Reichenbach, 1922b, 365). The fact that he tried to follow this path, regardless of its empirical correctness was a "genial advance [*genialer Vorstoß*]" in the philosophical foundation of the relations between geometry and physics (Reichenbach, 1922a, 367f.). Concerning the application of this mathematical apparatus to reality, Reichenbach embraces a two-theory interpretation[19]:

W-I In Weyl geometry, like in Riemannian geometry the length of vectors $l^2 = g_{\mu\nu}A^\nu A^\mu$ can be compared at the same point in different directions. Weyl dropped the assumption that l remains unchanged under parallel transport at a distant point. If a vector of length l is displaced from x_ν to $x_\nu + dx_\nu$, it will in general have a new length $l + dl$, so that $dl/l = \varphi_\nu dx_\nu$. "The change in scale is measured by 4 quantities φ_μ forming a vector field". As Reichenbach pointed out, "this procedure is a purely mathematical discoery" (Reichenbach, 1922b, 366), and as such is neither true nor false. It can applied to reality, if one coordinates the length l as reading of some physical measuring instruments. As we have seen, in general relativity the length ds of the time-like vector dx_ν is measured by a clock, e.g.the spectra lines of an atomic clock. If this coordination is maintained so that "still possible to measure also in this case" (Reichenbach, 1922b, 366). However, the existence of atoms with the same spectral lines shows that clocks behave differently than predicted by Weyl's theory. If atomic clocks changed their periods as a function of their spacetime paths, one would expect that atoms with different pasts would radiate different spectral lines. However, this is not the case.[20] Thus, it turned out that this axiom "is quite well fulfilled in reality, so that the first way of generalization seems unsuitable. The latter was therefore rejected by Weyl" (Reichenbach, 1922b, 366)

W-II Weyl adopted a different strategy. He "defines an ideal process of scale transfer, which however has nothing to do with the behavior of real scales" (Reichenbach, 1922b, 367). He needs this "Verpflanzungsprozeß" only because, he "he wants to identify the vector field φ_ν with the electromagnetic potential", like in general relativity the $g_{\mu\nu}$ where identified with the gravitational potentials (Reichenbach, 1922b, 367). Once one has individuated the basic geometrical field-quantities, the next step is to find the field equations "then obvious forms for the most general physical equations arise" via "the 'action principle' [*Wirkungsprinzip*]" (Reichenbach, 1922b, 367)—a variational principle applied to the invariant integral $\int \mathfrak{W} dx$ for a specific Lagrangian $\mathfrak{W}$. According to Reichenbach, however, in this way the "theory loses its convincing character [*überzeugenden Charakter*] and comes dangerously close to a mathematical formalism"[21] (Reichenbach, 1922b, 367). For this

[19]Reichenbach might have been inspired by Pauli (1921). However, his name is not mentioned.

[20]This is, of course, the celebrated objection against Weyl's theory Einstein's (1918b).

[21]This choice of words is practically similar who claims the in the second form the theory lost his *Uberzeugunggkraft* (Pauli, 1921, 763; tr. 1958, 196).

reason, according to Reichenbach, "Weyl's theory is viewed very cautiously by physicists (especially by Einstein)" (Reichenbach, 1922b, 367)

Ultimately, Reichenbach seems to imply that both strategies led to a dead end. From the point of view of W-I Weyl geometry is empirically inadequate from that of W-II, it does not have empirical content. Nevertheless, Reichenbach conceded that his original objections against Weyl's theory missed the point. Neither W-I nor W-II can be considered attempts to prove *a priori* that Weyl's non-Riemannian geometry must be true for reality because mathematically :

> However, I have to retract my earlier objection [Reichenbach, 1920a, 73] that Weyl wants to deduce physics from reason, after Weyl has cleared up this misunderstanding [Weyl, 1921b, 475]. Weyl takes issue with the fact that Einstein simply accepts the unequivocal transferability of the standards. He does not wish to dispute the Riemann-class axiom for natural standards, but only to demand that the validity of this axiom, since it is not logically necessary, should be understood as 'a consequence of a law of nature.' I can only agree with Weyl's demand; it is the importance of mathematics that they are. I can only agree with Weyl's demand; it is the importance of mathematics that, in uncovering more general possibilities, it marks the special facts of experience as special and thus preserves physics from naivity [*Simplizität*]. Admittedly, Weyl succeeds in explaining the unambiguous transferability of natural standards only very imperfectly. But the fact that Weyl tried to go this way, regardless of the empirical correctness of his theory, remains an ingenious advance towards the philosophical foundation of physics (Reichenbach, 1922b, 367f.).

Weyl's point was not that the axiom of Riemann class is necessarily false for *a priori* reasons, but that is not obviously true as it was previously assumed: It cannot be a coincidence if two measuring rods placed next to each other are of the same length regardless of their location; this coincidence cries out for an explanation. Weyl's explanation of the apparent Riemannian behavior of "durch Einstellung der Maßstäbe auf den Krümmungsradius der Welt«" (Reichenbach, 1922b, 368; fn. 1) only means posing a problem rather than providing an answer. The problem would be solved only by developing a proper theory of matter. However, according to Weyl, it was legitimate to deduce the Riemannian behavior of real clocks from a theory based on the non-Riemannian behavior of geometrical vectors. In this way, however, the "congruent transplantation [...] remains physically empty" (Reichenbach, 1922b, 368; fn. 1). If the non-Riemannian congruent transplantation of vectors must be, then the real rods should better behave in a non-Riemannian way..

Stachel on measuring rods One should require that solutions to the appropriate dynamical equations exist exhibiting the postulated kinematical behavior of the ideal entities.1

Thus, Reichenbach concluded, the main achievement of Weyl was mathematical. As usual mathematics serve to enlarge the range of possibilities among which physicists are allowed to chose. This processes is however far from being concluded with Weyl's rather special affine connection:

> The philosophical significance of Weyl's discovery consists in the fact that it proved that the problem of space cannot be closed even with Riemann's concept of space. If the epistemology of today wanted to extend the assertion of Kant's transcendental aesthetics to the point that the geometry of experience must in any case at least have a Riemannian structure, it is held back by Weyl's theory. For that Weyl's space is at least possible for reality cannot be denied. One must not even believe that Weyl's theory has reached the highest level of generality. Einstein (1921b) has shown that Weyl's requirement of the relativity of magnitude can also be satisfied without making use of Weyl's method of measurement. After that, Eddington (1921a) again developed a generalization of which Weyl's space class is only a special case, and Eddington's space class is again included as a special case in a more general one found by Einstein (1921b). The merit of Schouten's theory is that it gives the conditions under which the class of space developed is the most general; they are very general conditions, like differentiability and the like. But of course there is no absolutely most general space class; and the history of the mathematical problem of space may teach epistemology never to make general claims. There are no most general terms (Reichenbach, 1922b, 368; fn. 1).

This passage essentially repeats the arguments against the idea of a most general geometry that Reichenbach had used in his habilitation. Ultimately, there is nothing special in Weyl geometry. At the same time it shows, how Reichenbach followed closely the advances of the unified field theory-project. Reichenbach was familiar with Einstein's (1921b) 'conformal' theory distances can be compared only at a single point with light rays, but the comparison at distant points with transportable rods and clocks was not defined; he also knew Eddington's (1921a) purely affine approach in which lengths go vectors cannot be compared even not at the same place in different directions. Moreover, Reichenbach, quite surprisingly, was even acquainted with Schouten's (1922) recent systematic classification of connections. Thus, he was already aware that, in principle, also the natural assumption of the symmetry of the $\Gamma^{\tau}_{\mu\nu}$ could be dropped. In general, by further relaxing the constraints on the symmetry and on the relationship between the connection and the metric, one could a great number of possibilities to incorporate the electromagnetic field into the geometrical structure of spacetime. In Reichenbach's view, the physicists should be completely free to chose among all these mathematical possibilities; however, mathematics alone cannot provide a criterion of choice for which possibility is realized in nature. Mathematics is the science of possibility, physics only is the science of reality.

For Reichenbach there should have been no limit, in the choice of what mathematical structure. However, once the choice has been made, it was essential to 'coordinate' the the structure chosen with the behavior of various idealized physical entities used as probes. Only in this way, claims about the geometrical structure of spacetime can be tested empirically had a physical meaning. Weyl had initially proceeded following this epistemological model W-I. However, since his geometrical setting turned out to be empirically inadequate Weyl embraced W-II. He introduced a sort a conspirtatorial distortion of all measuring instruments, and thus deprived geometry of any empirical content. However, Weyl disagreed with Reichenbach's historical reconstruction, but for reasons that reveals a completely different frame of mind. In a letter to Reichenbach written when the latter's review article was already in press, Weyl confessed that he actually never abandoned W-I in favor of W-II. As a matter of fact, he never adopted W-I in the first place: "I never gave up the plan to identify rigid rods with my transplantation, because I've never had that plan"; on the contrary, "I was surprised when I said that physicists had interpreted that into my words" Weyl to Reichenbach, May 20, 1922; HR, 015-68-02. The atoms that we use as clocks are physical systems like any other and do not have in principle any privileged relation with the abstract mathematical behavior of vectors. It is the theory that decides whether we should use them as reliable clocks or not. In general, the physical interpretation of mathematical structure of the theory in terms of the behavior of idealized physical entities, like rods and clocks can only be provisional. Ultimately one has to find the field equations governing that structure, and require that solutions to these equations exist exhibiting the postulated behavior of rods and clocks. This reasoning applies to Einstein and Weyl's theory: "Einstein has to show that from the dynamics of the rigid body it follows that the rod always has the same length, measured in his ds. Similarly, I have to show that the rod has always has the same length normalized ds normalized by $R = const$" (Weyl to Reichenbach, May 20, 1922; HR, 015-68-02). In both cases the behavior of rods and clocks comes out as a byproduct of the theory.[22] Einstein would have ultimately agreed that this was this philosophical stance was in principle correct. However, he found unacceptable that in Weyl's theory the Riemannian behavior of rods and clocks that came out from the theory contradict the non-Riemannian geometry on which the theory was based (Du Pasquier to Einstein, Dec. 13, 1921; CPAE, Vol. 12, Doc. 379)

2 Geometrization: The Reichenbach-Einstein Correspondence (1926–1927)

Up to this point, Reichenbach had good reasons to believe that his criticisms of Weyl's approach were broadly in agreement with Einstein's point of view. As a matter of fact Einstein had continued to express skepticism towards Weyl's attempt and in general found the entire research in the field way to speculative. (Einstein to Weyl, Jun. 6, 1922; CPAE, Vol. 13, Doc. 219; Einstein to Zangger, Jun. 18, 22; CPAE, Vol. 13, Doc. 241). However, the situation changed by the end of the 1922, when Einstein, during a trip to Japan, started to realize that Eddington's theory had potentialities that had not been fully exploited. On the shipboard he jotted down a five-page manuscript dated January 1923 from Singapore (CPAE, Vol. 13, Doc. 417). Ironically, the third, fourth, and fifth pages were written on the back of the the typescript of Reichenbach's Jena's talk (Reichenbach, 1922a). Eddington (1921a) had extended Weyl's approach, by using only the coefficients of an affine connection $\Gamma^{\tau}_{\mu\nu}$, rather than metrical quantities $g_{\mu\nu}$ and φ_{ν}, as fundamental variables. In this context, vectors' lengths are not comparable even not at the same place; thus, in Einstein's view the theory avoided Weyl's inconsistency of having geometrical lengths behaving differently from real rods and clocks. On February of 1923, Planck presented the paper 'On the general theory of relativity' to the Prussian Academy of Sciences that Einstein sent from Japan (Einstein, 1923b). After he returned to Berlin, Einstein published two further integrations on the same approach in May Einstein, 1923b,c

At about the same, May 2, 1923, Reichenbach requested a copy of Einstein's paper "on Eddington's extension [*Erweiterung*]" (Einstein, 1923b) (Reichenbach to Einstein, May 2, 1923; EA, 20 080). As

[22]The unit of time should defined a certain number of spacing between the atoms of a cubic crystal system; each of atom in turn consists of electrons and protons arranged according to a specific law. A specific solution to the field equations must provide information about all the details of this arrangement. The unit of time is a certain multiple of the vibration in an hydrogen atom, which in turn corresponds to a solution of the field equations.

he later confessed to Einstein, Reichenbach was not impressed by this approach. In the Eddington-Einstein theory the choice of 40 coefficients of symmetric affine connection $\Gamma^{\tau}_{\mu\nu}$ as fundamental variables was not physically motivated and these numbers could not be obtained as the result of measurment. Einstein's goal was admittedly to find the most simple field equations governing these quantities via a variational principle. Einstein was indeed able to recover Maxwell and Einstein field equation from a single Lagrangian leading to a true unification of the two fields. However, the theory did not deliver any new empirical results. The comparison with experience would have taken place only *post facto* by integrating such equations and finding solutions corresponding to elementary particles and their interactions (CPAE, Vol. 13, Doc. 417). However, this result was far from being at hand (Einstein, 1923c, 140).

Nevertheless, Reichnebach did not comment on Einstein's unification attempt.[23] In his correspondence with Einstein, Reichenbach was rather concerned with more mundane matter of finding a publisher for his work on the axiomatization of special relativity that he had just finished (Reichenbach to Einstein, Apr. 19, 1923; EA, 20 079, Reichenbach to Einstein, May 2, 1923; EA, 20 080, Einstein to Reichenbach, Jun. 9, 1923; EA, 20 081, Reichenbach to Einstein, Jul. 10, 1923; EA, 20 082). Do to lack of founding, Reichenbach managed to publish the book only a year later in March 1924. With the *Axiomatik der relativistischen Raum-Zeit-Lehre* Reichenbach (1924) Reichenbach's philosophy started to assume a more recognizable contour. In particular, Reichenbach introduced for the first time, his celebrated distinction between "conceptual definitions" used in mathematics and "coordinate definitions" used in physics which relate the concept of a theory to a "piece [*Ding*] of reality" (Reichenbach, 1924, 5; tr. 1969, 8). There is little doubt that Reichenbach believed that this epistemological model was Einsteinian in spirit. However, at about that time, Einstein explicitly confessed that he has changed his mind on the topic (Einstein, 1924, 1692, see Giovanelli, 2014). In particular, he denied that every individual concept of a theory should received a measurement-operational justification.[24] Ultimately only geometry and physics taken together could be compared with experience,[25] a claim that seems to have a quite different meaning that Reichenbach had initially surmised.

The *Axiomatik der relativistischen Raum-Zeit-Lehre* (Reichenbach, 1924) received a lukewarm reception from philosophers, who probably found the book overly technical. However, it was Weyl's (1924) negative review that was a hard blow for Reichenbach and put an end to their previously amicable relationship. Reichenbach felt that Weyl had used his authority as mathematician to attack his empiricist reading of relativity (Reichenbach, 1925). What was worse, Reichenbach probably must have sensed that Weyl's reading of relativity had taken over relativistic research. Einstein's last works seemed to show that he had also come under its spell. It is not surprising that Reichenbach might have felt necessary to make the case for his reading of relativity theory in a more accessible form. At about the same time, he started work on a two-volume book with the ambitious title *Philosophie der exakten Naturerkenntnis*. Only the first volume on space and time will be published. He wrote the first chapters in March 1925 (HR, 044-06-25). During those same months, Reichenbach, despite the support of Max Planck, was struggling to obtain his *Umhabilitation*[26] from Stuttgart to Berlin in order to be appointed to a chair of natural philosophy that had been created there (Hecht and Hoffmann, 1982). Reichenbach had been attacked for his pacifists positions during the war. After the situation seemed to have turned for the better, in October 1925 he started to work more consistently on his book-project. He interrupted the drafting of

[23] As might infer from Reichenbach's other writings, his point of view might have been again similar to that of Pauli. In a long latter to Eddington of September 1923, Pauli insisted that a good theory should start "with the definition of the used field quantities, of how this quantities can be measured" (Pauli to Eddington, Sep. 23, 1923; WPWB, Doc. 45). This one of the great achievement of relativity theory that the coefficients $g_{\mu\nu}$ could be measured with rods and clocks. Pauli insisted again that Weyl attempted to pursue this strategy but then abandoned this approach. (Pauli to Eddington, Sep. 23, 1923; WPWB, Doc. 45). In this way he produced, what Eddington had rightly called a 'graphical representation' of the two fields in unified formalism, but not a 'natural geometry' found experimentally as in general relativity (see Eddington, 1923, 197). Similarly, in Einstein-Eddington new theory "[t]he quantities [$\Gamma^{\tau}_{\mu\nu}$] cannot be measured directly". The measurable quantities $g_{\mu\nu}$ and $F_{\mu\nu}$ can be calculated from the $\Gamma^{\tau}_{\mu\nu}$ only true quite complicated calculations. But the "we do not have a not only 'natural geometry' but also not a 'natural theory' " (Pauli to Eddington, Sep. 23, 1923; WPWB, Doc. 45).

[24] "In particular, I would like to mention that criticism was rightly aimed against one statement by the reviewer: that a concept should only be permissible in physics when it can be established whether or not it applies in concrete cases of observation; it is objected that, in general, it is not to an individual concept that possible experiences must correspond but to the system as a whole" (Einstein, 1924, 1691).

[25] In general relativity, the $g_{\mu\nu}$ had a physical meaning *ex ante*; they were supposed to be measurable with rods and clocks with respect to given coordinate system. In his recent theory, Einstein introduced the $\Gamma^{\tau}_{\mu\nu}$ as fundamental field variable without giving to this quantity any physical meaning. If using the $\Gamma^{\tau}_{\mu\nu}$ leads to the right set of field equations, then the initial choice would turned out to be justified *post facto* (see Einstein, 1924). In this sense only geometry ($g_{\mu\nu}$, $\Gamma^{\tau}_{\mu\nu}$, etc.) and physics (field equations) together could be compared with experience (e.g., by finding appropriate exact solutions corresponding to electrons) "From this point of view is the whole content of geometry conventional. Which geometry one should chose depends on how 'simple' the physics can be brought in harmony with experience" (Einstein, 1926, 19).

[26] The process of obtaining the *venia legendi* at another university.

the manuscript to follow the emerging quantum revolution at the turn 1926, and must have started gain a few months later: "March-April 1926 Weyl's theory was worked on and the peculiar solution of §49 was found. The entire Appendix was also written at that time. (Correspondence with Einstein)" (HR, 044-06-25). The correspondence with Einstein mentioned in this passage has been preserved. It testifies about Reichenbach's concern Einstein's style of doing physics becoming progressively more speculative.

2.1 Reichenbach's Geometrization of the Electromagnetic Field

During a trip to South America in 1925 Einstein became interested in the rationalistic and realistic reading of relativity proposed by Émile *La déduction relativiste* (Meyerson, 1925) CPAE, Vol. 14, Doc. 455, 6; March 12 who could provide a more adequate philosophical support for the search of a unified field theory that Schlick's or Reichenbach's 'positivism'.[27] However he also realized that the Weyl-Eddington-Schouten line had dry up (CPAE, Vol. 14, Doc. 455, 9; March 17).[28] By returning from South America he embraced what he considered to be a new approach. He introduced non-symmetric $\Gamma^{\tau}_{\mu\nu}$ and the $g_{\mu\nu}$ to be treated as independent fields in the variation. The antisymmetric part of the $g_{\mu\nu}$ was the natural candidate for the representation of the electromagnetic field, at least for infinitely small fields. The physical test depended, as usual, on the construction of exact regular solutions corresponding to elementary particles. The paper was published in September of 1925 with the ambitious title "Nichteuklidische Geometrie und Physik" (Einstein, 1925b). However, by that time Einstein seemed to have already lost his confidence in that approach and moved on.[29]

At the turn of the year, after working on the new quantum mechanics must have come to read Einstein's new paper. On March 16, 1926, Reichenbach sent a letter to Einstein in which, after discussing his academic misfortunes, he made some critical remarks (Einstein, 1925a). Reichenbach was quite skeptical of the viability of Einstein's current style of doing physics:

> I have read your last work on the extended Rel. Th.[30] more closely, but I still can't get rid of a sense of artificiality which characterizes all these attempts since Weyl. The idea, in itself very deep, to ground the affine connection independently of the metric on the $\Gamma^{\tau}_{\mu\nu}$ alone, serves only as a calculation crutch here in order to obtain differential equations for the $g_{\mu\nu}$ and the φ_{ν} and the modifications of the Maxwell equations which allow the electron as a solution. If it worked, it would of course be a great success; have you achieved something along these lines with Grommer? However, the whole thing does not have the beautiful convincing power [*Ueberzeugungskraft*] of the connection between gravitation and the metric based on the equivalence principle of the previous theory (Reichenbach to Einstein, Mar. 16, 1926 EA, 20-83).

Reichenbach's objections are quite sensible. In general relativity the choice of the $g_{\mu\nu}$ as fundamental variables anchored in the principle of equivalence. The latter justified the double meaning of the $g_{\mu\nu}$, as determining the behavior rods and clocks, as well as the gravitational field. On the contrary, Einstein's new theory introduces the non-symmetric affine connection $\Gamma^{\tau}_{\mu\nu}$ independently of the metric $g_{\mu\nu}$ without giving to these field variables any physical motivation. The separate variation of the metric and connection was nothing more than a 'calculation device' to find the desired field equations. Only in hindsight, for formal reasons, the symmetric part was identified of $g_{\mu\nu}$ was identified with the gravitational field and antisymmetric with the electromagnetic field. In this form the theory has little he 'convincing power' (*Überzeugungskraft*)—-the same expression that Reichenbach (1922a, 367) had used for characterizing Weyl's theory in his second form. Reichenbach would have been ready to retract his cricitism, if Einstein's theory delivered the 'electron.' This concession, however, barely hide his skepticism that his was a concrete possibility

[27]Meyerson rationalistic realism that well supported the unified field theory-project. In particular, to philosophical alternative to both empiricists and positivists. Against the positivists he defended the logical independence of concepts from sensory experiences; against the Kantians that uses non-empirical 'ideal' conceptual constructions were mere conventions. Against both Meyerson justified that the physicists are justified to assume that certain conceptual construction exist in reality, say electromagnetic field, electron independently of observation.

[28]These doubts became certainty when Einstein returned to Europe. "On June 1, I got back from South America," Einstein wrote to Besso, "I am firmly convinced that the whole line of thought Weyl-Eddington-Schouten does not lead to anything useful from a physical point of view and I found a better trail that is physically more grounded" (Einstein to Besso, Jun. 5, 1925; CPAE, Vol. 15, Doc. 2).

[29]In July he was still convinced that he had "really found the relationship between gravitation and electricity" (Einstein to Millikan, Jul. 13, 1925; CPAE, Vol. 15, Doc. 20). However, during the summer, Einstein had already started to nurture some skepticism (Einstein to Ehrenfest, Aug. 18, 1925; CPAE, Vol. 15, Doc. 49; Einstein to Millikan, Jul. 13, 1925; CPAE, Vol. 15, Doc. 20; Einstein to Ehrenfest, Sep. 18, 1925; CPAE, Vol. 15, Doc. 71). The paper was published at the beginning of September, and by that time, Einstein probably already moved on (Einstein to Rainich, Sep. 13, 1925; CPAE, Vol. 15, Doc. 106; see Einstein, 1927a).

[30]Einstein, 1925a.

Einstein replied on March 20 that he agreed with Reichenbach's 'Γ-Kritik': "I have absolutely lost hope of going any further using these formal ways"; "without some real new thought" he continued, "it simply does not work" (Einstein to Reichenbach, Mar. 20, 1926; EA, 20-115). Einstein's reaction reflects his disillusion with the attempts to achieve the sought-for unification of gravitational and electromagnetic field by searching form some combination of $\Gamma^{\tau}_{\mu\nu}$ and $g_{\mu\nu}$. He would have probably been less ready to embrace the actual implications of Reichenbach's Γ-critique, the requirement that the operation of parallel displacement of vectors should received a 'coordinative definition' fro the outset. Reichenbach took the opportunity of Einstein's positive reaction and on March 31, 1926 he sent him a note in which he developed the Γ-critique in details. In the note—which is extant—Reichenbach had developed his own unified field theory, a theory that upheld the Γ-requirement. note

The content of the note has been presented in details elsewhere (Giovanelli, 2016b), however the basic idea can be briefly summarized. As it is well known, in general relativity, uncharged particles under the influence of gravitational and electromagnetic field describe are not attracted by a force, but move along the straightest line defined by the $\Gamma^{\tau}_{\mu\nu}$. On the contrary, charged particles accelerate with respect to a given straightest lines. Thus, one can say that gravitation has been 'geometrized,' but electromagnetism has been not. In order to geometrize the electromagnetic field as well, Reichenbach introduced a more general affine connection $\bar{\Gamma}^{\tau}_{\mu\nu}$ in which the length of vectors is preserved under parallel transport but the condition of symmetry is abandoned $\bar{\Gamma}^{\tau}_{\mu\nu} \neq \bar{\Gamma}^{\tau}_{\nu\nu}$. Reichenbach provides a coordinative definition of the abstract notion parallel-displaced vector in terms of the physical notion of the velocity vector $u^{\tau} = dx_{\nu}/d\tau$ of a charged mass point. By parallel-displacing a vector u^{τ} indicating the direction of a curve $x_{\nu}(\tau)$ at any of its points, one can define physically a special class of curves, the straightest lines among two points. In Riemannian geometry the straightest lines are identical with the shortest lines. If the connection is non-symmetric, the straightest lines do not generally coincide with with the shortest lines. Reichenbach's connection $\bar{\Gamma}^{\tau}_{\mu\nu}$ was so defined that, under influence of both the electromagnetic and the gravitational field, charged mass points move (or their velocity four-vector is parallel-transported) along the straightest lines, and uncharged particles move on the straightest lines that are at the same time the shortest ones. In this way, in Reichenbach's view both the gravitational and the electromagnetic field had been geometrized.

Einstein was not impressed (Einstein to Reichenbach, Mar. 31, 1926; CPAE, Vol. 15, Doc. 239). The definition the connection, he argued, was arbitrary. Most of all, Reichenbach's equations of motion can be valid only for a certain charge-density-to-mass-density ratio ρ/μ[31] (Einstein to Reichenbach, Mar. 31, 1926; CPAE, Vol. 15, Doc. 239). Reichenbach rushed to point out that Einstein had misunderstood the spirit of the typescript. As Reichenbach explained, he was working on a philosophical presentation of the problem of space. "Thereby I wondered what the geometrical presentation of electricity actually means" (Reichenbach to Einstein, Apr. 4, 1926 EA, 20-086) . Reichenbach wanted to challenge the idea that geometrizing a field is per se a useful heuristic strategy. Thus, Reichenbach decided to provide a toy model of a proper geometrization. Update letters

The theory started with a non-symmetric $\Gamma^{\tau}_{\mu\nu}$, in which vanishing non-metricity, a choice that was of course arbitrary. In comparison with Eddington or Einstein's last theories, however, Reichenbach insisted that his approach had "the advantage [...] that *the operation of displacement possesses a physical realization [Realisierung]*" (Reichenbach to Einstein, Apr. 4, 1926 EA, 20-086; m.e.) , namely, the velocity-vector of charged mass particles. In this way, the notion of straightest and shortest lines are physically meaningful and the geometrical predictions of the theory were suitable to be tested empirically. For this reason, in Reichenbach's view his geometrization was comparable to that provided by general relativity in which the predicted $g_{\mu\nu}$ are in principle comparable with the observed $g_{\mu\nu}$ measured by rods and clocks. Nevertheless, Reichenbach's theory, differently from Einstein's theory of gravitation, did not lead to any new physical prediction. Thus, Reichenbach concluded, a successful geometrization does not lead to a successful physical theory. Although Einstein probably continued to find the technical details of Reichenbach's attempt questionable, his philosophical point clearly resonated with Einstein:

> You are completely right. It is incorrect to believe that 'geometrization' means something essential. It is instead a mnemonic device [*Eselsbrücke*] to find numerical laws. If one combines geometrical representations [*Vorstellungen*] with a theory, it is an inessential, private issue. What is essential in Weyl is that he subjected the formulas, beyond the invariance with respect to [coordinate] trans-

[31] In a given displacement, there is only one straightest line passing through a point in a given direction, but different test particles with different charge-to-mass ratios accelerate differently in the same electric field. Thus they cannot all travel on the same straightest line of the *same* connection. In Reichenbach's theory particles with different charge-to-mass-ratio would travel on geodesic of a *different* connections. This clearly make the theory anodyne.

formation, to a new condition ('gauge invariance').[32] However, this advantage is neutralized again, since one has to go to equations of the 4. order,[33]which means a significant increase of arbitrariness (Reichenbach to Einstein, Apr. 8, 1926 EA, 20-117).

Einstein seem endorsed Reichenbach's claim that a 'geometrization' is not an essential achievement of general relativity. However, it is worth noticing, however, that Einstein goes further an claims that very notion of 'geometrization,' and for that matter the very notion of 'geometry' is meaningless (Lehmkuhl, 2014). The $g_{\mu\nu}$, $\Gamma^{\tau}_{\mu\nu}$, etc. are ultimately multi-components mathematical objects characterized by their transformation properties under coordinate transformation. There is nothing 'geometrical' about those quantities. Einstein's point is only apparently similar to that of Reichenbach. Einstein declared that the difference between geometry and rest of mathematics was inessential. On the contrary, as we shall see, Reichenbach intended to show that difference between geometry and physics was essential. Einstein's argument was meant to provide a support of the unified field theory-project. Against those that believed that geometrization program could not be extended beyond the gravitational field, he could argue that geometrization has never been the issue in the first place.[34] Reichenbach's argument was on the opposite an attack on the unified field theory-project, which was based on the idea the geometrization in itself would have led to physical results.

2.2 The Appendix to the Philosophie der Raum-Zeit-Lehre

Strengthened by Einstein's apparent support in May Reichenbach presented the note in Stuttgart at the regional meeting of the German physical Society (Reichenbach, 1926a). In the following months, Reichenbach must have further work on the manuscript of his book and by the end of the year, he could write to Schlick that "[t]he first volume that deals with space and time [was] finished"der erste Band der Raum und Zeit behandelt, ist fertig (Reichenbach to Schlick, Dec. 6, 1926; SN). Reichenbach hoped to publish the book in the forthcoming Springer series 'Schriften zur wissenschaftlichen Weltauffassung' directed by Schlick and Philipp Frank. However, Springer rejected the book as being too long. By July Reichenbach could announce to Schlick that he had reached a publication arrangement with de Gruyter (Reichenbach to Schlick, Jul. 2, 1927; SN). The publisher agreed to publish only the first volume under the title *Philosophie der Raum-Zeit-Lehre.* According to Reichenbach's recollections, the manuscript of the first volume was not changed significantly after February 1927 (HR, 044-06-25). The drafts were finished in September and the preface was dated October 1927. The note that Einstein had sent to Einstein became the §49 of the Appendix of the book bearing dedicated to the geometrical interpretation of electriciy. Most readers have insisted on Reichenbach's on the problem problem of the *coordinative* in the philosophy of geometry. However, the book is also an attack on the *geometrization* in physics.

The core of he general theory of relativity was the equivalence principle. The latter is based on the *empirical fact* of the equality of inertial and gravitational mass implies that free-fall is locally indistinguishable from inertial motion. The equivalence principle is the *physical hypothesis* that this indistinguishability can be extended to all non-mechanical phenomena (Reichenbach, 1928a, 264; tr. 229f.). Because of the equivalence principle, gravitation is a *universal force* that cannot be neutralized or shielded. Thus, there is no way to separate the geometrical measuring instruments that are not affected by the field (rods and clocks, light rays, force-free particles) from the dynamical ones that react to the field (charged particles). One does not speak of the deformation of our measuring instruments "produced by the gravitational field", but we regard "the measuring instruments as 'free from deforming forces' in spite of the gravitational effects" (Reichenbach, 1928a, 294; tr. 256). The same measuring instruments as those used for geometry are at once indicators of the gravitational field. Rods and clocks are coordinated with $ds \pm 1$. In this respect, Reichenbach continues, "we may say that gravitation is *geometrized*" (Reichenbach, 1928a, 294; o.e.; tr. 256). However, Reichenbach wants to disabused his readers of this apparently obvious conclusion. "*It is not the theory of gravitation that becomes geometry, but it is geometry that becomes an expression of the gravitational field*" Reichenbach, 1928a, 294; tr. 1958, 256.

[32]That is, invariance by the substitution of g_{ik} with λg_{ik} where λ is an arbitrary smooth function of position (cf. Weyl, 1918b, 468). Weyl introduced the expression 'gauge invariance' (*Eichinvarianz*) in Weyl, 1919a, 114.

[33]Cf. Weyl, 1918b, 477. Einstein regarded this as one of the major shortcomings of Weyl's theory; see Einstein to Besso, Aug. 20, 1918; CPAE, Vol. 8b, Doc. 604, Einstein to Hilbert, Jun. 9, 1919; CPAE, Vol. 9, Doc. 58.

[34]Pauli's (1926) review of the German translation of Eddington (1925) is a typical example of this type of criticism: "This natural geometry with the gravitational field and is based on the empirical fact of the equality of heavy and inert mass. An attempt at an anatogenic geometrical interpretation of the electromagnetic mass is now faced with the difficulty that there is no empirical fact corresponding to the equality of heavy and inert mass, which would make such an interpretation appear "natural". One has therefore helped oneself by taking a sufficiently general geometry as a basis, which initially makes no mention of a direct connection between the introduced geometric quantities and the observed behavior of the scales and clocks".

The Appendix to the *Philosophie der Raum-Zeit-Lehre* was nothing but the continuation of this line argument, which only partially developed in the last chapter of the book. "The geometrical interpretation of gravitation", Reichenbach wrote using an effective analogy "is merely the visual cloak in which the factual assertion" encoded by the equivalence principles (Reichenbach, 1928a, 354; tr. [493]). The cloak might be conceived as an inextensible network of rods and clocks, that have to be tailored to the body of the gravitational field. "It would be a mistake to confuse the cloak with the body which it covers; rather, we may infer the shape of the body from the shape of the cloak which it wears. After all, only the body is the object of interest in physics" (Reichenbach, 1928a, 354; tr. [493]). The fact that an Euclidean cloak, so to speak, does not fit the body of a real gravitational field allows to now something new about shape of the body, that is to make the new predictions about the behavior of free falling mass particles, light rays, clocks, etc. Unfortunately, according to Reichenbach recent relativistic research seemed to have confused the cloak for the body itself. "The great success, which Einstein had attained with his geometrical interpretation of gravitation" led many "to believe that similar success might be obtained from a geometrical interpretation of electricity" (Reichenbach, 1928a, 352; tr. [491]).

After general relativity was accepted by the physics community, the search for a suitable geometrical cloak that could cover the naked body of the electromagnetic field began. The separation of the 'operation of displacement of vectors' $\Gamma^{\tau}_{\mu\nu}$ from the operation of comparison of length at distance $g_{\mu\nu}$ gave physicists new mathematical degrees of freedoms that could be exploited to accommodate the electromagnetic field alongside the gravitational field. "However, the fundamental fact which would correspond to the principle of equivalence is lacking" (Reichenbach, 1928a, 354; tr. [493]). Thus, physicists needed proceed by trial and error in the search for suitable geometrical-field variables. Initially attempts were made to identify these geometrical structures with 'true' the geometry of spacetime. The latter was supposed to be endowed with a more general general affine structure. To give this claim empirical content, Weyl initially provided a "realization of the process of displacement" in terms of the behavior of rods and clocks. Weyl's project failed, since rods and clocks did not behave as predicted by the theory. "This means that we have found a cloak in which we can dress the new theory, but we do not have the body that this new cloak would fit" (Reichenbach, 1928a, 353; tr. [493]).

Nevertheless, physicists did not abandon the geometrization program. Rather they came to the conclusion that that "such 'tangible' [*handgreifliche*] realizations does not lead to the desired field equations" (Reichenbach, 1928a, 371; tr. [517]). Thus, theories were proposed by "Weyl, Eddington and Einstein" which "renounced such a realization of the process of displacement" (Reichenbach, 1928a, 371; tr. [517]). The geometrical structure chosen did not have the ambition to the geometrical structure of spacetime and does not have any physical meaning from outset. "Einstein, in particular, has devised several new formulations in which the geometrical interpretation is reduced to the role of a mathematical tool [*Rechenhilfsmittels*]" (Reichenbach, 1928a, 369; tr. [516]). The trick was to 'guess' the right action and the right dynamical quantities to produce the desired equations, that is Maxwell and Einstein's field equations in first approximation. Practitioners of the unified field theory-project seemed convinced that, "[[...] [i]n this 'guessing' the geometrical interpretation of electricity is supposed to be the guide" (Reichenbach, 1928a, 371; tr. [517]). The fundamental geometrical field quantities have no physical meaning, thus the prediction of the theory cannot be directly compared with experience as in the case of general relativity. (Reichenbach, 1928a, 369; tr. [516]). The unified field theory can be confronted with reality indirectly only *post facto* by delivering the electron: "The resulting differential equation would have to have a solution corresponding to the electron, and would have to show the discreet nature of the electron as a mathematical necessity" (Reichenbach, 1928a, 371; tr. [517]).

In Reichenbach's assessment, this post-general-relativistic style of doing physics was ultimately motivated by the fundamental misunderstanding that the success of general relativity was due to the fact that that theory 'geometrized' the gravitational field; thus, the geometrization of other fields would have lead to similar results. Reichenbach conceded that general relativity was indeed a geometrical interpretation of the gravitational field. However, this interpretation was possible due to rather peculiar circumstances. The geometrical interpretation of relativity theory was (a) *physically motivated* since the equivalence principles justified the use of geometrical indicators like rods and clocks for the gravitational field (b) *heuristically powerful*, it made new predictions, which were confirmed by measurements carried out with real physical systems. In absence of an analogon equivalence principle the geometrical interpretation of electricity can indeed be carried through (Reichenbach, 1928a, 369; tr. [515]). This was what Reichenbach tried to show in section §49 of Appendix by providing a toy-geometrization of the electromagnetic field. A geometrization of a field is always possible, e.g. by introducing a suitable definition of the affine connection. One can even provide a proper geometrical interpretation of the combined gravitational/electromagnetic field in which the operation of parallel-transport of vectors has a physical meaning. However, as Reichenbach's theory shows a successful geometrization does not necessarily lead to a successful physical theory.

Reichenbach was quite skeptical that the geometrization program was very improbable that geometrization program was worth pursuing. "The many ruins along this road urgently suggest that solutions should be sought in an entirely different direction". Why did physicists still persist? Reichenbach quite perspectively grasped their psychological motivation: "It is not the geometrical interpretation of electricity" but a deeper assumption which lies at the basis all these attempts; namely, "the assumption that the road to a simple conception, in the sense of a geometrical interpretation, is also the road to true relationships in nature" (Reichenbach, 1928a, 370; tr. [517]). The point of departure in this approach is "the (unwritten) assumption that whatever looks *simple* and *natural* from the viewpoint of the geometrical interpretation will lead to the desired changes in the equations of the field" (Reichenbach, 1928a, 370; tr. [517]). Indeed, by reading papers on the unified field theory one is struck by the fact that they are full of expressions like 'most natural assumption,' 'simplest invariant' , etc. "It is this assumption which constitutes the *physical hypothesis* contained in these attempts" (Reichenbach, 1928a, 372; tr. [519]) . General relativity was based on physical hypothesis based on the equivalence principle, which was hover based on an empirical fact, the identity of gravitational and inertial mass. The unified field theory-project is is based a different physical hypothesis of more speculative nature that the world is geometrically simple. Needless, to say the idea that the 'simplicity' of mathematics could have have bearing for the truth of the theory was Reichenbach the consequence of a sever conceptual mistake (Reichenbach, 1928a, 372; tr. [519]), in which again the separation between mathematics and physics was .

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"The final decision regarding this new physical territory must be left to the physicist, whose physical instinct provides the sole illumination" (Reichenbach, 1928a, 372; tr. [519]). However, ultimately scientists' "physical instinct" pertains to the realm of the logic of discovery and thus outside epistemology. However, Reichenbach made no mysteries that he hoped that his epistemological analysis could tie scientists to the mast of empiricism protecting them from "the sirens' enchantment [*Sirenenzauber*] of a unified field theory" (Reichenbach, 1928a, 373). *Philosophie der Raum-Zeit-Lehre* was not only a book about the problem of the *coordination* between geometry and reality. It was an attack against the rhetoric of the *geometrizaton* of physics that seemed to have started to dominate the relativistic community. If there is something we can learn from general relativity, Reichenbach argues, it is that abstract geometry has been lowered to physics, and certainly not that physics has been absorbed into geometry.

3 Unification: Reichenbach-Einstein Correspondence (1929–1930)

In October 1927, Reichenbach moved back to Berlin where he took the position of an "unofficial associate professor" (Hecht and Hoffmann, 1982). At about the same time, Einstein read the manuscript of the *Philosophie der Raum-Zeit-Lehre* (Einstein to Elsa Einstein, Oct. 23, 1927; CPAE, Vol. 16, Doc. 34). Soon thereafter he wrote a short book review. Einstein was quite perceptive in pointing out the two themes that Reichenbach had treated in the Appendix: (1) "In the Appendix, the foundation of the Weyl-Eddington theory is treated in a clear way and in particular the delicate question of the *coordination* of these theories to reality" (Einstein, 1928c, 20; m.e.). As we have seen, Reichenbach had insisted, that as in any other theory, also in unified field theory based on the affine connection as fundamental variable, one should give physical meaning the operation of displacement from the outset. Einstein did not comment further on this issue, since over the years, he had come to realize that this requirement was too strict. However, Einstein seemed to be in full agreement with the second point made by Reichenbach: (2) In the Appendix, "in my opinion quite rightly—it is argued that the claim that general relativity is an attempt to *reduce physics to geometry* is unfounded" (Einstein, 1928c, 20; m.e.). As we have seen, Reichenbach and Einstein had already discussed this topic in a private correspondence less than two years earlier (Giovanelli, 2016a).

Simultaneously with Reichenbach's, Einstein's a more extensive review of *La déduction relativiste* written by the French philosopher Émile Meyerson (Meyerson, 1925) appeared in the Einstein (1928a). The review reveals how Einstein's point view had become quite different from that of Reichenbach on both issues. Einstein embraced Meyerson's rationalist philosophy, insisting on the deductive-speculative nature of physics enterprise, implicitly disavowing the operational-empirical rhetoric that seemed to have dominated his early philosophical pronoucements. However, Einstein strongly disagreed with Meyerson's insistence that Einstein's, Weyl's and Eddington's theories were the crowning momento of long process of geometrization of physics. He insisted again that geometry in this context is "*devoid of meaning*" (Einstein, 1928a, 165; m.e.). However, he also clarified the motivations against his critique of the geometrization program: "The essential point of the theories of Weyl and Eddington", was not to geometrize the electromagnetic field, but to "represent gravitation and electromagnetic *under a unified point of view*, whereas beforehand these fields entered the theory as logically independent structures" (Einstein, 1928a, 165; m.e.). Einstein's further attempts at unified field theory in the immediately following months reveal more clearly Einstein's motivations behind this change in philosophical attitude.

In Spring 1928, during a period of illness, Einstein came up with a new proposal for a unified field theory. On June 7, 1928 Planck presented a note to the Prussian Academy on a 'Riemannian Geometry, Maintaining the Concept of Distant Parallelism' (Einstein, 1928d), a flat space-time that is nonetheless non-Euclidean since the connection $\Gamma^{\tau}_{\mu\nu}$ is non-symmetrical. He introduced a new formalism, based on the concept of *n-Bein* (or *n*-legs), n unit orthogonal vectors representing a local coordinate system attached at a point of n dimensional continuum. Vectors at distance points considered as equal and parallel if they have the same local coordinates with respect to their n-bein. The vierbein-field h^{ν}_{a} defines both the metric tensor $g_{\mu\nu}$ and the electromagnetic four-potential φ_{μ}. Its sixteen components can be considered as the fundamental dynamical variables of the theory. The question arises as to the field equations that determine the vierbein-field. On June 14, 1928 he submitted a second paper in which the field equations are derived from a variational principle (Einstein, 1928b).

A few months later, when the paper appeared in print, Reichenbach managed to prepare a typescripted note (Reichenbach, 1928b) with some comments that he send Einstein for feedback:

> Dear Herr Einstein,
> I did some serious thinking on your work on the field theory and I found that the geometrical construction can be presented better in a different form. I send you the ms. enclosed. Concerning the physical application of your work, frankly speaking, it did not convince me much. *If geometrical interpretation must be, then I found my approach simply more beautiful, in which the straightest line at least means something.* Or do you have further expectations for your new work? (Reichenbach to Einstein, Oct. 17, 1928 EA, 20-92; m.e.).

In this passage, Reichenbach makes two apparently unrelated points, which, however, seems to be part of single two-pronged argument. In the note sent to Einstein Reichenbach had shown that, if one lets aside from the n-bein formalism, Einstein's new geometrical settings could be easily inserted into the Weyl–Eddington–Schouten lineage, as a special case of a metric space in which the connection is flat, but non-symmetric.[35] If so, Reichenbach could raise the same objection he had raised against Einstein's previous theories. According to Reichenbach, a "real physical achievement is obtained only if, moreover, the operation of displacement is filled with physical content" (Reichenbach, 1928c, 7). Einstein's geometry, being flat, implies the existence of a straight line, a line of which all elements are parallel to each other, which is nevertheless not identical with a geodesic (Einstein, 1928b, 224). However, as Reichenbach reported, the latter has no physical meaning in Einstein's theory. "If geometrical interpretation must be", Reichenbach concluded, then his §49-theory was preferable, since the straightest lines and shortest line correspond to the motion of charged and uncharged test particles under the influence of the combined gravitational-electromagnetic field. Once again, Einstein's goal was to use this geometrical apparatus as a starting point find the right 'action' from which a set of field equations. However, Reichenbach commented, nothing new came out of it: "[T]he derivation of the Maxwellian and gravitational equation from a variational principle was already achieved by other approaches" (Reichenbach, 1928c, 6), like, say, Einstein–Eddington purely affine theory.

In the subsequent letter, Einstein defended his classification of geometries, but did not comment on Reichenbach's objection. However, he invited Reichenbach and his first wife Elisabeth for a cup of tea on November 5, 1928. On that occasion, Einstein might have informed Reichenbach about his plan to abandon the variational strategy to find the field equations. However, it is quite probable that Einstein might have explained to Reichenbach that his goal was *not* to provide a *geometrization* of the electromagnetic field, but to provide their *unification* of both fields. Thus, Einstein's choice of the field-structure was not motivated by geometrical considerations, nor had a geometrical meaning. The goal was to recover a set of field equations yielding the classical equations of gravitation and of electromagnetism only to first order. That is theory should predict *new* effects in the case of strong fields. To obtain this result, Einstein was ready to adopt a whatever-it-takes strategy. Not only he was ready to forgo any physical interpretation of the fundamental variables of the theory; he was even ready to abandon the variational approach as in the paper he was working on.

It is hard to imagine that their philosophical disagreement did not emerge during those discussions. In a semi-popular paper Einstein had submitted a few week later. *Festschrift* on the occasion of the

[35] One starts from a general non-symmetric affine $\Gamma^{\tau}_{\mu\nu}$ connection, and imposes the condition that length of vectors does not change under parallel transport. Then Einstein and Riemann space could be obtained via the "exchangeability of the specializations" (Reichenbach, 1928c, 5). If one imposes that the Riemann tensor vanishes one obtains Einstein space; if one imposes that the connection is symmetric one obtains Riemannian space.

seventieth birthday of Aurel Stodola Einstein insisted on the speculative nature of the new theory. One starts from this mathematical structure and then searches for the simplest and most natural field equations that the vierbein-field can satisfy (Einstein, 1929c, 131). The physical soundness of the field equations can be confirmed only by integrating them, finding particle solutions and the laws governing of their motions in the field. However, this was usually a very difficult task. Einstein warned his readers of the dangers of proceeding "along this speculative road" (Einstein, 1929c, 127). "Meyerson's comparison with Hegel's program [*Zielsetzung*]" Einstein put it in a footnote, "illuminates clearly the danger that one here has to fear" (Einstein, 1929c, 127).

3.1 Reichenbach's Articles on Fernparallelismus field theory

In the late 1920s, Reichenbach was a regular contributor to the *Vossische Zeitung*, at that time Germany's most prestigious newspaper; not surprisingly he was asked for a comment on Einstein's theory, which had started attracting irrational attention in the daily press (see Pais, 1982, 346). With the advantage of having personally discussed the topic with Einstein a few weeks earlier, Reichenbach published a brief didactic paper on Einstein's theory on January 25, 1929 (Reichenbach, 1929c). Reichenbach seems to have indeed profited from the conversation with Reichenbach He did not present anymore the unified field theory-project as a geometrization program. In particular, Reichenbach reported that the novelty of *Fernparallelismus* consisted in the fact that it no longer seeks to establish a formal synthesis between already established theories; instead, it produces new laws, of which gravitational and electromagnetic field equations are only a first approximation. For strong fields, there would be a much closer interdependence between electromagnetism and gravitation. In principle, the theory could receive experimental proof if the effects predicted did not remain beyond the threshold of experimental detection. However, the problem of the constitution of matter or the quantum problem were far from being satisfactorily addressed. Thus, Reichenbach concluded that "for the time being, no pronouncement can be made concerning the physical significance of the theory" (Reichenbach, 1929c; tr. 1978, 1:262).

Einstein was very upset for Reichenbach's decision to leak a private conversion to the press Einstein to Vossische Zeitung, Jan. 25, 1929; EA, 73-229. The exchange of the letters that ensued (Reichenbach to Einstein, Jan. 27, 1929; CPAE, Vol. 16, Doc. 384, Einstein to Reichenbach, Jan. 30, 1929; CPAE, Vol. 16, Doc. 390, Reichenbach to Einstein, Jan. 31, 1929; CPAE, Vol. 16, Doc. 391) put a serious strain in their personal relationships. However, philosophical views that have become irreconcilable. If Reichenbach's private letters expressing Reichenbach's woe for Einstein's betrayal of their personal relationship of trust, his published writings point to his disappointment for Einstein's betrayal of their shared philosophical ideals. By the time of the publication of the article for the *Vossische Zeitung*, Reichenbach had already written two papers on the *Fernparallelismus*. The first article in order of publication was entitled "Die neue Theorie Einsteins über die Verschmelzung von Gravitation und Elektrizität" (Reichenbach, 1929b) and appeared in February of 1929 in the *Zeitschrift für Angewandte Chemie*. The second article was an extended version of the manuscript that Reichenbach had sent to Einstein in October and bore the same title "Zur Einordnung des neuen Einsteinschen Ansatzes über Gravitation und Elektrizität" (Reichenbach, 1929d). It was published only in September in the *Zeitschrift für Physik*. These articles represent Reichenbach's last important contribution to issues related to relativity theory and spacetime theories. On the one hand, Reichenbach attempted to make his previous reflections about the unified field theory-project in the Appendix to the *Philosophie der Raum-Zeit-Lehre* to bear fruit (Reichenbach, 1928a, §46). On the other hand, he added new elements of clarification by clearly distinguishing the 'geometrization program' and the 'unification program' .

In the first paper for the *Zeitschrift für Angewandte Chemie*, Reichenbach introduced the history of the unified field theory in an entirely different manner than he had done before. In the Appendix to the *Philosophie der Raum-Zeit-Lehre* the history of the unified field theory-project program was ultimately presented as linear evolution of the geometrization program which had progressively became more abstract. Now Reichenbach, probably following his discussion with Einstein, describes the history of the unified field theory as the progressive *downfall* of the geometrization program and the concurrent *rise* of the unification one. After the failure of Weyl's first attempts, most physicists, including Einstein (1923, 1925) considered preferable to sacrifice the geometrical interpretation—i.e., to relinquish the coordination of geometrical notion of parallel transport of vectors with the behavior rods and clocks—and then to use the geometrical variables ($\Gamma^{\tau}_{\mu\nu}$, φ_{ν} and so on) as 'calculation device' for the greater good of finding the field equations. From the field variables, one has to attempt to establish the simplest differential invariants that can be used as an action function. However, the laws of Einstein and Maxwell were supposed to be modified. They should contain additional terms representing the interaction of the gravitational and the electromagnetic fields

Reichenbach had come to understand that, in Einstein's view, the aim of the unified field theory-project was not the geometrization of the electromagnetic field alongside the gravitational field; it was the unification of the electromagnetic and gravitational field. Thus, Reichenbach's concern became to explain what 'unification' means in this context. The problem was addressed in detail in the more technical paper, which grew out of the manuscript that Reichenbach had sent to Einstein (Reichenbach, 1929d). The first part of the paper reproduces the manuscript he sent to Einstein, with minor changes. In the second, part Reichenbach introduced a more extensive epistemological discussion. He formulated the distinction between (a) a formal unification and (b) an inductive unification . This distinction seems to be an application of Reichenbach's more famous classification of two types of simplicity (Reichenbach, 1924, 9, 1929a, §11) to the case of unified field theories. In this way Reichenbach could describe two opposite approaches to the unified field theory-project. In this setting, his §49-theory came in handy. Reichenbach's theory uses a similar geometrical setting as Einstein's theory. Both use a non-symmetric affine connection. Only, in Einstein's approach the further conditions that the geometry is flat is imposed, allowing for distant parallelism.

According to Reichenbach, his §49-theory was able to provide a *proper* geometrical interpretation of the combined gravitational/electromagnetic field. However, the theory could achieve only a *formal* unification **??** because no new testable predictions were made:

> The author [Reichenbach] has shown that the first way can be realized in the sense of a combination of gravitation and electricity to one field, which determines the geometry of an extended Riemannian space; it is remarkable that thereby *the operation of displacement receives an immediate geometrical interpretation, via the law of motion of electrically charged mass-points.* The straightest line is identified with the path of electrically charged mass-points, whereas the shortest line remains that of uncharged mass points. In this way one achieves *a certain parallelism to Einstein's equivalence principle.* By the way [the theory introduces] a space which is cognate to the one used by Einstein, i.e., a metrical space with non-symmetrical $\Gamma^{\tau}_{\mu\nu}$. The aim was to show that the geometrical interpretation of electricity does not mean a physical value of knowledge per se (Reichenbach, 1929d, 688; m.e.).

If one wants to give a geometrical interpretation of a combined gravitational/electromagnetic field using the affine connection $\Gamma^{\tau}_{\mu\nu}$ as a fundamental variable; in that case, one should at least provide a coordinate definition of the operation of parallel displacement of vectors before starting to search for the field equations. Otherwise, it is hard to understand in which sense one could test whether the latter made correct predictions. However, Reichenbach's theory was precisely meant to show that a successful geometrical interpretation is not sufficient to achieve a substantive unification. For Reichenbach, this should have been a warning that the very hope that the geometrical interpretation of a physical field itself was the key to new physical insights was misplaced.

Einstein *Fernparallelismus*-field theory is an instance of a the second approach, which claims to achieve **??**, an inductive unification, by forgoing to the geometrical interpretation, that is without providing an operational (through measurement) meaning to the fundamental field variables:

> On the contrary, Einstein's approach of course uses the second way, since it is a matter of increasing physical knowledge; it is the goal of Einstein's new theory to find such a concatenation of gravitation and electricity, that only in first approximation it is split in the different equations of the present theory, while is in higher approximation reveals a reciprocal influence of both fields, which could possibly lead to the understanding of unsolved questions, like the quantum puzzle. However, it seems that this goal can be achieved only *if one dispenses with an immediate interpretation of the displacement, and even of the field quantities themselves.* From a geometrical point of view this approach looks very unsatisfying. Its justification lies only on the fact that the above mentioned concatenation implies more physical facts that those that were needed to establish it (Reichenbach, 1929d, 688; m.e.).

In Reichenbach's view, *Fernparallelismus* appeared not only as a formally satisfying unification but as a real advance over the available theories. It entails some coupling between the electromagnetic and gravitational fields that was not present in the given individual field theories. However, Reichenbach argues that Einstein could only achieve this result at the expense of a physical interpretation of the fundamental geometrical variables, the h^{ν}_{a}. Einstein's flat affine connection defines a set of straight lines as privileged paths; however these lines are not interpreted as paths of particles. Thus very definition of field quantities in force they excerpt on test particles is meanigless. This approach, however, made the theory impossible to be confirmed or disproved experimentally by observing the behavior of suitable indicators. One cannot define the field quantities in advance in terms of the paths of test particles, as in other field theories. The laws governing the latter are unknown before integrating the field equations (Einstein to Cartan, Jan. 7, 1930; Debever, 1979, A-XVI, (Einstein, 1930e, 23))

In Reichenbach's diagnoses, the stagnation of the unified field theory-project depended on the presence of a sort of *trade-off between geometrization and unification* of which physicists were only partially aware. General relativity was the only theory that was able to combine both virtues: (1) the theory provided a proper *geometrical interpretation* of the gravitational field because it introduced a coordinative definition of the field variables $g_{\mu\nu}$, in terms of the behavior of those that were traditionally considered geometrical measuring instruments, such as rods and clocks, light rays, free falling particles (2) the theory provided a *proper unification* by predicting that the gravitational field had certain effects on such measuring instruments that were not implied by previous theories of gravitation—such as gravitational time dilation (Reichenbach, 1928a, 350). Successive attempts to include the electromagnetic field in the frame of general relativity failed to uphold this standard. According to Reichenbach, the reason for this failure was ultimately the lack of a proper analogon of a physical fact that could play the role of the *equivalence principle*.

The effective interplay between geometrization and unification did not seem reproducible without the equivalence principle. Thus, to replicate the success of general relativity, physicists were forced to make a choice. Two strategies seem to have been available, which ultimately depended on physicists' interpretation of Einstein's theory of gravitation. (a) many, e.g. Weyl, considered general relativity a successful theory *because* it had provided a geometrical interpretation of the gravitational field; then, one could hope to obtain the same success by geometrization the electromagnetic field as well. (b) For others, in particular, for Einstein, general relativity was a successful theory *because* it had achieved the unification of two different fields, gravitational and inertial field. In this way, however, the gravitational/inertial field was provisionally isolated from a more general field of unknown mathematical structure, encoding quantities corresponding to the electromagnetic field. Like many others, Reichenbach believed that without a new *physical hypothesis*—that is a physical fact that played the role of the strict equality of inertial and gravitational mass—, both strategies, item a and item b had little hope of success.

Einstein was caught between a rock and a hard place. As may had pointed out, without the equivalence principle a further geometrization of electromagnetic fields was not worth pursuing since it had not physical justification. Einstein could counter these objections by claiming that geometrization had never been the goal. The achievement general relativity was have combined inertial and gravitational just like special relativity has combined magnetic and electric field. However, without an analogon of the equivalence principle, there seem to be also no physical justification for searching for a further unification of the electromagnetic and gravitational field. Nevertheless, Einstein considered the separation between the two fields as theoretically unbearable (Einstein, 1930e, 24). However, we do not have any physical fact that gives any clue as to what may be the more comprehensive mathematical structure in which electromagnetic and gravitational field will appear as two components. As Reichenbach, as surmised, Einstein ultimately could only rely on a different *physical hypothesis* that that nature was mathematically simple. One searches for the most natural field structure, and the simplest field equations that such structure satisfies. The only warranty of the success of this speculative groping in the chaos of mathematical possibilities was the unification power of the field equations obtained, and in particular the its capacity to deliver a proper theory of matter.

It should not come as a surprise that this philosophical outlook was for Reichenbach anathema. As we have seen, as early as in his habilitation, considered the great achievement of relativity theory the *separation of mathematical necessity and physical reality*. Reichenbach had always perceived this separation as nothing more than a philosophical distillation of Einstein's scientific practice. However, in the search of a unified field theory, Einstein had come implicitly to question this distinction coming close to plea for a *reduction of physical reality to mathematical necessity*. Einstein put it candidly in his Stodola-*Festschrift*'s contribution—that he sent for publication toward the end of January (Einstein to Honegger, Jan. 30, 1929; CPAE, abs. 864). The ultimate goal of understanding reality is achieved when one could prove that "even God *could not have established these connections otherwise* than they actually are, just as little as it would have been in his power to make the number 4 a prime number" (Einstein, 1929c, 127).

4 Conclusion

Just after the publication of the new expected derivation of the *Fernparallelismus*-field equations, (Einstein, 1929d), Einstein wrote a popular account of the theory on the first page of their Sunday supplement of the *New York Times* on February 3 and in *The Times* of London in two installments on February 4 and 5 (Einstein, 1929a,b, also published as Einstein, 1930d). Einstein insisted on the highly speculative nature of unified field theory-project, without being afraid endorsing even his somewhat outrageous comparison with Hegel. It is hard to deny that the fact that Einstein choses to mention Meyerson rather than Reichenbach as a philosophical interlocutor has a symbolic significance. After a decade of personal friendship and intellectual exchange that had shaped the history of 20th-century philosophy of science and Einstein seems to have put into question the very core of his philosophical alliance with Reichenbach. Whereas Reichenbach considered the separation between mathematics and physics the great achievement of the theory, Einstein saw in mathematical simplicity itself the key to the unification.

Although Einstein's *Fernparallelismus* attracted the attention of mathematicians, Reichenbach's skepticism was shared by the physics community.[36] Einstein was fully aware of the marginality of his position, but, throughout 1929, continued express his confidence in *Fernparallelismus* program. He continued to defend the theory in public (in talks given in October and December) (Einstein, 1930a,b,c), as well as in as well in private correspondence.[37] However, only a few months later Einstein and Walther Mayer presented a new approach (Einstein and Mayer, 1931) that, by generalizing the n-bein formalism to five dimensions. The optimism once again faded away quickly, since the theory was unable to solve the problem of matter. In a popular talk given in Vienna towards mid-October of 1931, Einstein could only describe his field-theoretical work since general relativity as a "cemetery of buried hopes" (Einstein, 1932, 441).[38]

However, Einstein's philosophical motivation for continuing of this path as not changed. Many of his former philosophical allies considered this attitude hard to phatom.[39] However, Einstein 1933 Oxford lecture address leave no room for doubt. Einstein's quest for unification was motivated by deep-seated conviction that "nature is the realization of the most simple mathematical ideas" (Einstein, 1933a). Einstein conceded, that experience remains the sole criterion of the physical adequateness of a mathematical construction, however, he insisted that the true creative role belongs to mathematics: "I hold it to be true that pure thought is competent to comprehend the real, as the ancients dreamed" (Einstein, 1933a, 167). After all, he now claims, the search field theories has always followed the same heuristic pattern:

[36]Weyl, who had always been scolded by Einstein for his speculative style of doing physics could relaunch the accusation in a paper (Weyl, 1929) in which he had uncovered the gauge symmetry of the Dirac theory of the electron (Dirac, 1928a,b). "The hour of your revenge has come", Pauli wrote to Weyl in August: "Einstein has dropped the ball of distant parallelism, which is also pure mathematics and has nothing to do with physics and *you* can scold him" (Pauli to Weyl, Aug. 26, 1929; WPWB, Doc. 235). As Pauli complained, writing to Einstein's close friend Paul Ehrenfest, "God seems to have left Einstein completely!" (Pauli to Ehrenfest, Sep. 29, 1929; WPWB, Doc. 237).

[37]Pauli did not hesitate to describe Einstein's presentation at the Berlin Colloquium as a "terrible rubbish" (Pauli to Jordan, Nov. 30, 1929; WPWB, Doc. 238). When he received the drafts of Einstein's *Annalen* paper, he wrote only slightly more politely. Pauli wrote that he did not find the derivation of the field equations convincing; they show "no similarities with the usual facts confirmed by experience" (Pauli to Einstein, Dec. 19, 1929; WPWB, Doc. 239). In particular, Pauli missed the validity of the classical tests of general relativity, perihelion motion and gravitational light bending: "These results seem to be lost in your sweeping dismantling of the general theory of relativity. However, I hold on to this beautiful theory, even if it is betrayed by you!" (Pauli to Einstein, Dec. 19, 1929; WPWB, Doc. 239). When Einstein expressed caution towards the definitive validity of his equations, he, "so to speak, took the words right out of my mouth of criticism-loving physicists" (Pauli to Einstein, Dec. 19, 1929; WPWB, Doc. 239). Pauli knew that Einstein would not have changed his mind, but he was ready to "make any bet" that "after a year at the latest you will have given up all the distant parallelism, just as you had given up the affine theory before" (Pauli to Einstein, Dec. 19, 1929; WPWB, Doc. 239). Einstein complained that Pauli's remarks were superficial and asked him to return on the issue after some months (Einstein to Pauli, Dec. 19, 1929; WPWB, Doc. 140). Although the unified field theory-project was disavowed by its own initiators (Weyl, 1931), Einstein insisted in the pursuit of *Fernparallelismus* discussing with Mayer two solutions of his last field equations (Einstein and Mayer, 1930).

[38]It is interesting to notice how one of the reason that induced Einstein to abandon the theory was of Reichenbach's criticism: "The main reason for the uselessness of the distant parallelism construction lies, I feel, in that one can attribute absolutely no physical meaning to the 'straight lines' of the theory, while the physically meaningful (macroscopic) equations of motion cannot be obtained from it [3]. In other words, the h_{sv} give rise to no useful representation of the electromagnetic field" (Einstein to Cartan, May 21, 1932; Debever, 1979, A XXXV). Thus, for Einstein it was legitimate to abandon the physical interpretation of the straight line from the outset, if the theory provided the laws of motion of the electrons at the end.

[39]At the end of 1931 Lanczos wrote a semi-popular presentation of distant parallelism approach (**Lanczos1931**), in which he distinguished between a *positivist-subjectivist* interpretation of relativity theory and a *metaphysical-realistic* perspective. Many readers might have easily recognized someone like Pauli in Lanczos's 'positivist'; however, others were baffled to find out that Einstein was classified among the 'metaphysicians.' It is probably this article of Lanczos that Frank read with some bewilderment, as he reports in his Einstein's biography (Frank, 1947). Frank was "quite astonished" to find the theory of relativity characterized as the expression of a realist program "since I had been accustomed to regarding it as a realization of Mach's program" (Frank, 1947, 215). However, when Frank met Einstein in Berlin at around the same time, he found out that Lanczos had indeed well characterized Einstein's point of view (Frank, 1947, 215f.). According to his recollection, Einstein complained that "[a] new fashion" had arisen in physics according to which quantities that in principle cannot be measured do not exist, and that to "to speak about them is pure metaphysics" (Frank, 1947, 216). Frank objected that this was the very same philosophical attitude that led to relativity theory. By contrast, Einstein insisted, the essential point of relativity theory is to "regard an electromagnetic or gravitational field as a physical reality, in the same sense that matter had formerly been considered so" (Frank, 1947, 216). The theory of relativity teaches us the connection between different descriptions of one and the same reality. Was not a theory about the behavior of rods and clocks, but a unification of two fields.

"the theorist's hope of grasping the real in all its depth" lies "in the limited number of the mathematically existent simple field types, and the simple equations possible between them" (Einstein, 1933a, 168). Maxwell's equations are the simplest laws for an anti-symmetric tensor field which is derived from a vector, Einstein's equations are the simplest equations for the metric tensor, etc. This strategy applies to Einstein's last attempt at a unified field theory on a theory based on semi-vectors (**Einstein1932c**, **Einstein1933c**, **Einstein1934b**, **Einstein1933d**). After ordinary vectors, the latter are the simplest mathematical fields that are possible in four dimensions, and seems to describe certain properties of elementary particles. One has to search for the the simplest laws these semi-vectors satisfy (Einstein, 1933a, 168).

In September 1933, three months after the Oxford lecture, Einstein left Europe for Princeton. Reichenbach started to teach at University of Istanbul in the fall of the same year. He tried to obtain a position in Princeton a few years later (Verhaegh, 2020). However, Reichenbach was concerned about Weyl's possible opposition: "He is my adversary since a long time," he wrote to Charles W. Morris; in the latter, Weyl was described a supporter of a form a "mathematical mysticism" that was "very much opposed to my empiricist interpretation of relativity" (Reichenbach to Morris, Apr. 12, 1936; HR, 013-50-78). Thus, in April 1936, Reichenbach turned to Einstein to ask his support: "I surmise that Weyl's opposition persists to these days and therefore I'd be grateful if you could put a word in my favor" (Einstein to Reichenbach, May 2, 1936; EA, 20-118). Einstein replied disillusioned that he had heard from Rudolf Carnap that even Princeton did not want to hire more Jews (Einstein to Reichenbach, May 2, 1936; EA, 20-118). Althoogu Reichenbach feard Weyl's opposition, he must have certanly aware that it was Einstein who, by that time, had turned into a 'believing rationalist' (Einstein to Lanczos, Jan. 24, 1938; EA, 15-268), convinced that physical truth lies in mathematical simplicity (**Ryckman2014**).

In 1938 Reichenbach managed to move to the United States (Verhaegh, 2020). Soon thereafter, Reichenbach and Einstein came into epistolary contact again to support Bertrand Russell who had been dismissed from the City College of New York because of his anti-religious stance (Reichenbach to Einstein, Aug. 14, 1940; EA, 20-127, Einstein to Reichenbach, Aug. 22, 1940; EA, 20-110). Later both contributed (**Reichenbach1944**, **Einstein1944b**) to a volume in Russell's honor for the series *Library of Living Philosophers* edited by Paul Schilpp (1944). Reichenbach was asked contribute to a similar volume in honor of Einstein a few years later (Schilpp, 1949). In some unpublished notes about Reichenbach's contribution, Einstein (1949b) he praised him for never trying to pursue "the universality of knowledge by sacrificing clarity" (Einstein, 1949b). However, Einstein ultimately he disagreed with many of Reichenbach's philosophical tenets. Reichenbach's claim "'the meaning of a statement is reducible to its verifiability'[40]" appears to be problematic; in particular Einstein found "dubious whether this conception of 'meaning'[41] can be applied to the single statement[42]" (Einstein, 1949b).

As is well-known, in the so-called 'Reply to criticisms' included in the Schilpp-volume. Einstein reformulated this line of argument by staging a dialogue between Reichenbach-Helmholtz, Poincaré, and an anonymous non-positivists, who claims that geometry and physics can be compared with experience only as whole. The question at stake, Einstein put it jokingly, was nothing but Pilates's famous question 'What is truth'? Although this dialogue has become famous, its meaning cannot be fully understood if one does not take into account that Einstein's philosophical digressions were ultimately motivated by his tireless pursue of the the theory of the 'total field.' At that time, Einstein had returned to his 1925 metric-affine approach introducing non-symmetric $g_{\mu\nu}$ and $\Gamma^{\tau}_{\mu\nu}$ as fundamental variables **Einstein1945**, **Einstein1945-04**. In private correspondence, Einstein's long-life friend Michele Besso raised against Einstein objections similar that Reichenbach had raised over twenty years earlier against the same theory. The symmetric part of the $g_{\mu\nu}$ and the corresponding $\Gamma^{\tau}_{\mu\nu}$, Besso claimed, should define a a straightest line which at the same time is the shortest. Do these lines represent the trajectories of test particles? What is their physical meaning? (Besso to Einstein, Apr. 11, 1950; Speziali, 1972, Doc. 171). Einstein's reply reveals his fundamental philosophical conundrum:

> Your questions are fully legitimate, but not answerable for the time being [...] This is because there is no real definition of the field in a consistent field theory. It is true that this puts you in a Don Quixotic situation, in that you have absolutely no guarantee whether it ever possible to know if the theory is 'true.' *A priori* there is no bridge to empiricism. For example, there isn't a 'particle' in the strict sense of the word because, the existence of particles doesn't fit the program of representing reality by everywhere continuous, even analytic functions. For example, in theory there is a symmetric $g_{\mu\nu}$ [...] and then a geodesic line. But from the outset one has no clue that these lines have any physical meaning, not even approximately [...] It boils down to the fact that a comparison with

[40] In English in the text.
[41] In English in the text.
[42] In English in the text.

what is empirically known can only be expected from the fact that strict solutions of the system of equations can be expected found, that reproduce the behavior of empirically 'known' structures and their interactions. Since this is extremely difficult, the skeptical attitude of contemporary physicists is probably is completely understandable. In order to really grasp this conviction of mine, you must read *again and again* my answer in the anthology [*Sammelband*][43] (Einstein to Besso, Apr. 15, 1950; Speziali, 1972, Doc. 172).

This passage summarizes many of the issues that Reichenbach and Einstein have discussed over the years. It explains Reichenbach legitimate concern that geometrical concepts of the theory, like that of the straightest lines, should receive a physical interpretation from the outset in terms of the motion of test particles. However, it also explains why Einstein did not find this approach viable in pursuing for a theory in which there were no particles, but only regions of the field whose the equations of motions of particles should be derived from the field equations. In the current state of the theory it was not possible it is not possible to judge whether the interpretation of the fundamental quantities which represent the field is correct or not. Usually a field is defined in the first place by the actions that it exerts on particles. However, currently we do not know the law of these actions the discovery of this law requires the integration of the equations of the field, which has not yet been carried out. In this context there is no separation between empty scheme, and the coordinative defintions. The of mathematical si, was not only a non-positivist, he was a tamed metaphysicias.

Abbreviations

CPAE	Albert Einstein (1987–). *The collected papers of Albert Einstein.* Ed. by John Stachel et al. 15 vols. Princeton: Princeton University Press, 1987–.
EA	*The Albert Einstein Archives at the Hebrew University of Jerusalem.*
ECW	Ernst Cassirer (1998–). *Gesammelte Werke. Hamburger Ausgabe.* Ed. by Birgit Recki. 26 vols. Hamburg: Meiner, 1998–.
HR	*Archives of Scientific Philosophy* (1891–1953). *The Hans Reichenbach Papers.* 1891–1953.
SN	*Schlick Nachlass.* Noord-Hollands Archief, Haarlem.
WPWB	Wolfgang Pauli (1979–). *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a.* Ed. by Karl von Meyenn. 4 vols. Berlin/Heidelberg: Springer, 1979–.

References

Afriat, Alexander (2009). "How Weyl stumbled across electricity while pursuing mathematical justice." *Studies in history and philosophy of science. Part B: Studies in history and philosophy of modern physics* 40, 20–25.

Bacciagaluppi, Guido and Antony Valentini, eds. (2009). *Quantum theory at the crossroads. Reconsidering the 1927 Solvay conference.* Cambridge: Cambridge Univerity Press, 2009.

Born, Max and Albert Einstein (1968–1971). *The born-einstein letters. Correspondence between albert einstein and max and hedwig born from 1916 to 1955 with commentaries by max born.* Ed. by Max Born and Hedwig Born. London/ Basingstoke: MacMillan, 1968–1971.

Cassirer, Ernst (1921). *Zur Einsteinschen Relativitätstheorie. Erkenntnistheoretische Betrachtungen.* Berlin: B. Cassirer, 1921. Repr. in ECW, Vol. 10.

Debever, Robert, ed. (1979). *Élie Cartan - Albert Einstein. Letters on absolute parallelism 1929-1932.* Princeton: Princeton Univerity Press, 1979.

Dirac, Paul Adrien Maurice (1928a). "The quantum theory of the electron." *Proceedings of the Royal Society of London.* Series A 117, 610–624.

— (1928b). "The quantum theory of the electron." II. *Proceedings of the Royal Society of London.* Series A 118, 351–361.

Dongen, Jeroen van (2010). *Einstein's unification.* Cambridge/New York: Cambridge University Press, 2010.

Dyson, Frank Watson, Arthur Stanley Eddington, and Charles Rundle Davidson (1920). "A determination of the deflection of light by the sun's gravitational field, from observations made at the total eclipse of May 29, 1919." *Philosophical transactions of the Royal Society of London.* Series A, Containing Papers of a Mathematical or Physical Character 220, 291–333.

Eddington, Arthur Stanley (1921a). "A generalization of Weyl's theory of the electromagnetic and gravitation fields." *Proceedings of the Royal Society London* 99, 104–121.

— (1921b). "The relativity of field and matter." *Philosophical magazine* 42, 800–806.

— (1923). *The mathematical theory of relativity.* Cambridge: University Press, 1923.

— (1925). *The domain of physical science.* Ed. by Joseph Needham and Arthur James Balfour. New York: The Macmillan company, 1925, 187–218.

Ehrenfest, Paul (1907). "Die Translation deformierbarer Elektronen und der Flächensatz." *Annalen der Physik.* 4th ser. 23, 204–205.

Einstein, Albert (1905). "Zur Elektrodynamik bewegter Körper." *Annalen der Physik.* 4th ser. 17, 891–921. Repr. in CPAE, Vol. 2, Doc. 23.

— (1914). "Die formale Grundlage der allgemeinen Relativitätstheorie." *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Halbband 2, 1030–1085. Repr. in CPAE, Vol. 6, Doc. 9.

[43]Einstein, 1949a.

— (1916). “Die Grundlage der allgemeinen Relativitätstheorie.” *Annalen der Physik.* 4th ser. 49, 769–822. Also issued as a *separatum*, Leipzig: Barth. Repr. in CPAE, Vol. 6, Doc. 30.
— (1918a). “Nachtrag zu H. Weyl, *Gravitation und Elektrizität* [Weyl, 1918a].” *Sitzungsberichte der Preußischen Akademie der Wissenschaften*, 478–80. Repr. in CPAE, Vol. 7, Doc. 8.
— (1918b). “Review of Weyl, *Raum–Zeit–Materie* [Weyl, 1918b].” *Die Naturwissenschaften* 6, 373. Repr. in CPAE, Vol. 7, Doc. 10.
— (1919a). “Lecture notes for course on general relativity at the university of Berlin.” Summer semester. 1919. Pub. in CPAE, Vol. 7, Doc. 19.
— (1919b). “What is the theory of relativity?” *The Times.* Nov. 28, 1919. Repr. in CPAE, Vol. 7, Doc. 25.
— (1920). *Äther und Relativitätstheorie.* Rede gehalten am 5. Mai 1920 an der Reichs-Universität zu Leiden. Berlin: Springer, 1920. Repr. in CPAE, Vol. 7, Doc. 38.
Einstein, Albert et al. (1920). “Discussion following Weyl, ‘Elektrizität und Gravitation’ [Weyl, 1920b].” *Physikalische Zeitschrift* 21, 650–651.
Einstein, Albert (1921a). “Geometrie und Erfahrung.” Lecture before the Prussian Academy of Sciences, January 27, 1921. *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Halbband 1, 123–130. repr. as: *Geometrie und Erfahrung.* Erweiterte Fassung des Festvortrages gehalten an der Preussischen Akademie der Wissenschaften zu Berlin am 27. Januar 1921. Berlin: Springer, 1921. Repr. in CPAE, Vol. 7, Doc. 52.
— (1921b). “Über eine naheliegende Ergänzung des Fundamentes der allgemeinen Relativitätstheorie.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Halbband 1, 261–264. Repr. in CPAE, Vol. 7, Doc. 54.
— (1923a). “Grundgedanken und Probleme der Relativitätstheorie.” In: *Les Prix Nobel en 1921-1922.* Ed. by Carl Gustaf Santesson. Stockholm: Nobel Foundation, 1923, 1–10. Nobel prize lecture, delivered before the Nordische Naturforscherversammlung in Göteborg July 11, 1923.
— (1923b). “The theory of the affine field.” *Nature* 2812, 448–449. Repr. in CPAE, Vol. 14, Doc. 123.
— (1923c). “Zur affinen Feldtheorie.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 137–140. Repr. in CPAE, Vol. 14, Doc. 52.
— (1923d). “Zur allgemeinen Relativitätstheorie.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 32–38, 76–77. Repr. in CPAE, Vol. 13, Doc. 425.
— (1924). “Review of Elsbach, *Kant und Einstein* [Elsbach, 1924].” *Deutsche Literaturzeitung* 45, 1685–1692. Repr. in CPAE, Vol. 14, Doc. 321.
— (1925a). “Einheitliche Feldtheorie von Gravitation und Elektrizität.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 414–419. Repr. in CPAE, Vol. 15, Doc. 17.
— (1925b). “Nichteuklidische Geometrie und Physik.” *Die neue Rundschau* 36, 16–20. Repr. in CPAE, Vol. 14, Doc. 220.
— (1926). *Space-time.* In: *Encyclopædia Britannica.* Ed. by James Louis Garvin. 13th ed. London/New York: Encyclopædia Britannica, Inc., 1926, 608–609. Repr. in CPAE, Vol. 15, Doc. 148.
— (1927a). “Über die formale Beziehung des Riemannschen Krümmungstensors zu den Feldgleichungen der Gravitation.” *Mathematische Annalen* 97, 99–103.
— (1927b). “Zu Kaluzas Theorie des Zusammenhanges von Gravitation und Elektrizität.” Erste Mitteilung. *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 23–25.
— (1927c). “Zu Kaluzas Theorie des Zusammenhanges von Gravitation und Elektrizität.” Zweite Mitteilung. *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 26–30.
— (1928a). “A propos de ‘La Déduction Relativiste’ de M. Émile Meyerson [Meyerson, 1925].” *Revue philosophique de la France et de l’étranger* 105, 161–166.
— (1928b). “Neue Möglichkeit für eine einheitliche Feldtheorie von Gravitation und Elektrizität.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 224–227. Repr. in CPAE, Vol. 16, Doc. 259.
— (1928c). “Review of Reichenbach, *Philosophie der Raum-Zeit-Lehre* [Reichenbach, 1928a].” *Deutsche Literaturzeitung* 49, 19–20.
— (1928d). “Riemann-Geometrie mit Aufrechterhaltung des Begriffes des Fernparallelismus.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 217–221. Repr. in CPAE, Vol. 16, Doc. 256.
— (1929a). “Einstein explains his new discoveries.” *New York Times.* Feb. 3, 1929.
— (1929b). “The new field theory.” *London Times.* Feb. 4, 1929.
— (1929c). *Über den gegenwärtigen Stand der Feldtheorie.* In: *Festschrift zum 70. Geburtstag von Prof. Dr. A. Stodola.* Ed. by Emil Honegger. Zürich/Leipzig: Füssli, 1929, 126–132. Repr. in CPAE, Vol. 16, Doc. 313.
— (1929d). “Zur einheitlichen Feldtheorie.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 2–7. Repr. in CPAE, Vol. 16, Doc. 525.
— (1930a). “Das Raum-, Feld- und Äther-Problem in der Physik.” *Koralle* 5, 486–487.
— (1930b). “Das Raum-, Feld- und Äther-Problem in der Physik.” *Gesamtbericht, Zweite Weltkraftkonferenz* 19, 1–5.
— (1930c). “Raum, Äther und Feld in der Physik.” *Forum Philosophicum* 1, 173–180. tr. in the same volume, 180–184.
— (1930d). “The New Field Theory.” *The Observatory* 52, 82–87, 114–118. Repr. in CPAE, Vol. 16, Doc. 387.
— (1930e). “Théorie unitaire du champ physique.” *Annales de l’institut henri poincaré* 1, 1–24.
— (1932). “Gegenwärtiger Stand der Relativitätstheorie.” Nach einem von ihm am 14. Oktober im Physikalischen Institut der Wiener Universität gehaltenen Votrage. *Die Quelle* 82, 440–442.
— (1933a). *On the method of theoretical physics.* The Herbert Spencer Lecture, delivered at Oxford, June 10, 1933. Oxford: Clarendon Press, 1933. See Einstein, 1933b for the original German.
— (1933b). *Zur Methode der theoretischen Physik.* EA, 1114.1.
— (1949a). “Remarks concerning the essays brought together in this co-operative volume.” In: *Albert Einstein. Philosopher-scientist.* Ed. by Paul Arthur Schilpp. Evanston, Ill.: The Library of Living Philosophers, 1949, 665–688.
Einstein, Albert (1949b). *Unpub. Reply to H. Reichenbach.* EA, 2058.
— (1950). *On the General theory of Gravitation.* EA, 1155.1.
Einstein, Albert and Bruria Kaufman (1955). “A new form of the general relativistic field equations.” *The Annals of Mathematics* 62, 128.
Einstein, Albert and Walther Mayer (1930). “Zwei strenge statische Lösungen der Feldgleichungen der einheitlichen Feldtheorie.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften.* Physikalisch-mathematische Klasse, 110–120.

— (1931). “Einheitliche Theorie von Gravitation und Elektrizität.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften*. Physikalisch-mathematische Klasse, 541–557.

Elsbach, Alfred Coppel (1924). *Kant und Einstein. Untersuchungen über das Verhältnis der modernen Erkenntnistheorie zur Relativitätstheorie.* Berlin: de Gruyter, 1924. Repr. in CPAE, Vol. 14, Doc. 321.

Frank, Philipp (1947). *Einstein. His life and times.* New York: Knopf, 1947.

Freundlich, Erwin (1920). “Zu dem Aufsatze ‘Die Physik als geometrische Notwendigkeit’ von Arthur Haas.” (Naturwissenschaften 1920, Heft 3). *Die Naturwissenschaften* 8, 234–235.

Friedman, Michael (2001). *Dynamics of reason. The 1999 Kant lectures at Stanford University.* Stanford, Calif.: CSLI Publ., 2001.

Giovanelli, Marco (2014). “‘But one must not legalize the mentioned sin. Phenomenological vs. dynamical treatments of rods and clocks in Einstein’s thought.” *Studies in history and philosophy of science. Part B: Studies in history and philosophy of modern physics* 48, 20–44.

— (2016a). “‘... But i still can’t get rid of a sense of artificiality’: the Einstein-Reichenbach debate on the geometrization of the electromagnetic field.” *Studies in history and philosophy of science. Part B: Studies in history and philosophy of modern physics* 54, 35–51.

— (2016b). “Hermann cohen’s *Das Princip der Infinitesimal-Methode*. The history of an unsuccessful book.” *Studies in history and philosophy of science* 58, 9–23.

— (2021). “‘Geometrization of physics’ vs. ‘physicalization of geometry’. The untranslated Appendix to reichenbach’s *Philosophie der Raum-Zeit-Lehre*.” In: *From philosophy of nature to physics. Logical empiricism and the natural sciences.* Ed. by Sebastian Lutz and Ádám Tamas Tuboly. London/New York: Roudlege, 2021, 224–261.

Haas, Arthur (1920). “Die Physik als geometrische Notwendigkeit.” *Die Naturwissenschaften* 8, 121–127.

Hecht, Hartmut and Dieter Hoffmann (1982). “Die Berufung Hans Reichenbachs an die Berliner Universität.” *Deutsche Zeitschrift für Philosophie* 30, 651–662.

Hentschel, Klaus (1982). “Zur Rolle Hans Reichenbachs in den Debatten um die Relativitätstheorie (mit der vollständigen Korrespondenz Reichenbach-Friedrich Adler im Anhang).” *Nachrichtenblatt der Deutschen Gesellschaft für Geschichte der Medizin, Naturwissenschaft & Technik* 3, 295–324.

— (1990). “Philosophical interpretations of relativity theory. 1910-1930.” *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association* 2, 169–179.

Kaluza, Theodor (1921). “Zum Unitätsproblem der Physik.” *Sitzungsberichte der Preußischen Akademie der Wissenschaften*, 966–972.

Lanczos, Cornel (1932). “Stellung der Relativitätstheorie zu anderen physikalischen Theorien.” *Die Naturwissenschaften* 20, 113–116.

Laue, Max von (1920). “Theoretisches über neuere optische Beobachtungen zur Relativitätstheorie.” *Physikalische Zeitschrift* 21, 659–662. Repr. in Laue, 1961, Vol. 1, Doc. 37.

— (1961). *Gesammelte Schriften und Vorträge.* 3 vols. Braunschweig: Vieweg, 1961.

Lehmkuhl, Dennis (2014). “Why Einstein did not believe that general relativity geometrizes gravity.” *Studies in history and philosophy of science. Part B: Studies in history and philosophy of modern physics* 46, 316–326.

— (2017). “Introduction: towards a theory of spacetime theories.” In: *Towards a theory of spacetime theories.* Springer New York, 2017, 1–11.

Levi-Civita, Tullio (1916). “Nozione di parallelismo in una varietà qualunque e conseguente specificazione geometrica della curvatura riemanniana.” *Rendiconti del Circolo Matematico di Palermo (1884–1940)* 42, 173–204.

Mach, Ernst (1905). *Erkenntnis und Irrtum. Skizzen zur Psychologie der Forschung.* Leibzig: Barth, 1905.

Meyerson, Émile (1925). *La déduction relativiste.* Paris: Payot, 1925.

Padovani, Flavia (2009). “Relativizing the relativized a priori. Reichenbach’s axioms of coordination divided.” *Synthese* 181, 41–62.

Pais, Abraham (1982). *Subtle is the Lord. The science and the life of Albert Einstein.* New York: Oxford University Press, 1982.

Pauli, Wolfgang (1919). “Zur Theorie der Gravitation und der Elektrizität von Hermann Weyl.” *Physikalische Zeitschrift* 20, 457–467.

— (1921). *Relativitätstheorie.* In: *Enzyklopädie der mathematischen Wissenschaften.* Ed. by Arnold Sommerfeld. Vol. 5: Physik, Part 2. Leipzig: Teubner, 1921, 539–775. Repr. as *separatum* in: *Relativitätstheorie.* Leipzig: Teubner, 1921.

— (1926). “Review of Eddington, *The Mathematical Theory of Relativity* [Eddington, 1923].” *Die Naturwissenschaften* 13, 273–274.

— (1958). *Theory of relativity.* London: Pergamon Press, 1958.

Reichenbach, Hans (1916). *Der Begriff der Wahrscheinlichkeit für die mathematische Darstellung der Wirklichkeit.* Leipzig: Barth, 1916.

— (1920a). “Die Einsteinsche Raumlehre.” *Die Umschau* 24, 402–405.

— (1920b). *Relativitätstheorie und Erkenntnis apriori.* Berlin: Springer, 1920. Repr. in Reichenbach, 1977, Vol. 3, 191–332.

— (1921a). “Bericht über eine Axiomatik der Einsteinschen Raum-Zeit-Lehre.” *Physikalische Zeitschrift* 22, 683–687.

— (1921b). “Erwiderung auf H. Dinglers Kritik an der Relativitätstheorie.” *Physikalische Zeitschrift* 22, 370–384.

— (1922a). “Der gegenwärtige Stand der Relativitätsdiskussion. Eine kritische Untersuchung.” *Logos* 22, 316–378. Repr. in Reichenbach, 1977, Vol. 3, 375–406.

— (1922b). “Der gegenwärtige Stand der Relativitätsdiskussion. Eine kritische Untersuchung.” *Logos* 22, 316–378. Repr. in Reichenbach, 1977, Vol. 3, 375–406.

— (1922c). “La signification philosophique de la théorie de la relativité.” *Revue philosophique de la France et de l’étranger* 93, 5–61.

— (1924). *Axiomatik der relativistischen Raum-Zeit-Lehre.* Vieweg: Braunschweig, 1924. Repr. in Reichenbach, 1977, Vol. 3, 3–171.

Reichenbach, Hans (1925). “Über die physikalischen Konsequenzen der relativistischen Axiomatik.” *Zeitschrift für Physik* 34, 32–48. Repr. in Reichenbach, 1977, Vol. 3, 172–183.

— (1926a). “Die Weylsche Erweiterung des Riemannschen Raumes und die geometrische Deutung der Elektrizität.” *Verhandlungen der Deutschen Physikalischen Gesellschaft* 7, 25.

— (1926b). “Zur einheitlichen Feldtheorie von Gravitation und Elektrizität.” 1926. (HR, 025-25-010).

— (1928a). *Philosophie der Raum-Zeit-Lehre.* Berlin/Leipzig: Walter de Gruyter, 1928. Repr. in Reichenbach, 1977, Vol. 2.
— (1928b). "Zum Tode von H. A. Lorentz." *Berliner Tageblatt.* Feb. 6, 1928.
— (1928c). "Zur Einordnung des neuen Einsteinschen Ansatzes über Gravitation und Elektrizität." 1928. EA, 20-093.
— (1929a). "Allgemeine Grundlagen der Physik." In: *Ziele und Wege der physikalischen Erkenntnis.* Vol. 4: *Handbuch der Physik.* Ed. by Hans Geiger and Karl Scheel. 2nd ed. Berlin: Springer, 1929, 1–80.
— (1929b). "Die neue Theorie Einsteins über die Verschmelzung von Gravitation und Elektrizität." *Zeitschrift für Angewandte Chemie* 42, 121–123.
— (1929c). "Einstein's neue Theorie." *Vossische Zeitung.* Jan. 25, 1929. Engl. trans. as 'Einstein's New Theory', in Reichenbach, 1978, Vol. 1, Doc. 26.
— (1929d). "Zur Einordnung des neuen Einsteinschen Ansatzes über Gravitation und Elektrizität." *Zeitschrift für Physik* 53, 683–689.
— (1958). *The philosophy of space and time.* Ed. by Maria Reichenbach. Trans. by Maria Reichenbach and John Freund. New York: Dover Publ., 1958.
— (1969). *Axiomatization of the theory of relativity.* Ed. and trans. by Maria Reichenbach. With a forew. by Wesley C. Salmon. Berkeley: University of California Press, 1969.
— (1977). *Gesammelte Werke in 9 Bänden.* Ed. by Andreas Kamlah and Maria Reichenbach. Braunschweig/Wiesbaden: Vieweg, 1977.
— (1978). *Selected writings. 1909–1953.* Ed. and trans. by Maria Reichenbach. 2 vols. Dordrecht: Reidel, 1978.
Ryckman, Thomas (1995). "Weyl, Reichenbach and the epistemology of geometry." *Studies in history and philosophy of science* 25, 831–870.
— (1996). *Einstein agonists. Weyl and Reichenbach on geometry and the general theory of relativity.* In: *Origins of logical empiricism.* Ed. by Ronald N. Giere. Minneapolis: University of Minnesota Press, 1996, 165–209.
— (2017). *Einstein.* New York: Routledge, 2017.
Sauer, Tilman (2014). "Einstein's unified field theory program." In: *The Cambridge companion to Einstein.* Ed. by Michel Janssen and Christoph Lehner. Cambridge: Cambridge University Press, 2014, 281–305.
Schilpp, Paul Arthur, ed. (1944). *The philosophy of Bertrand Russell.* Evanston: The Library of Living Philosophers, 1944.
— ed. (1949). *Albert Einstein. Philosopher-scientist.* Evanston, M.: The Library of Living Philosophers, 1949.
Schlick, Moritz (1918). *Allgemeine Erkenntnisslehre.* Berlin: J. Springer, 1918. Repr. in Schlick, 2006, Vol. 1.
— (2006). *Gesamtausgabe.* Ed. by Friedrich Stadler and Hans Jürgen Wendel. Berlin: Springer, 2006.
Schouten, Jan Arnoldus (1922). "Über die verschiedenen Arten der Übertragung in einer n-dimensionalen Mannigfaltigkeit, die einer Differentialgeometrie zugrundegelegt werden kann." *Mathematische Zeitschrift* 13, 56–81.
Speziali, Pierre, ed. (1972). *Albert Einstein-Michele Besso. Correspondance 1903–1955.* Paris: Hermann, 1972.
Verhaegh, Sander (2020). "Coming to america: carnap, reichenbach, and the great intellectual migration. II: hans reichenbach." *Journal for the history of analytical philosophy.* Forthcoming.
Vizgin, Vladimir Pavlovich (1994). *Unified field theories in the first third of the 20th century.* Trans. by Julian B. Barbour. Boston, Basel/Stuttgart: Birkhäuser, 1994.
Weyl, Hermann (1918a). "Gravitation und Elektrizität." *Sitzungsberichte der Preußischen Akademie der Wissenschaften,* 465–480. Repr. in Weyl, 1968, Vol. 2, Doc. 31.
— (1918b). *Raum–Zeit–Materie. Vorlesungen über allgemeine Relativitätstheorie.* Berlin: Springer, 1918.
— (1918c). "Reine Infinitesimalgeometrie." *Mathematische Zeitschrift* 2, 384–411. Repr. in Weyl, 1968, Vol. 2, Doc. 30.
— (1919a). "Eine neue Erweiterung der Relativitätstheorie." *Annalen der Physik.* 4th ser. 59, 101–133. Repr. in Weyl, 1968, Vol. 2, Doc. 34.
— (1919b). *Raum–Zeit–Materie. Vorlesungen über allgemeine Relativitätstheorie.* 3rd ed. Berlin: Springer, 1919.
— (1920a). "Die Diskussion über die Relativitätstheorie." *Die Umschau* 24, 609–611.
— (1920b). "Elektrizität und Gravitation." *Physikalische Zeitschrift* 21, 649–650. Repr. in Weyl, 1968, Vol. 2, Doc. 40.
— (1921a). "Das Raumproblem." *Jahresbericht der Deutschen Mathematikervereinigung* 30, 92–93.
— (1921b). "Electricity and gravitation." *Nature* 106, 800–802. Repr. in Weyl, 1968, Vol. 2, Doc. 48.
— (1921c). "Feld und Materie." *Annalen der Physik.* 4th ser. 65, 541–563. Repr. in Weyl, 1968, Vol. 2, Doc. 47.
— (1921d). *Raum–Zeit–Materie. Vorlesungen über allgemeine Relativitätstheorie.* 4th ed. Berlin: Springer, 1921.
— (1921e). "Über die physikalischen Grundlagen der erweiterten Relativitätstheorie." *Physikalische Zeitschrift* 22, 473–480. Repr. in Weyl, 1968, Vol. 2, Doc. 46.
— (1921f). "Zur Infinitesimalgeometrie. Einordnung der projektiven und konformen Auffassung." *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen.* Mathematisch-physikalische Klasse, 99–112. Repr. in Weyl, 1968, Vol. 2, Doc. 43.
— (1923). *Mathematische Analyse des Raumproblems.* Vorlesungen gehalten in Barcelona und Madrid. Berlin: Springer, 1923.
— (1924). "Review of Reichenbach, *Axiomatik der relativistischen Raum-Zeit-Lehre* [Reichenbach, 1924]." *Deutsche Literaturzeitung* 45, 2122–2128.
— (1929). "Elektron und Gravitation." *Zeitschrift für Physik* 56, 330–352. Repr. in Weyl, 1968, Vol. 3, Doc. 85.
— (1931). "Geometrie und Physik." *Die Naturwissenschaften* 19, 49–58. Repr. in Weyl, 1968, Vol. 3, Doc. 93.
— (1968). *Gesammelte Abhandlungen.* Ed. by Komaravolu Chandrasekharan. 4 vols. Berlin: Springer, 1968.
Wünsch, Daniela (2005). "Einstein, kaluza, and the fifth dimension." In: *The universe of general relativity.* Ed. by A. J. Kox and Jean Eisenstaedt. Boston: Birkhäuser, 2005, 277–302.