Epistemology of General Relativity

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Early philosophical interpretations of the general theory of relativity are very diverse, each trying to identify Einstein as a follower of that philosophy. Mach's supporters highlighted Einstein's attempt to implement a "relativization of inertia" in general relativity (GR), and his operationalist approach to simultaneity. Kantians and neo-Kantians have shown the importance of synthetic "intellectual forms" in GR, especially the principle of general covariance. Logical empiricists have emphasized the methodology of theory, the conventions to express the empirical content. [1]

Bertrand Russell noted that

> "There has been a tendency, not uncommon in the case of a new scientific theory, for every philosopher to interpret the work of Einstein in accordance with his own metaphysical system, and to suggest that the outcome is a great accession of strength to the views which the philosopher in question previously held. This cannot be true in all cases; and it may be hoped that it is true in none. It would be disappointing if so fundamental a change as Einstein has introduced involved no philosophical novelty." [2]

Most of Einstein's early work reveals that he is a supporter of Ludwig Boltzmann, rather than Ernst Mach, in the debate on atomism[3]. However, in 1912, Einstein's name was displayed among those who joined Mach in a call to form a "Society for Positivist Philosophy." At the end of his life, Einstein wrote about the "profound influence" exerted on him by Mach's School of Mechanics, and about the very high influence from youth of "Mach's epistemological position." [4] The occasional epistemological and methodological statements seem to indicate agreement with the essential parts of Mach's positivist doctrine[5]. Mach's idea that the mass and inertial motion of the body results from the influence of all other surrounding masses was probably the strongest motivation for developing a relativistic theory of gravity. [6]

A passage from Einstein's first full exposition showed that his general covariance requirement for the equations of the gravitational field (meaning that they remain unchanged under arbitrary, but continuously adequate change of spacetime coordinates), "takes away from space and time the last remnant of physical objectivity". Josef Petzoldt, a Machian philosopher, noted that Einstein is best

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[1] Thomas A. Ryckman, "Early Philosophical Interpretations of General Relativity," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2018 (Metaphysics Research Lab, Stanford University, 2018), https://plato.stanford.edu/archives/spr2018/entries/genrel-early/.

[2] Bertrand Russell, *Relativity: Philosophical Consequences, in Encyclopaedia Britannica: Thirteenth Edition Volume 31* (ENCYCLOPAEDIA BRITTANICA PRESS, 1926), 331.

[3] Thomas Ryckman, *Einstein*, 1 edition (London ; New York: Routledge, 2011), chap. 3.

[4] Albert Einstein, "Autobiographische Skizze," in *Helle Zeit — Dunkle Zeit: In memoriam Albert Einstein*, ed. Carl Seelig (Wiesbaden: Vieweg+Teubner Verlag, 1956), 21, https://doi.org/10.1007/978-3-322-84225-1_2.

[5] Albert Einstein, *Über die spezielle und die allgemeine Relativitätstheorie*, 23. Aufl. 2001. Nachdruck (Berlin: Springer, 2002).

[6] Ryckman, "Early Philosophical Interpretations of General Relativity."

characterized as a relativist positivist[7]. Contemporary philosophy has shown that Einstein's remarks were merely elliptical references to an "hole argument," according to which if a theory is in general covariant, the empty points of the spacetime manifestation cannot have an inherent primitive identity, and therefore no independent reality[8]. Thus, for a general covariant theory, no physical reality accumulates in the "empty space" in the absence of the physical fields, ideas that it is not a support for positivist phenomenalism.

The relativization of all inertial effects ("Mach's principle"), together with the principle of general relativity interpreted by Einstein as the principle of general covariance, and with the principle of equivalence, were considered by Einstein the three pillar principles on which his theory was based.

The retrospective portraits of Einstein's methodology in the genesis of general relativity focus on the idea of a strategy that takes into account mathematical aesthetics[9]. The positivists and the operationalists have argued with Einstein's analysis of simultaneity as a fundamental methodological element of the theory of relativity.

The Kantian philosophers did not pay much attention to the theory of relativity. Cassirer sees the general theory of relativity as a confirmation of the fundamental principles of transcendental idealism[10]. Natorp[11] appreciated the principle of relativity as being consistent with Kantianism by distinguishing between ideal, purely mathematical transcendental concepts of space and time and their relative physical measurements. From this relativization, says Natorp, it follows that " events are ordered, not in relation to an absolute time, but only as lawfully determined phenomena in mutual temporal relation to one another, a version of Leibnizian relationism." [12] Also, the constancy of the speed of light, considered an empirical presupposition, "reminded that absolute determinations of these measures, unattainable in empirical natural science, would require a correspondingly absolute bound." [13] Natorp considered the invariant requirement of the laws of

[7] Joseph Petzoldt, Giora Hon, and Ernst Mach, *Der Verhältnis der Machschen Gedankenwelt zur Relativitätstheorie, an appendix to Die Mechanik in ihrer Entwicklung: Historisch-kritisch dargestellt* (Xenomoi Verlag, 1921), 516.

[8] John D. Norton, "General Covariance and the Foundations of General Relativity: Eight Decades of Dispute," *Reports of Progress in Physics* 56 (1993): 791–858.

[9] Thomas Ryckman, "A Believing Rationalist," The Cambridge Companion to Einstein, May 2014, 377–420, https://doi.org/10.1017/CCO9781139024525.014.

[10] Ernst Cassirer, W. C. Swabey, and M. C. Swabey, *Substance and Function and Einstein's Theory of Relativity* (Courier Corporation, 2003), 172–73.

[11] Paul Natorp, *Die logischen Grundlagen der exakten Wissenschaften* (Sändig Reprint, H. R. Wohlwend, 1910), 399–404.

[12] Ryckman, "Early Philosophical Interpretations of General Relativity."

[13] Ryckman.

nature regarding Lorentz transformations as "perhaps the most important result of Minkowski's investigation." [14]

A number of neo-Kantian positions, including Marburg's and Bollert's[15], have argued that relativity theory has clarified the Kantian position in transcendental aesthetics by showing that not space and time, but spatiality (determinism in the positional order) and temporality (in the order of succession).) are *a priori* conditions of physical knowledge. This revision of the conditions of objectivity is essential for critical idealism.

The most influential neo-Kantian interpretation of general relativity was Ernst Cassirer's *Zur Einsteinschen Relativitätstheorie*[16], in which the theory is considered to be a crucial test for *Erkenntniskritik* (the epistemology of the physical sciences of Marburg's transcendental idealism). Recognizing the requirement of general covariance, Cassirer stated that the general theory of relativity, with the coordinates of space and time, represents only "labels of events (“coincidences”), independent variables of the mathematical (field) functions characterizing physical state magnitudes." [17] The general covariance would be the most recent refinement of the methodological principle of the "unit of determination" which determines the physical knowledge by moving from concepts of substance to functional and relational concepts. Cassirer concluded that the general theory of relativity presents "the most determinate application and carrying through within empirical science of the standpoint of critical idealism." [18]

E. Sellien[19] stated that Kant's views on space and time refer only to intuitive space, and thus were impervious to the space and time measurable of Einstein's empirical theory.

The logical empiricism of the philosophy of science has emerged largely as a result of Einstein's two theories of relativity, favoring conventionalism à la Poincaré over neo-Kantianism and Machian positivism. The philosophy of logical empiricism of science itself is considered to have been formed from the lessons learned from the theory of relativity. Some of the most characteristic doctrines of this philosophy (interpreting *a priori* elements in physical theories as conventions, dealing with the necessary role of conventions in developing theoretical concepts from observation, insisting on observational language in defining theoretical terms) were used by Einstein in modeling those two theories of relativity. [20]

[14] Natorp, *Die logischen Grundlagen der exakten Wissenschaften*, 403.

[15] Karl Bollert, *Einstein's Relativitätstheorie und ihre Stellung im System der Gesamterfahrung* (T. Steinkopf, 1921).

[16] Ernst Cassirer, *Zur Einstein'schen relativitätstheorie: Erkenntnistheoretische betrachtungen* (B. Cassirer, 1921), 1–125.

[17] Ryckman, “Early Philosophical Interpretations of General Relativity.”

[18] Cassirer, Swabey, and Swabey, *Substance and Function and Einstein's Theory of Relativity*, 412.

[19] Ewald Sellien, *Die erkenntnistheoretische Bedeutung der Relativitätstheorie* (Christian-Albrechts-Universität zu Kiel, 1919).

[20] Ryckman, “Early Philosophical Interpretations of General Relativity.”

Reichenbach developed the thesis of "the relativity of geometry", that an arbitrary geometry for spacetime can be developed if the laws of physics are modified accordingly by the introduction of "universal forces". But Reichenbach's first work on relativity[21] was written from a neo-Kantian perspective. According to Friedman[22] and Ryckman[23], Reichenbach modified the Kantian conception of synthetic *a priori* principles, rejecting the meaning of "valid for all time", while retaining the "constitutive of the object (of knowledge)", resulting in a specific "relativized *a priori*" theory. Thus, a transformation appears in the method of epistemological research of science whereby the method of analyzing science is proposed as "the only way that affords us an understanding of the contribution of our reason to knowledge." [24] The methodology of rationalization implies the clear distinction between the subjective role of the principles and the contribution of the objective reality. Relativity theory is a shining example of this method because it showed that the spacetime metric describes an "objective property" of the world, once the subjective freedom of coordinate transformation (the coordinating principle of general covariance) is recognized. [25] [26]

Einstein, in a January 1921 lecture entitled "Geometry and Experience", argued that the question of the nature of spacetime geometry is an empirical problem only with respect to certain stipulations. Reichenbach's conventional conception reached maturity in 1922. Reichenbach argued that problems regarding the empirical determination of the spacetime metric must take into account the fact that both geometry and physics support the observational test, this being the case in the Einstein's general relativity(Reichenbach's method has been called the "logical analysis of science.") Thus, the empirical determination of the spacetime metric by measurement requires the choice of "metric indicators" by establishing a coordinating definition. Einstein, together with Schlick and Reichenbach, developed a new form of empiricism, suitable for arguing general relativity against neo-Kantian criticism. [27] [28]

Einstein implemented a relational or relativistic conception of the movement, in accordance with Leibniz's relationalist attitude to space and time and in contrast to Newton's absolutist attitude. By this, constraints are placed on the ontology of the spacetime theories, limiting the field in which the quantifiers of the theories are located to the set of physical events, that is, in the set of spacetime

[21] Hans Reichenbach, *Relativitätstheorie Und Erkenntnis Apriori* (J. Springer, 1920).

[22] Michael Friedman, "Geometry, Convention, and the Relativized A Priori: Reichenbach, Schlick, and Carnap," Reconsidering Logical Positivism, July 1999, 21–34, https://doi.org/10.1017/CBO9781139173193.006.

[23] Thomas Ryckman, *The Reign of Relativity: Philosophy in Physics 1915-1925*, 1 edition (Oxford ; New York: Oxford University Press, 2005).

[24] Reichenbach, *Relativitätstheorie Und Erkenntnis Apriori*, 74.

[25] Reichenbach, 90.

[26] Ryckman, "Early Philosophical Interpretations of General Relativity."

[27] Moritz Schlick, "Kritizistische Oder Empiristische Deutung Der Neuen Physik?," *Société Française de Philosophie, Bulletin* 26, no. n/a (1921): 96.

[28] Hans Reichenbach, *Philosophie der Raum-Zeit-Lehre*, 1 Plate (De Gruyter, 1928).

points that are actually occupied by objects or material processes[29]. Reichenbachian relations, on the other hand, impose constraints on the ideology of spacetime theories, limiting the vocabulary to a certain set of preferred predicates, such as predicates defined in terms of "causal" relations.

Conventionalism, like relationalism, is skeptical of the structures postulated by spacetime theories. It raises the problem of geometric (metric) properties and relations defined in this field. Friedman asserts that conventionalism is closely linked to ideological relationalism. Basic conventionalism argues that certain incompatible description systems at first glance, such as Euclidean and non-Euclidean geometries, are in fact "equivalent descriptions" of the same facts, both of which may be true in relation to the various "coordinative definitions" chosen arbitrarily. This represents an epistemological problem in choosing between competing theories, resulting in a problem of theoretical underdetermination. Thus, Friedman asserts that relativity theory seems to be based on a conception of "equivalent descriptions" derived directly from the conventionalist strategy[30]. The development of relativity theory is based on a methodology from the perspective of the theoretical unification process.

A decade after the emergence of the general theory of relativity, there was talk of a reduction of physics to geometry[31], leading to distinct philosophical problems, of methodology but also of epistemology and metaphysics, along with technical issues. This implicit reduction of physics to geometry was obtained crucial in the epistemological framework of what Hilbert called the "axiomatic method." [32]

After completing general relativity, Einstein attempted to develop a theory that unified gravity and electromagnetism, by generalizing Riemannian geometry or adding additional dimensions, but excluding the reduction of physics to geometry[33]. Until 1925 he invented the first geometric "unified field theories"[34]. None of these efforts were successful. In his research program for geometric unification, Einstein's research methodology underwent a dramatic change[35], relying

[29] Michael Friedman, *Foundations of Space-Time Theories: Relativistic Physics and Philosophy of Science* (Princeton University Press, 1983).

[30] Friedman.

[31] Oliver Lodge, "The Geometrisation of Physics, and Its Supposed Basis on the Michelson-Morley Experiment," News, Nature, 1921, 795–802, https://doi.org/10.1038/106795a0.

[32] K. A. Brading and T. A. Ryckman, "Hilbert's 'Foundations of Physics': Gravitation and Electromagnetism within the Axiomatic Method," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 39, no. 1 (January 1, 2008): 102–153, https://doi.org/10.1016/j.shpsb.2007.08.002.

[33] Marco Giovanelli, "The Forgotten Tradition: How the Logical Empiricists Missed the Philosophical Significance of the Work of Riemann, Christoffel and Ricci," *Erkenntnis* 78, no. 6 (December 1, 2013): 1219–1257, https://doi.org/10.1007/s10670-012-9407-2.

[34] Tilman Sauer, "Einstein's Unified Field Theory Program," The Cambridge Companion to Einstein, May 2014, 281–305, https://doi.org/10.1017/CCO9781139024525.011.

[35] Ryckman, *Einstein*, chaps. 9, 10.

more and more on "mathematical aesthetics, of "logical simplicity", and the inevitability of certain mathematical structures under various constraints, adopted essentially for philosophical reasons." [36]

The mathematician Hermann Weyl, in 1918, attempted to reconstruct Einstein's theory on the basis of epistemology of "pure infinitesimal geometry." [37]

In December 1921, the Berlin Academy published Theodore Kaluza's new proposal on the unification of gravity and electromagnetism based on a five-dimensional Riemannian geometry.

All attempts to geometry the physics in the unified program accepted the ability of mathematics to understand the fundamental structure of the outer world. Thus, the program of the geometrically unified field seems thus to be framed in a form of scientific realism called "structural realism", with a Platonic hue. A form of "structural realism" assumes that no matter the intrinsic character or nature of the physical world, only its structure can be known. This version was supported by Russell, who included the general theory of relativity in this framework. [38]

In its contemporary form, structural realism has both an epistemic and an "ontic" form, in which the structural features of the physical world are ontologically fundamental[39]. Thomas A. Ryckman asserts that geometric unification theories fit this kind of realism. For Weyl and Eddington, "geometrical unification was an attempt to cast the harmony of the Einstein theory of gravitation in a new epistemological and so, explanatory, light, by displaying the field laws of gravitation and electromagnetism within the common frame of a geometrically represented observer-independent reality." [40]

Regarding the geometry of physics, there has been a permanent controversy over the conventions in science[41], and whether the choice of geometry is empirical, conventional or *a priori*. Duhem[42] states that hypotheses cannot be tested in isolation, but only as part of the theory as a whole (theoretical holism and underdetermination of choice of theory by empirical evidence). In a 1918 address to Max Planck, Einstein stated about underdetermination:

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[36] Ryckman, "Early Philosophical Interpretations of General Relativity."

[37] Hermann Weyl, Axel Hildebrand, and Dieter Schmalstieg, *Raum. Zeit. Materie: Vorlesungen über allgemeine Relativitätstheorie*, 7. (Berlin Heidelberg New York London Paris Tokyo: Springer, 1988), 115–16.

[38] Bertrand Russell, *The Analysis of Matter*, First Paperback Edition edition (Nottingham: Spokesman Books, 2007), 395.

[39] Pierre Maurice Marie Duhem, Jules Vuillemin, and Louis de Broglie, *The Aim and Structure of Physical Theory*, trans. Philip P. Wiener, 9932nd edition (Princeton: Princeton University Press, 1991).

[40] Ryckman, "Early Philosophical Interpretations of General Relativity."

[41] Paul Arthur Schilpp, ed., *Albert Einstein, Philosopher-Scientist: The Library of Living Philosophers Volume VII*, 3rd edition (La Salle, Ill.: Open Court, 1998).

[42] Duhem, Vuillemin, and Broglie, *The Aim and Structure of Physical Theory.*

> "The supreme task of the physicist is ... the search for the most general elementary laws from which the image of the world must be obtained by pure deduction. No logical path leads to these elementary laws; it is only intuition that is based on an empathetic understanding of experience. In this state of methodological uncertainty, it can be believed that many, in themselves, equivalent systems of theoretical principles are possible; and this opinion is, in principle, certainly correct. But the development of physics has shown that, out of all the theoretical imaginable constructions, only one, at any given moment, proved superior unconditionally to all the others. None of those who have delved into this subject will deny that, in practice, the world of perceptions unequivocally determines the theoretical system, even if no logical path leads from perceptions to the basic principles of theory." [43]

Einstein considered that the physical real implies exclusively what can be constructed on the basis of the spacetime coincidences, the spacetime points being considered as intersections of the world lines (the "point-coincidence argument")[44]. Coincidences thus have a privileged ontic role because they are invariable and therefore uniquely determined[45]. The force in the GR is also "geometrized"[46]. The spacetime metric in GR is reducible to the behavior of material entities (clocks, light beams, geodesics, etc.) [47]. It turns out that the measurement depends on the measuring instruments chosen as standards, and the metric relationships involve the chosen standards.

Paul Feyerabend considers Einstein as a methodological "opportunist or cynic", respectively a methodological anarchist[48]. Arthur Fine states that Einstein adopts a vision close to the natural ontological attitude[49]. van Frassen considered Einstein a constructive empiricist[50]. Nicholas Maxwell asserts that aim-oriented empiricism, as a new method of discovery, is Einstein's mature vision of science[51] to overcome a severe scientific crisis: the disappearance of classical physics as a result of Planck's quantum theory of 1900. Aim-oriented empiricism claims that science makes permanent assumptions about the nature of the universe, independent of empirical considerations.

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[43] Albert (Author) Einstein, "Motive des Forschens.," 1918, 31, http://alberteinstein.info/vufind1/Record/EAR000079148.

[44] Don A. Howard, "Einstein's Philosophy of Science," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Fall 2017 (Metaphysics Research Lab, Stanford University, 2017), https://plato.stanford.edu/archives/fall2017/entries/einstein-philscience/.

[45] Nicolae Sfetcu, *Singularitățile ca limite ontologice ale relativității generale* (MultiMedia Publishing, 2018), http://doi.org/10.13140/RG.2.2.17470.18242.

[46] Adolf Grünbaum, *Philosophical Problems of Space and Time: Second, Enlarged Edition* (Springer Science & Business Media, 2012).

[47] Paul Feyerabend, *Against Method* (London: New Left Books, 1975).

[48] Michael Esfeld and Vincent Lam, "Moderate Structural Realism About Space-Time," *Synthese* 160, no. 1 (2008): 18, 56–57, 213n.

[49] Arthur Fine, *The Shaky Game: Einstein, Realism, and the Quantum Theory* (University of Chicago Press, 1986), 9.

[50] Fine, 108.

[51] Nicholas Maxwell, *Karl Popper, Science and Enlightenment* (London: UCL Press, 2017).

Popper[52], as well as Kuhn[53] and Lakatos[54], defend versions of standard empiricism in Einstein's case.

Vincent Lam and Michael Esfeld support the concept of ontic structural realism (OSR), in which "spacetime is a physical structure in the sense of a network of physical relations among physical relata (objects) that do not possess an intrinsic identity independently of the relations in which they stand," [55] which can take into account the fundamental GR characteristics of diffeomorphism invariance[56] and background independence[57]. The localization within the OSR is dynamic and background independent, being invariant diffeomorphic, thus well coding the GR characteristic of background independence.

According to Don A. Howard, "Einstein's own philosophy of science is an original synthesis of elements drawn from sources as diverse as neo-Kantianism, conventionalism, and logical empiricism, its distinctive feature being its novel blending of realism with a holist, underdeterminationist form of conventionalism." [58]

There are a few central ideas to Einstein's philosophy:

- Underdetermination of the theoretical option through evidence.
- Simplicity and choice of theory.
- Univocity in the theoretical representation of nature.
- Realism and separability.
- Distinction between the theories of the principles and the constructive theories.

For Einstein, *simplicity* is the main criterion in the theoretical choice when the experiments and observations do not give sufficiently clear indications[59]. *Univocity* in the theoretical representation of nature should not be confused with a denial of the *underdetermination* thesis. The principle of

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[52] Karl Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge*, 2nd edition (London ; New York: Routledge, 2002).

[53] Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 3rd edition (Chicago, IL: University of Chicago Press, 1996).

[54] Imre Lakatos, *The Methodology of Scientific Research Programmes: Volume 1: Philosophical Papers* (Cambridge University Press, 1980).

[55] Vincent Lam and Michael Esfeld, "The Structural Metaphysics of Quantum Theory and General Relativity," *Journal for General Philosophy of Science / Zeitschrift Für Allgemeine Wissenschaftstheorie* 43, no. 2 (2012): 243–258.

[56] The diffeomorphism is a smooth and bijective mapping between differentiated manifolds whose inversion is also smooth.

[57] Esfeld and Lam, "Moderate Structural Realism About Space-Time."

[58] Howard, "Einstein's Philosophy of Science."

[59] John Norton, *How Einstein Found His Field Equations: 1912-1915*, 1984, 21, 23.

univocality played a central role in Einstein's formulation of general relativity, including in the elaboration of the "hole argument" which some physicists mistakenly considered. [60]

Many philosophers and scientists consider that Einstein's most important contribution to the philosophy of science was the distinction he made between principle theories and constructive theories. According to Einstein, a ***constructive theory*** offers a constructive model for phenomena of interest. A ***principle theory*** consists of a set of well-substantiated individual empirical generalizations. Einstein states that the final understanding requires a constructive theory, but progress in theory can be "impeded by premature attempts at developing constructive theories in the absence of sufficient constraints by means of which to narrow the range of possible of constructive." The role of principle theories is to provide constraints, and progress is made on the basis of such principles. *Einstein states that this was his methodology in discovering the theory of relativity as the main theory, the other two principles being the principle of relativity and the principle of light.*

It is worth noting the similarity between the idea of the "principle theories" as Einstein's constraints, and the "hard core" of Lakatos (negative heuristics) that would have been the sum of Einstein's "principle theories".

The distinction between principle theories and constructive theories has played an explicit role in Einstein's thinking. Harman noted that early versions of this distinction have been used since the 19th century, by James Clerk Maxwell. [61]

Einstein's equations are difficult to solve exactly, but there are currently several exact solutions, such as the Schwarzschild solution, the Reissner-Nordström solution and the Kerr metric, each corresponding to a certain type of black hole in an otherwise empty universe[62], and the Friedmann-Lemaître-Robertson-Walker and de Sitter universes, each describing an expanding cosmos[63]. Other exact solutions include the Gödel universe (with the possibility of spacetime travel), the Taub-NUT solution (a homogeneous but anisotropic universe) and the anti-de Sitter space (with the Maldacena conjecture) [64]. Due to the difficulty of these equations, solutions are currently being sought by numerical integration on a computer or by examining small perturbations of exact solutions. From the approximate solutions found by the disturbance theories is also part of the post-Newtonian extension, developed by Einstein, with a distribution of matter that moves slowly compared to the speed of light. A particularization of this extension is the *parameterized post-Newtonian formalism*, which allows quantitative comparisons between the predictions of general relativity and alternative theories.

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[60] P. M. Harman and Peter Michael Harman, *The Natural Philosophy of James Clerk Maxwell* (Cambridge University Press, 2001).

[61] Subrahmanyan Chandrasekhar, *The Mathematical Theory of Black Holes* (Clarendon Press, 1998).

[62] Jayant Vishnu Narlikar, *Introduction to Cosmology* (Jones and Bartlett, 1983).

[63] Albert Einstein, *The Principle of Relativity* (S.l.: BN Publishing, 2008), 78.

[64] Stephen W. Hawking et al., *The Large Scale Structure of Space-Time*, New Ed edition (Cambridge: Cambridge University Press, 1975).

By imposing the general covariance, all the spacetime checks assume a determination of the spacetime coincidences[65]. Schlick states that the passage from Einstein's 1916 paper dealing with this aspect represents the birth of the modern observation/theory distinction, and the beginning of empirical and truthful interpretations of later positivism[66].

Einstein hoped that general relativity would extend the relativity of motion from the Galilean equivalence to the equivalence of all states of motion, including rotation, based on the assumption that general covariance or equivalence of coordinate descriptions guarantees the desired equivalence. But by itself, general covariance is not such an argument, unable to solve the original problem of Einstein's relationship between movement. This problem is, in essence, one of geometric structure[67]. According to Disalle, Einstein made an epistemological confusion by accepting the idea that relative movements can be known independently of any spatial theory, in order to allow relative movements to have an epistemologically privileged position. Disalle concludes that classical relationalism, considered to be an epistemological critique of spacetime theory, is itself a spatial theory.

Riemann (1867) and Helmholtz (1870) stated that all geometric measurements depend on the physical assumptions underlying the measurement method, because empirical geometry must postulate not only a geometrical structure, but also a representation of an idealized physical process[68]. For Riemann, the connection between geometry and physics will have to be based on physical objects and more complicated processes. Such a connection implies a physical principle, an idea taken up by Einstein for the curvature of spacetime. [69]

Poincare stated that any measurement can agree with any geometry, if we eliminate the discrepancies by the hypothesis of a distorting force that affects the measuring instruments[70]. Reichenbach and Schlick systematized this concept by the notion of "coordinative definition", directing empiricism toward conventionalism, with a geometry with definitions that correlate

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[65] A. Einstein, “The Foundation of the General Theory of Relativity,” in *The Principle of Relativity. Dover Books on Physics. June 1, 1952. 240 Pages. 0486600815, p. 109-164*, 1952, 117, http://adsabs.harvard.edu/abs/1952prel.book..109E.

[66] Moritz Schlick, *Space and Time in Contemporary Physics: An Introduction to the Theory of Relativity and Gravitation* (Mineola, N.Y: Dover Publications, 2005).

[67] Robert Disalle, “Spacetime Theory as Physical Geometry,” *Erkenntnis* 42, no. 3 (1995): 317–337.

[68] Bernhard Riemann and Hermann Weyl, *Über die Hypothesen, welche der Geometrie zu Grunde liegen* (Berlin Heidelberg: Springer-Verlag, 1919), 133–52, https://www.springer.com/gp/book/9783662423165.

[69] Albert Einstein, *Geometrie und Erfahrung: Erweiterte Fassung des Festvortrages Gehalten an der Preussischen Akademie der Wissenschaften zu Berlin am 27. Januar 1921* (Berlin Heidelberg: Springer-Verlag, 1921), 123–30, https://www.springer.com/de/book/9783642499036.

[70] Henri Poincare, *The Foundations of Science; Science and Hypothesis, the Value of Science, Science and Method* (Place of publication not identified: TheClassics.us, 2013), 81–84.

fundamental concepts with an empirical given object[71] [72]. Thus, Reichenbach stated that: "the philosophical significance of the theory of relativity consists in the fact that it has demonstrated the necessity for metrical coordinative definitions in several places where empirical relations had previously been assumed." [73]

An example of this is simultaneity. Newtonian physics considered the simultaneity of events as an empirical fact, while Einstein imposed simultaneity as a physical principle. Since the speed of light was considered invariant, it turned out that simultaneity is relative. Disalle states that Einstein's definition of simultaneity is circular, since it already implies a principle of time measurement. Einstein denied, saying that the definition does not imply anything about light, the invariance of the speed of light being not a hypothesis, but "a stipulation that I can make according to my own free discretion, in order to achieve a definition of simultaneity." [74] Disalle concludes that the problem of the nature of spacetime is not whether a theoretical entity provides a causal explanation for appearances, but whether physical measurement processes are in accordance with geometrical laws. In conclusion, Reichenbach denies the role of geometry in explaining the root cause of spatial relations. [75]

But Einstein links spacetime not only with a certain procedure, but with a system of natural laws, the laws of electrodynamics, which he considers to be fundamental invariants. Thus the coordinative definition of the states of motion is a more subtle process than Reichenbach has proposed, implying not choosing a resting frame but establishing the laws of motion. In practice, the laws of motion have thus become, through coordinative definitions, postulates of the space-time geometry. [76]

According to Lakatos, Einstein's theory is no better than Newton's because of the refutation of Newton's theory: there are also "anomalies" of Einstein's theory. But this represents a breakthrough compared to Newton's theory, because he explained everything that successfully explained Newton's theory, and also explained the anomalies of that theory. In addition, he successfully predicted events about which Newton's theory said nothing.

[71] Hans Reichenbach, *The Philosophy of Space and Time*, 1st edition (New York, NY: Dover Publications, 1957).

[72] Moritz Schlick, *Allgemeine Erkenntnislehre: Abteilung I / Band 1*, ed. Hans Jürgen Wendel and Fynn Ole Engler, Abteilung I: Veröffentlichte Schriften (Wien: Springer-Verlag, 2009), https://www.springer.com/gp/book/9783211327685.

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