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The Third Way to General Relativity

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Einstein and Mach in Context

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> If I let all things disappear from the world, then, according to Newton, the Galilean inertial space remains, while according to my view, *nothing* is left.
> Albert Einstein, 9 January 1916
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> Space, brought to light by the corporeal object, made a physical reality by Newton, has in the last few decades swallowed ether and time and seems about to swallow also the field and the corpuscles, so that it remains as the sole medium of reality.
> Albert Einstein, 1930

1. Introduction

The relationship between Einstein and Mach is often discussed as a prototypical case of the influence of philosophy on physics.[1] It is, on the other hand, notoriously difficult exactly to pinpoint such influences of philosophy on science, in particular with regard to modern physics. To a working scientist it must appear, in any case, as if the period in which such influences were effective belongs to the past. There seems to be little room left for philosophy in the practice of today's physics. It plays no part in the physics curriculum; and scholars who are at the same time active physicists and philosophers are rare exceptions. It almost seems as if only dead physicists could have been good philosophers, or at least, that the time of an exchange between philosophy and physics is definitely over. In view of this situation it may be appropriate to reexamine the mythical role that philosophy played for one of the founding heroes of modern physics, Albert Einstein. It is indeed conceivable that the disjoint remarks on philosophy which are dispersed in his oeuvre can be integrated to a coherent image of what may then rightly be called "his philosophy." But even if such a reconstruction should be successful and yield more than an eclectic collection of

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[1] The literature on this subject is considerable; for more or less comprehensive accounts, see among others: Blackmore 1992, Boniolo 1988, Borzeszkowski and Wahsner 1989, in particular pp. 49 - 64, Goenner 1981, Holton 1986, Chapter 7, Norton 1993b, Pais 1982, pp. 282-288, Pfister 1993, Reichenbach 1958, Sciama 1959, Sewell 1975, Stein 1977, Torretti 1978, Torretti 1983, pp. 194-202, Wolters 1987, as well as other literature quoted below. An earlier version of the present paper (in Italian) is found in Pisent and Renn 1994.

occasional reflections, the more decisive question of the utility of philosophy for his science would be left unanswered. In fact, Einstein as a philosopher may have been a rather different *persona* from Einstein the physicist, and having two souls in one breast would not be an atypical state of affairs for a German intellectual. In this paper I will therefore not undertake any systematic attempt at reconstructing his philosophy but rather limit myself to a case study of the interaction between philosophy and physics, reexamining the impact of Mach's philosophical critique of classical mechanics on Einstein's discovery of General Relativity.[2] Such a reexamination is made possible by newly discovered documentary evidence on Einstein's research as well as by the achievements of recent studies of the history of General Relativity.[3] Both factors contribute to an historical understanding of the relationship between Mach's philosophy and Einstein's physics that is not only richer in detail but also in context and hence able to reveal the alternatives available to the historical actors in the search for a new theory of gravitation.

The main result of the analysis presented below is that the theory of General Relativity can be seen to have emerged as the result of one among several possible strategies to deal with conceptual problems of classical physics, strategies which were worked out in different degrees in the course of the historical development. Since this development was, in other words, not completely determined by the intrinsic features of the scientific problems which the historical actors confronted, it is now possible to evaluate more clearly the external factors affecting the choice between different strategies. The approach pursued by Einstein can be characterized as a combination of field theoretical and mechanistic approaches shaped by his philosophical outlook on foundational problems of physics. In the following, two conclusions are drawn in particular, both of which will have to be substantiated by later detailed studies:

i) The heuristics under the guidance of which Einstein elaborated General Relativity was rooted in the heterogeneous conceptual traditions of classical physics. At least in its intermediate stages of development, the conceptual framework of Einstein's theory rather resembled the peculiar combination of field theoretic and mechanistic elements in

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[2] For Mach's critique, see Mach 1960.

[3] For the new evidence, see in particular the various volumes of the *Collected Papers of Albert Einstein* which have appeared. Recent historical studies of the development of General Relativity that are relevant to our purpose here include the many papers by Stachel and Norton (in particular Norton 1992b, 1993a, 1993b, and 1993c) as well as a recent paper by Hoefer (Hoefer 1994).

Lorentz’s electron theory than the coherent and self-contained conceptual framework of Special Relativity which then superseded the conceptual patchwork of Lorentz's theory.[4] Mach’s ideas were one element in this mixture of traditional conceptual frameworks; their interpretation by Einstein depended on the context provided by the other elements. In particular, the heuristic role of Mach’s ideas have to be seen in the wider context of the role which classical mechanics played for the emergence of General Relativity. Just as other heuristic elements, Mach’s ideas were eventually superseded by the conceptual consequences of General Relativity, as Einstein saw them. In particular, Mach’s concept of inertia as a property not of space but of the interaction between physical masses played a role comparable to that of the ether in Lorentz’s theory of electrodynamics: it introduced a helpful heuristics that was to lead to its own elimination since the conceptual preconditions of the development of General Relativity turned out to be incompatible with its outcome.

ii) What distinguished Einstein’s early approach to the problem of gravitation from that of his contemporaries was his refusal to accept that a mechanistic and a field theoretic outlook on physics were mutually exclusive alternatives. It was his philosophical perspective on foundational problems of physics which allowed him to conceive field theory and mechanics as complementary resources for the formulation of a new theory of gravitation. Contrary to most contemporary physicists dealing with the problem of gravitation, he attempted to incorporate in his new theory both foundational assumptions of classical mechanics and their critical revision by Mach; and contrary to most physicists searching for a physical implementation of Mach's analysis of the foundations of mechanics he took into account the antimechanistic philosophical intentions of this critique. Einstein's philosophical perspective is, however, not only characterized by his interest in and understanding of such philosophical intentions but even more by his integrative outlook on the conceptual foundations of physics. His peculiar approach to the specific problem of gravitation can only be understood if one acknowledges that for him, the problem of a new theory of gravitation was, at the same time, the problem of developing new conceptual foundations for the entire body of physics. Although it may not be common to label such an integrative perspective as "philosophical" - in view of the predominantly metatheoretical concerns of the philosophy of science -, it was also no longer a self-evident preoccupation of science at the beginning of this century, let alone of

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[4] See the reconstruction of the discovery of Special Relativity in Renn 1993.

science today. Be that as it may, the fruitfulness of Einstein's approach argues for its reconsideration by both philosophy and science.

In the following, I will first discuss how Einstein's project of generalizing the principle of relativity emerged in the context of his own research as well as in that of other contemporary approaches to the problem of gravitation (section 2); I will then examine some of the historical presuppositions of the conceptual innovation represented by General Relativity with particular attention to the contributions of mechanics and field theory to its development; the aim is to describe the horizon of possibilities open to the historical actors (section 3); I will next follow in some detail the influence of Mach's critique of classical mechanics on the creation and interpretation of General Relativity by Einstein (section 4); and I will finally come back to the question of Einstein's philosophical perspective on the foundational problems of physics and its role for the emergence of General Relativity (section 5).

2. A New Theory of Gravitation in the Context of Competing World Views

A relativistic theory of gravitation as a problem of "normal science"

When in 1907 Einstein first dealt with the problem of a relativistic theory of gravitation philosophical interests seemed to be a long way from the center of his concerns. Although he was employed by the Swiss patent office at that time, he was no longer an outsider to academic physics. By way of his publications, his correspondence, and his personal relationships he was already then becoming a well respected member of the physics establishment. The times had passed when philosophical readings in the mock "Olympia" academy, which Einstein had founded some years earlier together with other bohemian friends, formed one of the centers of his intellectual life. Einstein was first confronted with the task of revising Newton's classical theory of gravitation in the light of the relativity theory of 1905, when he was asked to write a review paper on relativity theory that would also have to cover its implications for various areas of physics not directly related to the electrodynamics of moving bodies which had been its birth place.[5] Hence the revision of Newton's theory of gravitation entered Einstein's intellectual horizon not as the consequence of a philosophically minded ambition to go beyond the original special theory towards a more general theory of relativity but as a necessity of the day, as part of the usual "mopping up

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[5] See Einstein 1907b, section V. See also Einstein's later recollections, e. g. those reported in Wheeler 1979, p. 188. For a historical discussion of this paper, see Miller 1992.

operation" by which new results are integrated with the traditional body of knowledge.

Newton's gravitational force law turned out not to be compatible with the new concepts of space and time introduced by the Special Theory of Relativity in 1905. Whereas classical gravitation is an action at a distance propagated without loss of time, the concept of velocity in Einstein's new kinematics excludes any physical action at a speed greater than that of light. The resulting necessity of modifying the classical theory of gravitation appeared to Einstein and his contemporaries all the more pressing as already within the conceptual framework of classical physics an asymmetry could be observed between the instantaneous propagation of the gravitational force and the propagation of the electromagnetic field with the finite speed of light. It comes therefore as no surprise that not only Einstein but also several of his contemporaries addressed the problem of formulating a field theory of gravitation that was to be in agreement with the principles suggested by the theory of the electromagnetic field, and most importantly with the new kinematics of relativity theory.[6]

The proliferation of alternative approaches to the problem of gravitation

It appears to be a phenomenon characteristic of the development of science that in such a situation of conceptual conflict alternative approaches to the solution of the conflict begin to proliferate. Among the factors accounting for this proliferation are the diverse resources upon which the alternative approaches can draw. Even after the establishment of Special Relativity the instruments available for a revision of Newton's theory of gravitation essentially had to be taken from the arsenal of classical physics, in particular from classical mechanics and classical electrodynamics. As these two branches of classical physics were founded on different conceptual structures - on the one hand the direct interaction between point particles, on the other hand the propagation of continuous fields in time - the use of resources from one or the other branch to solve the same problem could present itself as a choice between conceptual alternatives. In this way, the problem of a new theory of gravitation contained right from its beginning the dimension of a foundational question of physics. The choice among alternative approaches to the problem of gravitation was

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[6] See, among others, Poincaré 1905, in particular pp. 1507-1508, Poincaré 1906, in particular pp. 166-175, Minkowski 1911a (1908), in particular pp. 401-404, Minkowski 1911b (1909), in particular pp. 443-444, Ritz, 1909, Lorentz 1910, Abraham 1912a and b, Nordström 1912, and Mie 1914.

therefore also related to the way in which such foundational questions were handled at that time.

Even before the turn of the century, that is, long before the great conceptual revolutions of early twentieth century physics, many physicists saw themselves at a bifurcation point at which they had to decide between alternative conceptual foundations for their field. Mechanics for a long time had played the double role of a subdiscipline and of an ontological foundation of physics. And at the threshold to the twentieth century there were still physicists who adhered to the ontological primacy of mechanics and were therefore convinced that the entire body of physics should be built on conceptual foundations rooted in mechanics. With the formulation of classical electrodynamics by Maxwell, Hertz, and Lorentz, the difficulty of achieving such a reduction of physics to the conceptual apparatus of mechanics became, however, more and more evident. Although field theory was initially itself formulated in a mechanical language, it came to represent, towards the end of the century, an autonomous conceptual framework largely independent of that of mechanics. To some physicists such as Wien and Lorentz, field theory even appeared to offer an alternative conceptual foundation for all of physics; they speculated about an electrodynamic world view in which mechanics would have to be reformulated as a field theory rather than the other way around. Finally, with the development of classical thermodynamics in the middle of the nineteenth century, including the formulation of the principle of conservation of energy, a third alternative conceptual foundation of physics seemed to offer itself which was discussed under the name of "energetics." The mechanistic conception of physics, the electromagnetic world view, and energetics hence distinguished themselves by the choice of the subdiscipline of classical physics to which they granted a foundational role for the entire field.[7]

The formulation of a field theory of gravitation in analogy to or even on the basis of the Maxwell-Lorentz theory of the electromagnetic field was hence not a far-fetched thought in the context of the electrodynamic world picture and had been approached by several authors.[8] In such a theory gravitation would have to propagate with a finite speed, just as electrodynamical actions. The establishment of the theory of relativity in 1905 had not only not made attempts in this direction obsolete but made them even more urgent, since Newton's theory violated one of the fundamental principles of this theory, namely

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[7] For a brief account of the different approaches prevalent at the turn of the century, see Jungnickel and McCormach 1986, Chapter 24.

[8] For contemporary reviews, see Zenneck 1903 and Abraham 1915.

the requirement that no physical action be propagated with a velocity greater than that of light. The primary task was to reformulate the experimentally well confirmed Newtonian law of gravitation in accordance with the principles of the new kinematics, in particular with the Lorentz transformations of space and time coordinates, under which the classical law does not remain invariant. It is in fact not difficult to formulate a Lorentz covariant field equation which can be interpreted as a direct generalization of Newton's law. Around 1907 Einstein apparently pursued this line of research without, however, achieving satisfying results.[9] Indeed, if such a Lorentz covariant generalization of Newton's theory could have been formulated without problems there would have been no reason for Einstein to look beyond the Special Theory of Relativity of 1905 and enter the thorny path that was to lead him to the formulation of the General Theory of Relativity of 1915.

One of the difficulties encountered by Einstein concerns the concept of mass, or rather the relationship between the two aspects which characterize according to classical mechanics the concept of mass: gravitation and inertia. According to the Special Theory of Relativity the inertial mass of a body depends on its energy content.[10] It was on the other hand empirically known in the context of classical mechanics that the inertial mass is always exactly equal to the gravitational mass. In a relativistic theory of gravitation the gravitational mass of a physical system should therefore also depend on its total energy in an exactly known way. In a later recollection Einstein summarized his view of this implication of classical mechanics and the Special Theory of Relativity for a relativistic theory of gravitation: "If the theory did not accomplish this or could not do it naturally, it was to be rejected. The condition is most naturally expressed as follows: The acceleration of a system falling freely in a given gravitational field is independent of the nature of the falling system (especially therefore also of its energy content)."[11] It was precisely this requirement, however, which turned out not to be fulfilled in the early attempts at a special relativistic theory of gravitation.[12]

In other words, a straightforward relativistic generalization of Newton's gravitational law seemed to be in conflict with what I will call in the following "the Galileo Principle" of the equality of speeds of bodies

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[9] For a reconstruction of Einstein’s failed attempt to incorporate gravitation within the relativity theory of 1905, see Norton 1992b. For Einstein's later recollections, see Einstein 1992, pp. 58-63.

[10] See Einstein 1907a, in which this conclusion is rederived in a general way, possibly already in the light of the problems of a relativistic theory of gravitation.

[11] Einstein 1992, p. 61.

[12] See the reconstruction of Einstein's early attempts in Norton 1992b.

falling in a gravitational field.[13] Quantitatively, however, the deviation from classical mechanics may have been negligibly small, as Mie, for instance, claimed for his later special relativistic theory of gravitation.[14] Researchers such as Mie, whose outlook on this question was shaped by the electrodynamic world view, were all the more willing to give up the Galileo Principle as they did not feel obliged to consider implications of classical mechanics as foundational for physics, unless they perceived an unavoidable conflict with experimental evidence. As it turned out in particular as a result of Nordström's research on a special relativistic theory of gravitation in the years 1912 to 1914 Einstein had indeed prematurely given up this line of research.[15] Nordström, with the help of contributions from von Laue and Einstein himself, was indeed able to show that a consistent special relativistic field theory of gravitation could be formulated which included the equality of gravitational and inertial mass and which at that time was not contradicted by any experimental evidence. What is more, this theory even contained insights upon which its further development in the direction of General Relativity could be based, such as the insight that clocks and rods are affected by the gravitational field; it hence constituted at least the beginning of an independent road towards a theory like General Relativity, "the route of field theory."

Mach's critique of mechanics and the three routes to General Relativity

From the conflict which Einstein perceived in 1907 between classical mechanics and the Special Theory of Relativity he drew a conclusion that was diametrically opposed to that of the followers of an electromagnetic world view. For him the equality of inertial and gravitational mass was not just an empirically confirmed but otherwise marginal result of classical mechanics, rather he held on to it as a

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[13] Galileo's name is usually but incorrectly associated with the introduction of the Principle of Inertia while the principle which is here named after him can be indeed found in his work; for historical discussion, see Damerow et al. 1991, Chapter 3.

[14] See Mie 1914. Similar views are found also in other authors pursuing a special relativistic field theory of gravitation, see e.g. Nordström 1912, p. 1129: "From a letter from Herr Prof. Dr. A. Einstein I learn that he had already earlier concerned himself with the possibility used above by me for treating gravitational phenomena in a simple way. He however came to the conviction that the consequences of such a theory cannot correspond with reality. In a simple example he shows that, according to this theory, a rotating system in a gravitational field will acquire a smaller acceleration than a non-rotating system. I do not find this result dubious in itself, for the difference is too small to yield a contradiction with experience." (my transl.)

[15] For a comprehensive historical study of Nordström's work, on which the following remarks are based, see Norton 1992b and Norton 1993a.

principle upon which a new theory of gravitation was to be based; he was therefore ready to accept that this theory would no longer fit into the framework of Special Relativity.[16] Einstein's further considerations hence did not lead him away from mechanics but rather brought him into contact with its foundational questions, in particular with the question of the role of inertial systems in classical mechanics. In a later recollection he described this crucial moment of contact between field theory and classical mechanics: "Now it came to me: the fact of the equality of inertial and gravitational mass, i. e., the fact of the independence of the gravitational acceleration from the nature of the falling substance ("the Galileo Principle" J. R.), may be expressed as follows: In a gravitational field (of small spatial extension) things behave as they do in a space free of gravitation, if one introduces into it, in place of an “inertial system,” a frame of reference accelerated to the former. If then one interprets the behavior of a body with respect to the latter frame of reference as caused by a “real” (not merely apparent) gravitational field, it is possible to regard this frame as an “inertial system” with as much justification as the original reference system. So, if one considers pervasive gravitational fields, not a priori restricted by spatial boundary conditions, physically possible, then the concept of “inertial system” becomes completely empty. The concept of “acceleration relative to space” then loses all meaning and with it the principle of inertia along with the paradox of Mach.”[17] In Einstein's understanding Mach's paradox was founded on the observation that, while from a geometrical standpoint all coordinate systems should be equivalent, the equations of mechanics claim validity only when referred to the very specific class of inertial systems.[18]

To Einstein, Mach's philosophical critique of the foundations of classical mechanics suggested that the problem of a new theory of gravitation had to be resolved in connection with a generalization of the relativity principle of classical mechanics and Special Relativity. Quite apart from the specific problem of gravitation, some of Mach's contemporary readers as well as researchers who had independently arrived at similar views had drawn the conclusion that one should look

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[16] Einstein (1914, p. 343), remarked with regard to the violation of the Galileo Principle in Abraham's and Mie's theories of gravitation: "These effects are not accessible to experiment because of their smallness. But to me there is much to argue that the relationship between inertial and gravitational mass is *in principle* preserved, independently of the forms of energy that enter it." (my transl.)

[17] Einstein 1992, pp. 60-63.

[18] See Einstein 1992, pp. 24-27.

for a new, generally relativistic formulation of mechanics.[19] Their conceptual and technical resources were mostly confined to those of classical mechanics and their chances of making contact with the more advanced results of physics at the turn of the century, which to a large extent were based on field theory (in particular classical electrodynamics), were, at least at that time, slender. Nevertheless, the line of research that extends from the work of these early followers of Mach (discussed in more detail in the next section) to the recent work of Barbour and Bertotti, Hoyle and Narlikar, Assis and others demonstrates that the project of formulating a generally relativistic theory of mechanics including a treatment of gravitation could be as successfully pursued as the project of a purely field theoretic approach to the problem of gravitation as it is represented in particular by the work of Nordström.[20] In the following I will call this approach "the mechanistic generalization of the relativity principle."

In view of this historical context the heuristics which guided Einstein's formulation of the General Theory of Relativity can now be identified as a "third way," as a peculiar mixture of field theoretical and mechanical elements.[21] This affirmation suggests several questions which will be addressed in the following: What are the advantages and the disadvantages of the different strategies? What exactly are the contributions of the field theoretical and of the mechanical tradition to Einstein's heuristic strategy? What is the relationship between the conceptual structures guiding Einstein's research and those that were newly established by it? As the development of the General Theory of Relativity was apparently not uniquely determined by the intrinsic nature of the problem to be solved, what then were the external factors that shaped Einstein's perspective and what role did philosophical positions play among them? The following sections do not, of course, claim to propose exhaustive answers to these questions, each of which merits a much more detailed study than can be given here.

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[19] For a survey of the interpretation of Mach's critique by contemporary readers, see Norton 1993c.

[20] See Goenner 1970 and 1981, as well as Assis 1993, Barbour 1993, and Pfister 1993 for historical overviews over attempts to incorporate Mach's critique in physical theories.

[21] A systematic account of the role of the third "world view" of classical physics (energetics) for the emergence of General Relativity lies outside the scope of this paper.

3. Roots of General Relativity in Classical Physics

Resources and stumbling blocks presented by the tradition of field theory

The conceptual roots of General Relativity in the tradition of field theory are more familiar than those in the tradition of mechanics. As I have mentioned before, not only Special Relativity but already the theory of the electrodynamic field made it plausible to conceive of gravitation as a field propagated with a finite velocity. But there were also other contributions of this tradition which sooner or later found their way into the development of General Relativity. Since field theory endows space with physical properties, it lay, for instance, in its tendency to blur the distinction between matter and space. That this tendency even taken by itself could suggest the introduction of non-Euclidean geometry as a physical property of space is illustrated by the work of Riemann and Clifford in the nineteenth century.[22] In any case, field theory enriched the limited ontology of classical mechanics by introducing the field as a reality in its own right, an apparently trivial consequence, which, however, as we shall see, took considerable time to achieve a firm standing even within the development of General Relativity. Field theory also suggested the existence of more general forces than the two-particle interactions usually considered in point mechanics, as is illustrated by the transition from Coulomb forces between point charges to electrodynamic interactions such as induction; and it offered a mechanism for unifying separate forces as aspects of one more general field, as can again be illustrated by the example of electrodynamics conceived as a unification of electric and magnetic interactions. It was therefore natural for those who pursued the program of formulating a field theory of gravitation either on the basis of or in analogy to electrodynamics to search for the dynamic aspects of the gravitational field, considering Newton's law in analogy to that of Coulomb as a description of its static aspects only. But the knowledge of the Newtonian special case could and did serve at the same time as a touchstone for any attempt at a more general theory including Einstein's General Theory of Relativity in whose development the question of the "Newtonian limit" was to play a crucial role.[23] The mature formulation of electrodynamic field theory by H. A. Lorentz also suggested a model for the essential elements of a field theory of gravitation and for their

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[22] See Riemann 1868 and Clifford 1976 (1889). On p. 149 of his paper, Riemann claims that non-Euclidean geometry could be important in physics if the concept of body should turn out not to be independent of that of space. He expected a relevance of this consideration for a future microphysics.

[23] See Norton 1989b.

interplay: a field equation was needed describing the effect of sources on the field and an equation of motion was needed in order to describe the motion of bodies in the field.[24] Finally, those who looked for an "electromagnetic" theory of gravitation were also very clear about the experimental evidence to be covered by the new theory: The explanation of the perihelion shift of mercury was in fact mentioned as an empirical check in almost all discussions of electromagnetic theories of gravitation, which, in this sense, can be said to have left a very tangible patrimony to General Relativity by pointing to one of its classical tests.[25]

But as much as the tradition of field theory was able to contribute to the conceptual development of General Relativity, it did not determine a heuristic strategy that clearly outlined the way to a satisfactory solution of the problem of gravitation. What is more, in hindsight, from the perspective of the accomplished theory of General Relativity, it becomes evident that the tradition of classical field theory also encompassed conceptual components that must be considered as stumbling blocks on the way to such a solution. I first turn to the problem of the heuristic ambiguity of field theory. As was mentioned above, there were indeed several different lines to follow within this tradition in order to formulate a field theory of gravitation.[26] One of the factors accounting for this proliferation of alternatives lay in the uncertainty as to which principles of mechanics were to be maintained in the new theory of gravitation, given the necessity of revising at least some of them. The electromagnetic approach to the problem of gravitation rather tended, in any case, to ignore the foundational problems of mechanics, as long as this seemed experimentally acceptable. An early example for this tendency characteristic of the electromagnetic world picture is provided by the stepmotherly way in which, before the advent of Special Relativity, the principle of relativity and the principle of the equality of action and reaction was treated in Lorentz's electron theory. The same attitude characterized his later attempts to integrate gravitation into the conceptual framework of field theory. In a review paper of 1910, for instance, Lorentz seemed not to be bothered very much by the fact that the relativistic law of gravitation he proposed violated the principle of the equality of action and reaction.[27] This difficulty is just one representative example for the

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[24] For a discussion of the historical continuity between Lorentz's electron theory and Einstein's Theory of General Relativity, see McCormmach 1970.

[25] See Zenneck 1903 for a contemporary survey of the problem of gravitation and the role of the perihelion shift.

[26] See note 6 above.

[27] Lorentz 1910.

problems associated with the task of reconstructing the body of knowledge accumulated in mechanics on the basis of purely field theoretic foundations. In addition to these problems, there was little experimental guidance as how to proceed in building the new theory of gravitation - apart from the speculations about the perihelion shift of Mercury mentioned above. To use a metaphor employed by Einstein: the task of constructing a field theory of gravitation was as if Maxwell's equations had to be found exclusively on the basis of knowing Coulomb's law of electrostatic forces, that is, without any empirical knowledge of non-static gravitational phenomena.[28]

Let me now come to the problem of the conceptual stumbling blocks. Their evaluation naturally depends on the point of view one takes. In view of the conceptual framework of the finished General Theory of Relativity, classical field theory must have been misleading in several respects. One obvious aspect is the linearity of the classical theory in contrast to the non-linearity of the field equations of General Relativity. A related aspect is the independence of the field equation and the equation of motion from each other in the classical theory as opposed to their interdependence in General Relativity. Closely associated with these more structural aspects and perhaps even more important are the conceptual changes brought about by General Relativity with respect to classical physics, such as the introduction of new concepts of space and time, but also the new role of the gravitational field acting as its own source, or the changes of the concepts of energy and force manifested, for instance, by the absence of a gravitational stress-energy tensor in General Relativity - in contrast to the existence of such a stress-energy tensor for the electromagnetic field in classical field theory. It is not only that these changes could not have been anticipated on the basis of classical field theory, it is rather that classical field theory necessarily raised expectations for the search of a new theory of gravitation which were flatly contradicted by the outcome of the search.

The foundational critique of mechanics and the mechanistic generalization of the relativity principle

The heuristic contributions of classical physics to the development of General Relativity as well as the conceptual stumbling blocks it presented for this development obviously require a more detailed treatment and should be discussed, in particular, in the context of the concrete theories which are subsumed here under the rather general

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[28] See Einstein 1913, p. 1250.

heading of "classical physics." For the purpose of the present paper such a more detailed examination will have to be approached only for the tradition of mechanics, of which it was primarily one particular strand that influenced the development of General Relativity - both directly and as an alternative to Einstein's theory.[29] This strand was represented by a revaluation of mechanics, which was the outcome of a debate on its foundations in the second half of the nineteenth century. In this period some basic concepts of classical mechanics had ceased to be as self-evident as they had once appeared to the Newtonian tradition.

A central example is Newton's claim that even a single body in an otherwise empty universe possesses inertia, a claim which - in spite of its metaphysical character - played a crucial role in his argument in favor of the existence of absolute space.[30] This argument involves a bucket filled with water which is considered once in a state in which the bucket rotates but the water is at rest and its surface flat, and once in a state in which both the bucket and the water rotate producing a curved surface. According to Newton's interpretation of this experiment, the second case represents an absolute rotation whereas the first case represents only a relative motion between water and bucket which does not cause physical effects. The conclusion that this argument provides evidence for the existence of absolute space is, however, only then legitimate if other physical causes of the curvature of the water in the second case can be excluded; in other words, the argument is convincing only under the physically not controllable assumption that a rotational motion of the water in an otherwise empty universe would also give rise to the same effect. This assumption in turn is based on the metaphysical premise that a system is composed of parts which carry their essential properties (such as inertia in the case of a material system) even when they exist in isolation in an empty space. It was also on this premise that Newton considered gravitation - in distinction to inertia - to be a universal but not an essential property of a material body.[31]

In the middle of the nineteenth century a motivation for revisiting such metaphysical foundations of mechanics was provided by the establishment of non-mechanical theories such as electrodynamics and thermodynamics as mature subdisciplines of classical physics.[32] As a

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[29] As mentioned earlier, the field theoretical route to a theory of gravitation is reconstructed *in extenso* in Norton 1992b.

[30] This has been shown in detail in Freudenthal 1986, on which also the following remarks are based.

[31] See the explanation of *Regula* III in Newton 1972 (1726), p. 389.

[32] Compare also the sequence in which Einstein, in his *Autobiographical Notes* (Einstein 1992), treats the *external* criticism of mechanics (the critique of

consequence of this development, mechanics not only lost its privileged status as the only conceivable candidate providing a conceptual basis for the entire building of physics, a status which was often associated with a claim to *a priori* truth, but the conceptual foundation of mechanics itself could now be critically reexamined, including, for instance, the concept of absolute space and its justification by Newton. This revision alone of the status of the fundamental concepts of mechanics helped to prepare the conditions for a change of these concepts, should such a change become necessary in view of the growing body of knowledge.[33]

In any case, the critical revaluation of the conceptual presuppositions of mechanics created a similar proliferation of alternatives as did the incorporation of the problem of gravitation into the framework of field theory. It was in fact possible either just to elaborate more clearly the presuppositions on which classical Newtonian mechanics was built, or to revise the theory by attempting to eliminate those assumptions which now appeared to be no longer acceptable, but without any other substantial changes, or to formulate a new theory altogether. Carl Neumann's paper "On the Principles of the Galilean-Newtonian Theory" of 1869 provides an example for the first alternative: In order to replace Newton's concept of absolute space he introduced the "Body Alpha" as the material embodiment of an absolute reference frame, comparing it with the luminiferous ether of electrodynamics as a likewise hypothetical but nevertheless legitimate conceptual element of the theory.[34] Nevertheless, by this reformulation Neumann did not intend to change the substance of Newton's theory, in particular with respect to the question of relative and absolute motion as the following passage illustrates: "This seems to be the right place for an observation which forces itself upon us and from which it clearly follows how unbearable are the contradictions that arise when motion is conceived as something relative rather than something absolute. Let us assume that among the stars there is one which is composed of fluid matter and is somewhat similar to our terrestrial globe and that it is

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mechanics as the basis of physics, pp. 22-23) and the "internal," conceptual criticism (pp. 24-31).

[33] Compare e. g. the remark by Carl Neumann in 1869: "Finally, just as the present theory of electrical phenomena may perhaps one day be replaced by another theory, and the notion of an electric fluid could be removed, it is also the case that it is not an absolute impossibility that the Galilean-Newtonian theory will be supplanted one day by another theory, by some other picture, and the Body Alpha be made superfluous." (Neumann 1993, p. 365) For the "Body Alpha" see below.

[34] "But a further question arises, whether this body exists - really, concretely, as the earth, the sun, and the remaining heavenly bodies do. We may answer this question, as I see it, by saying that its existence can be stated with the same right, with the same certainty, as the existence of the luminiferous ether or the electrical fluid." (Neumann 1993, p. 365)

rotating around an axis that passes through its center. As a result of such a motion, and due to the resulting centrifugal forces, this star would take on the shape of a flattened ellipsoid. We now ask: What shape will this star assume if all remaining heavenly bodies are suddenly annihilated (turned into nothing)? These centrifugal forces are dependent only on the state of the star itself; they are totally independent of the remaining heavenly bodies. Consequently, this is our answer: These centrifugal forces and the spherical ellipsoidal form dependent on them will persist regardless of whether the remaining heavenly bodies continue to exist or suddenly disappear."[35]

The critical examinations of the foundations of classical mechanics by Ludwig Lange and Ernst Mach represent the second alternative mentioned above, since they were both guided by the intention to revise mechanics by eliminating problematic assumptions.[36] They may be considered as attempts to provide a conceptual reinterpretation of the existing formalism of classical mechanics (possibly even including minor adjustments of this formalism), with no ambition to formulate a new theory or to cover new empirical ground. Lange's approach is today the less well known, probably precisely because his contribution was the introduction of the concept of an inertial system, a contribution that was so successful in becoming part of the generally accepted conceptual interpretation of classical mechanics. Mach's widely discussed critique of the foundations of classical mechanics, on the other hand, is characterized by vacillating between more or less successful attempts to reformulate Newtonian mechanics on a clearer and leaner conceptual basis and the suggestion to create a new theory. It seems plausible to assume that this ambiguity was actually not in conflict with Mach's intentions as the principal aim of his reformulation of elements of classical mechanics was to stress and clarify the dependence of this theory on experience and hence to open up the possibility of revising the theory if required by new empirical evidence.[37]

One of the principal targets of Mach's critique was Newton's interpretation of the bucket experiment as evidence in favor of the

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[35] Neumann 1993, note 8, p. 366.

[36] Lange 1886 and Mach 1960 (1883).

[37] This seems to be the most natural explanation for Mach's rather indifferent reaction to the controversy about the purpose of his critique as observed in Norton 1993c. Compare Mach's remarks on his revised principle of inertia: "It is impossible to say whether the new expression would still represent the true condition of things if the stars were to perform rapid movements among one another. The general experience cannot be constructed from the particular case given us. We must, on the contrary, *wait* until such an experience presents itself." (Mach 1960, p. 289).

existence of absolute space.[38] To Newton's argument, according to which the curvature of the surface of the rotating water is a physical effect of the rotation with respect to absolute space, he objected that in our actual experience this rotation can be considered as a relative rotation, namely with respect to the fixed stars: "Try to fix Newton's bucket and rotate the heaven of fixed stars and then prove the absence of centrifugal forces."[39] Mach thus questioned the fundamental metaphysical presupposition of Newton's conclusion that physical effects of absolute space would also occur if the rotation took place in an otherwise empty universe, i. e. the presupposition that all elements of a system retain their essential properties independently from their composition to a system: "Nature does not begin with elements, as we are obliged to begin with them."[40] On the grounds of his different philosophical view Mach demanded that the entire corpus of mechanics should be reformulated in terms of a concept of motion of material bodies relative to each other. For instance, he introduced a new definition of the concept of mass based on the mutual accelerations of bodies with respect to each other. He also suggested that inertial frames of reference should be determined on the basis of the observable relative motions of bodies in the universe, e. g. by determining a frame of reference in which the average acceleration of a mass with respect to other - ideally all - bodies in the universe vanishes. On the one hand, Mach's proposals for a reformulation of classical mechanics clearly presuppose its validity: both his new definition of mass by mutual accelerations and his idea of introducing better and better inertial frames of reference by taking into account more and more bodies, over whose relative motion an average can be taken, assume that the concept of an inertial frame makes sense exactly as it is understood in classical mechanics, in other words, that there is indeed such a privileged class of reference frames and that they can physically be realized with sufficient approximation.[41] Mach's analysis, on the other hand, pointed also to the limits of the validity of classical mechanics, in particular by explicitly relating the concept of inertial frame to the motion of cosmic masses. Without changing the substance of classical mechanics he thus succeeded nevertheless in making clear - by proposing an alternative formulation based on different philosophical presuppositions - that the range of application of classical mechanics may be more limited than hitherto assumed and that the theory might have to be changed eventually, for instance in view of the growing astronomical knowledge.

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[38] See Mach 1960, Chapter 2, section 6, in particular, pp. 279-284.

[39] Mach 1960, p. 279.

[40] Mach 1960, pp. 287-288.

[41] See the penetrating analysis in Wahsner and von Borzeszkowski 1992, pp. 324-328.

Only on the basis of such an increased knowledge could it then be decided whether Mach's suggestion to reformulate classical mechanics in terms of relative motions would actually amount to proposing a new theory, substantially different from Newton's.

Attempts to formulate such a new theory even in the absence of new empirical evidence form a third alternative reaction to the critical revaluation of the foundations of mechanics in the second half of the nineteenth century. Whether these attempts were stimulated by Mach or not, their common starting point was the rejection of Newton's philosophical presupposition that the properties of the elements of a physical system could be ascribed to each one of them also if they existed alone in empty space. It was thus that he had inferred from the inertial effects of a rotating bucket to the inertial behavior of a single particle in empty space, and from there to the physical reality of absolute space. Only by introducing an entity such as "absolute space" had Newton succeeded in distinguishing between the kinematical and the dynamical aspects of motion. Hence, if now this presupposition had become questionable so had the entire relationship between dynamics and kinematics. In particular, the distinction between motions to be explained by the action of forces and force-free motions had to be given a new grounding in terms of relative motions between ponderable bodies. While Mach had essentially presupposed the validity of classical mechanics and attempted to reconstruct its achievements on this new basis, it was also conceivable to start from first principles and formulate dynamics from the beginning in terms of relative motions between ponderable bodies, possibly even without using the concept of an inertial frame in the sense of classical mechanics. Attempts in this direction of a *mechanistic generalization of the relativity principle* were first undertaken around the turn of the century by Benedict and Immanuel Friedlaender, August Föppl, and Wenzel Hofmann, then decades later by Reissner and Schrödinger, and in our days by Barbour, Bertotti and others.[42]

The attempts at least of the first generation of physicists in this genealogy were confronted with the difficulty of taking up once again many of the foundational questions of mechanics discussed centuries earlier by Galileo, Descartes, Newton, Leibniz, and Huyghens and to recreate mechanics essentially from scratch. Indeed, apart from the foundational role given to the concept of relative motion even in dynamics and the known laws of classical mechanics, this approach of a

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[42] See, e. g., Friedlaender 1896, Föppl 1905a and b, Hofmann 1904, Reissner 1914 and 1915, Schrödinger 1925, and Barbour and Bertotti 1977.

mechanistic generalization of the relativity principle had few heuristic clues to go on. One of these clues was directly related to their criticism of Newton's interpretation of the bucket experiment: If it is indeed true that the curvature of the rotating water in the bucket is due to an interaction between the water and the distant cosmic masses, then a similar but smaller effect should be observable if large but still manipulable terrestrial masses are brought into rotation with respect to a test body. Experiments along these lines were suggested by several of these researchers and conducted by, among others, the Friedlaender brothers and Föppl - but all with a negative result.[43] Nevertheless, the theoretical efforts continued - even as they remained marginal - and eventually found additional resources and inspiration in the theory of General Relativity Einstein formulated in 1915.

Resources and stumbling blocks presented by the tradition of mechanics

After this discussion of the historical roots of the mechanistic generalization of the relativity principle, I am now in the position to summarize some of the principal heuristic contributions and obstacles which the tradition of mechanics presented to the development of General Relativity, just as I did in the beginning of this section for field theory. First and foremost it was the idea of abolishing the privileged status of the inertial frame, which, as we have seen, emerged from the foundational critique of mechanics in the nineteenth century, that proved to be an essential component to both Einstein's early research program for a generalized theory of relativity as well as to the competing tradition of a mechanistic generalization of the relativity principle until today. In fact, if separable material bodies are to be the ultimate basis of reality, as they are in the approach of a mechanistic generalization of the relativity principle, each material body should be equally suited and justified as a frame of reference and therefore enter on the same level with all other bodies into the laws of physics. The idea of abolishing the privileged status of inertial frames was associated with the interpretation of the so-called inertial forces (such as those acting on the rotating water in Newton's bucket) as aspects of a new, yet to be uncovered velocity-dependent physical interaction between masses in relative motion with respect to each other. Under the designation of "dragging effects" such interactions became an important theme of the later General Theory of Relativity; there they can be understood as a new aspect of the gravitational interaction between masses which was unknown in Newtonian mechanics. Finally, Mach's definition of inertial mass by the accelerations which two bodies cause to each other brought

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[43] See Friedlaender 1896 and Föppl 1905a

the concept of inertial mass even closer to the concept of gravitational mass than their numerical identity in classical mechanics already had. In fact it follows from this definition that, contrary to Newtonian mechanics, inertial mass can no longer be considered in distinction from gravitational mass as a property which bodies possess independently from their interaction with each other. The search for effects of the presence of other bodies on the inertial mass of a test body was to become a component of the heuristics guiding Einstein's research on a generalized theory of relativity.

While these were the specific and crucial contributions of the foundational critique of mechanics we have discussed at length, other aspects of mechanics in the nineteenth century also contained important heuristic hints and conceptual resources for the development of General Relativity, which, however, cannot be dealt with here systematically. In particular, the introduction of laws of motion expressed in generalized coordinates, the formulation of mechanics for non-Euclidean geometry, and the attempts at an elimination of the concept of force all represent resources which could be and in part were exploited in the development of General Relativity.[44] The study of motion constrained to curved surfaces in classical mechanics provided, for instance, the blueprints for the formulation of the geodesic law of motion as a generalization of the principle of inertia in General Relativity: in both cases the essential assertion is that motion not subject to external forces follows a geodesic line. But unlike what was the case for the foundational critique of mechanics, these other aspects of the development of classical mechanics did not constitute by themselves another independent research program for formulating a substantially new mechanics which might lead to a theory comparable to General Relativity. Rather their heuristic contribution to formulating such a new theory became relevant only in the context of Einstein's later attempt to solve the problem of gravitation and only on the basis of results which lay outside their scope. For instance, Hertz's mechanics is a reformulation of classical mechanics in which the elimination of the concept of force requires the introduction of hypothetical invisible masses acting as constraints for the visible motions.[45] Not only its formalism and in particular its generalized geodesic law of motion bear a number of similarities with the formalism of General Relativity, but also the general approach of replacing the concept of force by geometrical concepts is shared by both theories.[46] But while even in the context of classical mechanics the

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[44] For a recent historical account of these developments, see Lützen 1993.

[45] Hertz 1894.

[46] The geometrical interpretation of General Relativity is, however, a largely post-1915 development.

concept of force can be eliminated in the specific case of the gravitational interaction without introducing Hertz's speculative entities merely on the basis of what I have called "the Galileo Principle," that is, by realizing that all bodies move with equal speeds in a gravitational field, a systematic exploitation of formal results such as those by Hertz required not only a restriction of mechanics to the special case of gravitational interaction but also the introduction of Minkowski's reformulation of Special Relativity uniting the time with the space-coordinates into one space-time continuum. Only under these presuppositions did the formal achievements of nineteenth century mechanics become a resource for the insight that force-free motion in a gravitational field can be understood as a geodesic motion in a non-Euclidean space-time continuum.

Considered in the hindsight of General Relativity, the contributions to its development rooted in the tradition of classical mechanics were, however, also associated with conceptual obstacles to this development. As in the case of field theory discussed above there was, first of all, much ambiguity in the research program of a mechanistic generalization of the relativity principle. Since the General Theory of Relativity was formulated in 1915, that is, long before an elaborate and more or less successful realization of this program emerged, it is, however, impossible to assess the direction which this program would have taken by itself, without the guidance by Einstein's achievement in its later phase of development. By ca. 1915 it was, in any case, far less advanced than the attempts to solve the problem of gravitation in the context of field theory which we have discussed above. The papers proposing a mechanistic generalization of the relativity principle are mostly in the form of programmatic treatises. They contain few technical details and show even by their style that they deal with foundational problems of mechanics as they were commonly discussed in early modern times by Galileo and his contemporaries. In particular, in order to explore the new velocity-dependent interaction which a mechanistic generalization of the relativity principle surmised, it hardly had any tools comparable to those which the tradition of field theory had developed, for instance, in order to cope with the interaction of electric masses in motion with respect to each other. Even on the experimental level the mechanistic generalization of the relativity principle failed to identify evidence in favor of this new interaction between moving masses. It is therefore not surprising that the followers of a mechanistic generalization of the relativity principle remained a small group that played only a marginal role in contemporary discussions. But in addition to its weaknesses as an independent program of research, the idea of a mechanistic generalization of the relativity principle included aspects that were both stimulating and misleading if judged from the perspective of the accomplished theory of General Relativity: While the ideal of a theory in which all physical aspects of space are derived from the relationships between separable material bodies was an essential motivation for the search for a general theory of relativity, it turned out to be incompatible with its outcome since the gravitational field has an existence in its own right in General Relativity, which cannot be reduced to the effects of matter in motion.

The example of Benedict and Immanuel Friedlaender

The chances and difficulties of the mechanistic generalization of the relativity principle can best be illustrated by the contribution of the Friedlaender brothers. Their philosophical starting point is the critique of the concept of motion of a single body in an otherwise empty space, on which, as we have seen, Newton's argument for absolute space was founded: "Now consider (if you can) the progressive motion of a single body in a universe that is otherwise conceived as entirely empty; how can the motion be detected, i. e. distinguished from rest? By nothing we should think; indeed the entire idea of such an absolute progressive motion is devoid of sensual content."[47] As did other critics of Newtonian mechanics Immanuel and Benedict Friedlaender question the meaning of inertial frames and postulate a new velocity-dependent interaction between moving masses. But contrary to other representatives of a mechanistic generalization of the relativity principle they explicitly link this new interaction to gravitation: "Were this phenomenon detectable, this would be the incentive for a reformulation of mechanics and at the same time a further insight into the nature of gravity, since these phenomena must be due to the distant action of masses, and here in particular to the dependence of these actions on relative rotations."[48] How far they went in anticipating the relationship between gravitation and inertia as it is understood in General Relativity becomes clear from a speculation formulated towards the end of their paper: "It is also obvious that according to our view the motion of the bodies of the solar system could be seen as pure inertial motions, whereas according to the usual view the inertial motion, respectively its permanent gravitationally modified tendency, would strive to produce a rectilinear-tangential motion."[49] Another passage is formulated programmatically: "But it seems to me that the correct formulation of the law of inertia is not to be found before relative inertia as an influence of masses upon

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[47] Friedlaender 1896, p. 20.

[48] Friedlaender 1896, p. 15; translation adapted from Pfister 1993.

[49] Friedlaender 1896, p. 33; translation adapted from Pfister 1993.

each other, and gravity which equally represents an influence of masses upon each other, are reduced to a common law."[50]

At a first glance the insight formulated by the Friedlaenders into the relationship between velocity-dependent inertial forces and gravitation seems to contradict my claim that a mechanistic generalization of the relativity principle did not possess tools comparable to those used in the electromagnetic tradition to treat the interaction of electric masses in motion with respect to one another. A footnote to the same passage makes it, however, clear that the source of this insight into a possible relationship between gravity and inertia actually is the *combination* of the introduction of velocity-dependent forces by the mechanistic generalization of the relativity principle and the treatment of velocity-dependent forces in the electromagnetic tradition: "For this purpose it would be very desirable that the question whether Weber’s law is applicable to gravity, as well as the question of the propagation velocity of gravity be solved."[51] The reference is to Wilhelm Weber's fundamental law for the force between electric point charges, which is a generalization of Coulomb's law for the electrostatic force in that it takes into account also the motion of the charges. By including velocity-dependent terms Weber's law represents an attempt to cover electrodynamic interactions, too, while maintaining the form of an action at a distance, that is, of a direct interaction between the point charges without an intervening medium. In other words, the Friedlaenders established a connection between their foundational critique of mechanics and the contemporary discussions about an electromagnetic theory of gravitation.[52]

By the time of the publication of their paper, action-at-a-distance laws such as Weber's were, however, largely superseded by the field-theoretic approach to electromagnetism taken by Maxwell, Hertz, and others, who assumed a propagation of the electromagnetic force by an intervening medium, the ether.[53] The Friedlaenders seem themselves to have entertained considerations along these lines, without, however, drawing any technical consequences from them: "No mind thinking

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[50] Friedlaender 1896, p. 17; translation adapted from Pfister 1993. The first part of their jointly published booklet, pp. 5-17, is by Immanuel Friedlaender and the second part, pp. 18-35, by Benedict Friedlaender.

[51] Friedlaender 1896, p. 17; translation adapted from Pfister 1993.

[52] Hints to such a connection are also found in other authors, even if they are less explicit; see, e. g., Föppl 1905b, pp. 386-394; Mach 1960, p. 296 (with reference to the Friedlaender brothers and Föppl). For a discussion of Mach's position, see Wolters 1987, in particular pp. 37-70.

[53] For the role of Weber's law in the later tradition of generally relativistic mechanics, see Assis 1989 and Assis 1993; see also Barbour 1992, p. 145.

scientifically can have permanently and seriously believed in an unmediated action at a distance; the apparent action at a distance cannot be anything else but the result of the action of forces which are in some way mediated by the medium having its place between the two gravitating bodies."[54] But whether in the field-theoretic or in the action-at-a-distance form, it was the tools of the electromagnetic tradition of classical physics which allowed the Friedlaenders to establish the link between the new understanding of inertia and gravitation. It is therefore not surprising that they treat the dragging effects of masses in relative motion to each other in analogy to electromagnetic induction: "... only in order to indicate how the problem of motion which is here suggested and solved in a hypothetical manner is related to the nature of gravity but at the same time comes rather close to the known effects of electric forces, will the following parallel be pointed out: a body which approaches a second one or moves away from it would be without influence on the latter as long as the velocity of approach (to be taken either with a positive or a negative sign) remains unchanged; any change of this velocity would entail the above demonstrated [dragging] effect. As is well known, the presence of a current in a conductor is not sufficient for the generation of induction effects, either the magnitude of the current or the distance must vary; in our case the change of distance, i. e. the motion, would not suffice for the generation of the attractive or repulsive effects, but rather the velocity itself has to change."[55]

The historical horizon before Einstein's contribution

To summarize: In this section we have identified and discussed two entirely different strategies to deal with questions of the foundations of mechanics and gravitation theory around the time when Einstein began seriously to work on a relativistic theory of gravitation. The field theoretic approach to the problem of gravitation was, around this time, mainly stimulated by the incompatibility between Newton's theory of gravitation and the Special Theory of Relativity, while the starting point of the mechanistic generalization of the relativity principle was a philosophical critique of the foundations of Newtonian mechanics on the background of newly established branches of classical physics. Their mutual relationship can be understood in the context of the two principal competing world views of classical physics around the turn of the century, the electromagnetic world view and the mechanical world view: In particular, these world views apparently determined the

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[54] Friedlaender 1896, p. 19.

[55] Friedlaender 1896, p. 30.

different conceptual resources from which the two strategies drew rather exclusively, those of field theory and those of classical mechanics, respectively. Whereas the mechanistic generalization of the relativity principle remained at the margins of contemporary physics, the field theoretic approach to gravitation, at least for a while, took a place rather more in the center of contemporary discussions; and both strategies largely tended to ignore each other.

The two strategies encountered problems which, in hindsight, can be recognized as closely related to each other. On a general level, the difficulties of the two strategies were in an inverse relationship to each other: those following the field theoretic approach were confronted with the problem of reconstructing on a new conceptual basis the body of knowledge accumulated in classical mechanics, e. g. the insight into the equality of gravitational and inertial mass. The followers of a mechanistic generalization of the relativity principle, on the other hand, had to face the task of keeping up in their terms with the immense contribution of field theory to the progress of physics in the nineteenth century, a formidable challenge even for today's attempts to pursue the tradition of the mechanistic generalization of the relativity principle. But on the specific level of the gravitational and inertial interactions of masses, the problems faced by the two approaches can be rather characterized as complementary to each other: on the basis of concise theoretical considerations, the electromagnetic approach to the problem of gravitation required the existence of a velocity-dependent gravitational interaction in analogy to electromagnetic induction, for which there was, however, little if any experimental evidence; the mechanistic generalization of the relativity principle, on the other hand, postulated a new velocity-dependent interaction between inertial masses in order to explain well known observations such as the curvature of the water surface in Newton's bucket experiment, but it failed to develop a theoretical framework for its systematic treatment. Since each of the two traditions lived in its own world - with the remarkable but inconsequential exception of the Friedlaender brothers - the exploitation of their complementarity was not realized by any of their representatives until the advent of Einstein's contribution.

4. Mach's Principle between a Mechanistic Generalization of the Relativity Principle and a Field Theory of Gravitation

The emergence of a link between Einstein's research on gravitation and Mach's critique of mechanics in 1907

Let us turn away now from this attempt to characterize the horizon of possible approaches and finally come to the course of historical action. The problems of a field theory of gravitation, from which Einstein had started in 1907, pointed in a twofold way to Mach's critique of Newton's mechanics, that is, to his redefinition of the concept of mass and to his rejection of absolute space as a foundation for the understanding of inertial motion. As we have seen in the previous section, the concept of inertial mass and the concept of absolute space were in fact linked to each other in Newton's assumption that the essential properties of the elements are independent of their composition to a system. The refusal to accept this assumption simultaneously deprived both Newton's distinction between inertial and gravitational mass as essential and as non-essential properties, respectively, and his demonstration of absolute space of its basis. Einstein had been familiar with Mach's critique of Newton's mechanics since his student days[56] and probably reread the corresponding chapters of the *Mechanik* in the sequel of his first attack on the problem of gravitation in 1907.[57]

The physical asymmetry between inertial and gravitational mass, which was at the heart of the conflict between a special relativistic theory of gravitation and classical mechanics as Einstein perceived it in 1907 (i. e. the presumed violation of the Galileo Principle), may have pointed his attention to their more general asymmetry in Newtonian mechanics, according to which inertial mass is a property that can also be ascribed to a single body in an otherwise empty universe, whereas gravitational mass can only be conceived as a property of a system of

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[56] For an early reference to Mach, see Einstein to Mileva Maric´, 10 September 1899 (Renn and Schulmann 1992, p. 14; see also p. 85). For later recollections mentioning Mach, see Einstein 1933, Einstein 1954b, and Einstein 1992.

[57] For contemporary evidence of Einstein's rereading, see p. 58 of Einstein’s Scratch Notebook 1910-1914? (Appendix A in Klein et al. 1994a, p. 592), where Einstein wrote the title of the crucial section 6 of Chapter 2 of Mach's *Mechanics* (Mach 1960); pp. 7-8 of Einstein’s Lecture Notes for an Introductory Course on Mechanics at the University of Zurich, winter semester 1909/1910, (Klein et al. 1994a, pp. 15-16, discussed in more detail below); and the discussion of Mach's ideas in a notebook on Einstein’s Course on Analytical Mechanics, winter semester 1912/13, by Walter Dällenbach, (for a brief description, see Appendix A of Klein et al. 1994b).

bodies. Mach's analysis of the concept of inertial mass can be considered as an attempt to remove just this asymmetry, at least on the level of an operational definition of inertial mass. According to this definition, inertial mass is determined, as we have seen, on the basis of the mutual accelerations within a system of bodies, i. e. not as the independent property of a single body. Although Mach's intention was probably only to give a more concise account of classical mechanics without changing its content, his definition makes it nevertheless clear that in principle the interaction between two masses and hence their magnitude may depend on the presence of other masses in the world (remember that the inertial frame within which the accelerations are measured is, according to Mach's critique of absolute space, determined by the distribution of masses in the universe). In any case, according to Mach's definition, inertial mass is just as much defined by the interaction between bodies as gravitational mass so that it could give additional strength to Einstein's conclusion that the numerical equality of inertial and gravitational mass in classical mechanics points to a deeper conceptual unity that is to be preserved also in a new theory of gravitation.

Einstein's introduction of the Principle of Equivalence in order to express the equality of inertial and gravitational mass independent of the specific laws of motion of classical mechanics pointed, on the other hand, to Mach's critical discussion of Newton's problematic demonstration of absolute space. The successful use of a uniformly accelerated frame of reference to describe the behavior of bodies falling in a constant gravitational field must naturally have raised questions about the relationship between arbitrarily accelerated reference frames and more general gravitational fields. In Einstein's perspective, such questions pointed in particular to the problem of the privileged role of inertial frames in classical mechanics, as he confirms in the recollection quoted already in the first section: "So, if one considers pervasive gravitational fields, not *a priori* restricted by spatial boundary conditions, physically possible, then the concept of 'inertial system' becomes completely empty. The concept of 'acceleration relative to space' then loses all meaning and with it the principle of inertia along with the paradox of Mach."[58] In other words, the appearance of accelerated frames of reference in an argument concerning gravitation made it possible to relate two theoretical traditions to each other which so far had essentially led separate existences, the tradition of a field theory of gravitation in the sense of electrodynamics and the tradition of foundational critique of mechanics in the sense of what I have called

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[58] Einstein 1992, p. 63.

here "mechanistic generalization of the relativity principle." In the previous section we have seen that the idea of including accelerated frames of reference on an equal footing with inertial systems was as alien to the tradition of field theory as was the idea of a field theory of gravitation to the tradition of the mechanistic generalization of the relativity principle.

Now, however, Mach's critical examination of the privileged role of inertial frames in classical mechanics offered Einstein the context for considering his introduction of an accelerated frame of reference in the equivalence principle argument, not only as a technical trick to deal with a specific aspect of the problem of formulating a field theory of gravitation but as a hint towards the solution of a foundational problem of classical mechanics. But while Mach's critique justified the consideration of arbitrary frames of reference as a basis for the description of physical processes and hence the extension of the equivalence principle argument to include more general accelerated frames, such as the rotating frame of Newton's bucket,[59] it did not provide Einstein with the conceptual tools for dealing with the strange effects encountered in such frames. The tradition of field theory, in the context of which he had first approached the problem of gravitation, offered him, on the other hand, just the conceptual tools that allowed him to interpret the inertial forces in accelerated frames of reference as aspects of a more general notion of gravitational field, in the same sense as electromagnetic field theory makes it possible to conceive induction as an aspect of a more general notion of an electric field.

In other words, instead of attempting to resolve Mach's paradox of the privileged role of inertial frames in the context of a revised version of classical mechanics as did the adherents of a mechanistic generalization of the relativity principle, Einstein was now able to address this foundational problem of mechanics in the context of a field theory of gravitation in which inertial forces could be understood as an aspect of a unified gravito-inertial field. By establishing a "missing link" between the traditions of a mechanistic generalization of the relativity principle and field theory, he had found the key to the problems which appeared to be unsolvable within each of the two traditions taken

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[59] For the particular role of rotating frames in motivating this generalization, compare Einstein's later remark concerning an objection against the privileged role of inertial frames in classical mechanics and in Special Relativity: "The objection is of importance more especially when the state of motion of the reference-body is of such a nature that it does not require any external agency for its maintenance, e. g. in the case when the reference body is rotating uniformly." (Einstein 1961, p. 72)

separately. Where the followers of a field theory of gravitation searched in vain for an empirical clue which could have guided them beyond "Coulomb's law" of static gravitation (i. e. Newton's law) to a gravitational dynamics, Einstein succeeded with the help of Mach's critique in recognizing in the inertial effects of a rotating system such as Newton's bucket the case of a stationary gravitational field caused by moving masses. He interpreted this case as a gravitational analogue to a magnetostatic field in electrodynamics which can also be conceived as being caused by moving (in this case: electrical) masses. And vice versa, where the adherents of a mechanistic generalization of the relativity principle searched in vain for new effects which could reveal more about the mysterious interaction between distant masses in relative motion with respect to each other, which in the only case known to them was responsible for the curvature of the water surface in Newton's bucket, Einstein had no qualms about identifying this force as a dynamical aspect of universal gravitation and thus relate the unknown force to a well explored domain of classical physics. In summary, Einstein's experiences with a field theory of gravitation and his familiarity with the foundational problems of mechanics had set the stage for his reception of whatever these two traditions had to offer for his program to build a relativistic theory of gravity that was to be also a theory of General Relativity. What had previously seemed to be mutually exclusive approaches now became, to some extent, complementary from his perspective.

Hints at a Machian theory of mechanics in Einstein's research on gravitation between 1907 and 1912

In the following I will limit myself to an account of those features of Einstein's heuristics which reflect the complementary influence of the two traditions in the sense outlined above. While there is no direct contemporary evidence for the role of Mach's critique of mechanics on Einstein's formulation in 1907 of what later became known as the equivalence principle I have argued above that such an influence very likely forms the background for Einstein's reaction to the problems of a relativistic theory of gravitation.[60] Beyond shaping this reaction and opening the perspective towards a generalization of relativity theory, Mach's influence on the further development of this theory remained, however, at first secondary, even when Einstein began to elaborate his original insight into the equivalence principle in papers published in

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[60] See, in particular, Einstein 1954b for evidence that Einstein's perspective was indeed shaped by Mach's critique of mechanics already at a very early stage.

1911 and in 1912.[61] The principal reason for this secondary status is that, in this period, he drew mainly on the resources of field theory with the aim of constructing a field equation for the static gravitational field of his elevator thought experiment, in analogy to the field equation for Newton's gravitational field in classical physics.

Nevertheless, in the time between 1907 and 1912 Einstein seemed also to have collected hints pointing in the direction of a Machian theory of mechanics. For instance, he made use of Mach's analysis of the conceptual foundations of mechanics in preparing a course on classical mechanics at the University of Zurich for the winter semester 1909/1910[62] and referred to it in connection with his research on gravitation in correspondence to Ernst Mach of the same period.[63] To a friend he wrote about the same time: "I am just now lecturing on the foundations of that poor, dead mechanics, which is so beautiful. What will its successor look like? With that question I torment myself ceaselessly."[64] In the notes Einstein prepared for his lecture course he introduces Mach's definition of mass.[65] He emphasized the close relationship between gravitational and inertial mass, pointing to the independence of both on material properties: "The fact that the force of gravity is independent of the material demonstrates a close kinship between inertial mass on the one hand and gravitational action on the other hand."[66] The dependence of the concept of inertial mass on the entire system of bodies in the universe as it is implicit in Mach's definition of mass made it conceivable for Einstein that also the magnitude of the inertial mass of a given body may be a function of the system of other bodies that varies with their distribution around the given body.[67] In a paper published in 1912, he partially confirmed this

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[61] See, in particular, Einstein 1911, Einstein 1912a, Einstein 1912b, and Einstein 1912c.

[62] See Einstein’s Lecture Notes for an Introductory Course on Mechanics at the University of Zurich, winter semester 1909/1910 in Klein et al. 1994a.

[63] See Einstein to Ernst Mach, 9 August 1909 (Klein et al. 1993, Doc. 174, p. 204) and Einstein to Ernst Mach, 17 August 1909 (Klein et al. 1993, Doc. 175, p. 205).

[64] Einstein to Heinrich Zangger, 15 November 1911 (Klein et al. 1993, Doc. 305, p. 349).

[65] See pp. 7-8 of Einstein’s Lecture Notes for an Introductory Course on Mechanics at the University of Zurich, winter semester 1909/1910 (Klein et al. 1994a, pp. 15-16.

[66] See p. 15 of Einstein’s Lecture Notes for an Introductory Course on Mechanics at the University of Zurich, winter semester 1909/1910 (Klein et al. 1994a, p. 21, my transl.)

[67] This is in disagreement with the claim expressed in Barbour 1992, p. 135, that Einstein was not justified in maintaining that he was a following a stimulation by Mach in considering a dependence of inertial mass on the presence of other masses in the universe.

conclusion by calculating the effect on the inertial mass of a body due to the presence of a massive spherical shell around it; the same paper deals with the effect on this body by an accelerated motion of the spherical shell.[68] This paper, dedicated to Einstein's theory of the static gravitational field, is not only the first paper in which he publicly mentions Mach's critique as a heuristic motivation behind his search for a generalized theory of relativity, but it also carries a title expressing the translation of this heuristics into the language of field theory: "Is there a gravitational effect which is analogous to electrodynamic induction?"

In 1912 Mach's critique received a new importance for Einstein's work on gravitation also for another reason. After having convinced himself that he had found a more or less satisfactory theory of the static gravitational field he turned to what he considered to be the next simple case, the stationary field represented by the inertial forces in a rotating frame. In other words, after having, at least for the time being, exhausted the heuristic potential of the "elevator," he now turned to that of the "bucket." His contemporary correspondence confirms that he considered this case as well from the double perspective of field theory and the mechanistic generalization of the relativity principle: In a letter to Ehrenfest from 1912 he wrote with reference to his theory of the static gravitational field and to the generalization necessary to cope with situations such as that of a rotating ring: "In the theory of electricity my case corresponds to the electrostatic field, while the more general static case would further include the analogue of the static magnetic field. I am not yet that far."[69] In a roughly contemporary letter to Besso Einstein remarked, probably referring to the same state of affairs, i. e., to the treatment of the inertial forces in a rotating frame as generalized gravitational effects in a frame considered to be at rest - in the spirit of Mach's remark on Newton's bucket: "You see that I am still far from being able to conceive rotation as rest!"[70] Not only Einstein's publications and correspondence but also his private research notes document the influence of both traditions, that of electrodynamics and that of mechanics, on the terminology in which he expressed the heuristics of his theory, so that we can exclude the possibility that his choice of words was only a matter of making himself understood by his audience.[71]

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[68] Einstein 1912c.

[69] Einstein to Paul Ehrenfest, before 20 June 1912 (Klein et al. 1993, Doc. 409, p. 486).

[70] Einstein to Michele Besso, 26 March 1912 (Klein et al. 1993, Doc. 377, p. 436).

[71] See, in particular, Einstein's comments on his calculation of the effect of rotation and linear acceleration of a massive shell on a test particle in his and

Einstein's Machian heuristics and his discovery of the relevance of non-Euclidean geometry to the problem of gravitation in 1912

Einstein found it difficult to accomplish the transition from his treatment of the static special case to a more general theory including the dynamic aspects of the gravitational field. In the summer of 1912, however, he attained the insight into the crucial role of non-Euclidean geometry for formulating the gravitational field theory he searched for, an insight which in spite of the many difficulties still to be resolved definitely paved the way for the final theory of General Relativity published in 1915. In the following I will reconstruct this insight in some detail as an important example for the fruitfulness of the combined heuristics of "elevator" (i. e., Einstein's equivalence principle) and "bucket" (i. e., the bucket of Newton and Mach in Einstein's interpretation) on the development of General Relativity.

The story began with the discovery of a problem in the context of the elaboration of the Special Theory of Relativity, a problem which later became known as "Ehrenfest's paradox:" The consideration of a rigid disk set into uniform rotational motion posed the problem that while the circumference of the disk should shorten due to Lorentz contraction as measured from an observer at rest, the radius of the disk should remain invariant being perpendicular to the motion of the disk.[72] In other words, under these circumstances the ratio between the circumference of the disk and its radius is no longer given by π as in Euclidean geometry. While this consideration was generally perceived as posing a problem for the concept of rigid body in Special Relativity, Einstein - evidently on the background of his interest in generalizing the principle of relativity to rotating frames - referred it also to the problem of interpreting space and time coordinates in a generalized theory of relativity. In particular, he surmised that Euclidean geometry is no longer applicable in a theory generalized to include rotating frames.[73] The "heuristics of the bucket" thus suggested an extension of the realm of mathematical resources relevant to the theory of gravitation to include non-Euclidean geometry, without, however, pinpointing the exact place in which these resources could be applied.[74]

Michele Besso's Manuscript on the Motion of the Perihelion of Mercury, dated May 1913, in Klein et al. 1994b.

[72] See Ehrenfest 1909, p. 918.

[73] See Einstein to Arnold Sommerfeld, 29 September 1909 (Klein et al. 1993, Doc. 179, p. 210) and Einstein 1912a, p. 356. For a discussion of this argument, see also Barbour 1990, pp. 54-55.

[74] For a comprehensive discussion of the role of the problem of the rigid disk in the development of General Relativity, see Stachel 1989. For the Machian

That indication was provided instead by the "heuristics of the elevator," or to be more precise, by the further development of Einstein's theory of the static gravitational field. In May 1912 Einstein succeeded in formulating the equation of motion of a point-particle in a static gravitational field in such a form that its generalization to more general gravitational fields became a matter of writing down an algebraically more general formula:[75]

$$\delta\left\{\int\sqrt{c^2dt^2 - dx^2 - dy^2 - dz^2}\right\} = 0$$

While this formula contains only one variable representing the static gravitational potential (the variable speed of light c), it could easily be extended by introducing more variables in order to describe more general gravitational fields. Einstein's concluding remark in fact reads: "The Hamiltonian equation written at the end hints at the way in which the equations of motion for the material point in a *dynamical* gravitational field are built."[76] But that in fact arbitrary gravitational fields are represented by this algebraically more general expression could have been only a conjecture for Einstein at this point. As will become clear in the following, however, the conjecture received strong support by the interpretation of the expression found in May 1912 as a line element in the sense of Gauss's theory of curved surfaces and by an argument based on the relationship between gravitation and inertia as it was established by the equivalence principle.

The recognition of the potential relevance of non-Euclidean geometry to the understanding of gravitation which Einstein had achieved in the context of his study of rotational motion shaped the perspective under which he could now perceive the formalism of his static theory. A short explanation of some key aspects of Gaussian surface theory as it became relevant to Einstein may therefore be called for at this point. The expression for the line element describing the intrinsic geometry of a curved surface according to Gauss's theory, which was later elaborated by Riemann and others to a differential calculus including non-Euclidean geometries of arbitrary dimensions, can be conceived as a generalization of the theorem of Pythagoras applied to the coordinates of points on a surface. In fact, in both cases the distance between two points on a surface can be expressed in terms

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background of the discovery of the relevance of non-Euclidean geometry to the problem of gravitation, see Einstein's recollections in his Kyoto Lecture (Ishiwara 1971, pp. 78-88).

[75] Einstein 1912b, p. 458.

[76] Einstein 1912b, p. 458 (my transl. and emphasis).

of the coordinates introduced on the surface. But in contrast to the case of the usual orthogonal coordinates in the Euclidean plane, in the general case of curvilinear coordinates on a curved surface, the square of the distance is not simply the sum of the squares of the coordinate differences between the two points, even if they are taken to be infinitesimally close to each other. It is rather the later so-called "metric tensor" $g_{\mu\nu}$ (a 2-by-2 matrix in the case of a two-dimensional surface) which is itself a function of the coordinates, that enters the relationship between the distance of two infinitesimally close points and their coordinate differentials:

$$ds^2 = \sum_{\mu\nu} g_{\mu\nu} dx_\mu dx_\nu$$

With these basic ideas of Gaussian surface theory in mind Einstein could now recognize that the algebraically more general expression suggested by the crucial term in the equation of motion of his static theory precisely corresponds to the general form of the line element expressed in terms of a generic metric tensor (generalized from surface theory to Minkowski's four-dimensional space-time continuum with three space-dimensions and one time-dimension). This insight must furthermore have immediately suggested to Einstein that, in general, the gravitational potential can be represented by such a 4-by-4 metric tensor $g_{\mu\nu}$, while in the special case of a static field the metric tensor simplifies to an expression containing only one variable (for a suitable choice of coordinates). What is more, the equation of motion in a static field could now be interpreted as the equation for a geodesic line in a four-dimensional geometry characterized by this metric tensor:

$$\delta\left\{\int ds\right\} = 0$$

In other words, if it should turn out to be correct that gravitational potentials can in general be represented by metric tensors, then a substantial part of the task to formulate a gravitational theory - the problem to find the equations of motion in an arbitrary gravitational field - has already been solved.

But even after Einstein had recognized that the gravitational potential of his static theory can be interpreted as a component of the metric tensor of a four-dimensional geometry he would nevertheless have been, at least in principle, in the same situation as those who searched for a dynamic theory of the gravitational field starting from Newton's theory as the only known special case. It was his "Machian" insight that the inertial effects in accelerated frames can be considered as an aspect of a more general gravito-inertial field which provided him with an entire class of examples supporting the relationship between equation of motion, metric tensor, and gravito-inertial field which had emerged from the generalization of the static theory. In fact, Einstein could easily show that the inertial motion of a particle in an arbitrarily accelerated frame of reference can be described by the same type of equation as that published in May of 1912 for a static gravitational field, but involving not just one variable but indeed a 4-by-4 metric tensor. The use of accelerated frames of reference to describe physical processes in a space-time continuum without gravitational fields can be compared to the introduction of curvilinear coordinates on a plane surface. The well-known equation for the inertial motion of a point particle - corresponding to a straight line on the plane surface - can be rewritten in curvilinear coordinates as the expression for a geodesic line in terms of a non-trivial metric tensor. This metric tensor can then be related to the inertial forces occurring in such accelerated frames. If now these inertial forces are being considered as just a special aspect of a field which in general describes inertial as well as gravitational effects, then it becomes even more plausible to assume that the equation of motion in terms of the metric tensor representing an inertial field is just a particular case of the equation of motion in terms of a metric tensor representing an arbitrary gravito-inertial field.[77]

The breakthrough to which the introduction of the metric tensor into the theory of gravitation amounted for Einstein was hence a consequence of the combination of the technical elaboration of the formalisms at his disposal and of more qualitative conceptual insights. To recapitulate the above reconstruction, which vindicates Einstein's claim of Mach's role for the discovery of the relationship between non-Euclidean geometry and the problem of gravitation:[78] the heuristics of the bucket, i. e. the Machian idea to consider the water in the bucket as constituting a frame at rest, first provided the qualitative insight into a possible role of non-Euclidean geometry (the problem of the rotating disk). The heuristics of the elevator, i. e. the elaboration of the theory of the static gravitational field, then prepared, in combination with Minkowski's four-dimensional formalism, the technical environment for the concrete application of this insight to the problem of gravitation. The crucial link between the general idea and this technical environment was provided by Gaussian surface theory which made it possible to interpret the equation of motion suggested by the formalism of the static theory as a geodesic equation of a, in general, non-Euclidean

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[77] For this argument, cf. Einstein 1913, p. 1236.

[78] See Einstein's Kyoto Lecture (Ishiwara 1971, pp. 78-88).

geometry. It was only possible, however, to exploit the formal similarity between the two equations because of the deeper conceptual similarity between the problem of motion in a gravitational field and the problem of inertial motion in an accelerated frame of reference, which was suggested by Einstein's Machian interpretation of inertia. This conceptual similarity, together with the specific problem of the rotating disk, may have indeed helped Einstein to think of Gaussian surface theory in the first place, as he had been familiar with the relationship established in classical mechanics between motion constrained to a surface without external forces - which also can be conceived of as generalized inertial motion - and the geodesic equation in Gaussian surface theory since his student days.[79]

In any case, the outcome of this process, the metric tensor as representation of the gravito-inertial field, now offered Einstein a framework for capturing the resources of the traditions of field theory and of the mechanistic generalization of the relativity principle, as well as those of mathematical traditions relevant to the emergence of General Relativity, such as that established by Riemann and Christoffel. The tradition of field theory suggested, for instance, that - following the model of Poisson's equation for the gravitational potential in classical physics - some second order differential operator was to be applied to the metric tensor in order to yield the left-hand-side of a gravitational field equation. It therefore does not come as a surprise to find that the first entries in a research notebook of the period 1912-1913 in which Einstein tackled the problem of gravitation reflect his attempt to translate the field equation of the theory for the static field into a second order differential for the metric tensor.[80] As it turned out, however, the construction of a satisfactory field equation for the gravitational field was a most difficult task that would demand Einstein's attention for the next three years to come. In his search he could rely on the tradition of the mechanistic generalization of the relativity principle which offered him concrete examples for metric

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[79] This is suggested by the similarity between a page in a contemporary research notebook by Einstein (p. 41R of Research Notes on a Generalized Theory of Relativity, dated ca. August 1912, in Klein et al. 1994b) and p. 88 of the student notes on Geiser's lecture course on infinitesimal geometry, taken by Einstein's friend Marcel Grossmann in 1898 (Eidgenössische Technische Hochschule, Zurich, Bibliothek, Hs 421: 16); for Einstein's attendance of this course in the summer semester 1898, see Stachel et al. 1987, p. 366; for his later recollections on the significance of this course for his work on General Relativity, see Ishiwara 1971, pp. 78-88. The connection between Einstein's research notes and Grossmann's student notes was discovered by Tilman Sauer, to whom I am grateful for making a preliminary version of his paper available to me; see also Castagnetti et al. 1994.

[80] See p. 39L of Research Notes on a Generalized Theory of Relativity (dated ca. August 1912) in Klein et al. 1994b.

tensors to be covered by the new theory, such as the metric tensor for the Minkowski space (i. e. the four-dimensional space-time corresponding to the Special Theory of Relativity without gravitational fields) described from the perspective of a rotating frame of coordinates. The inertial forces arising in such a rotating frame are well-known from classical physics and could hence serve as criteria for the theory to be constructed. In another contemporary notebook, for instance, Einstein examined the question of whether or not the centrifugal and Coriolis forces in a rotating frame are the consequences of a tentative theory of gravitation he was then studying.[81]

Conflicts between Einstein's original heuristics and his research on a relativistic theory of gravitation in the period 1912 - 1913

In the course of Einstein's long-lasting search for a gravitational field equation he exploited the heuristics of "elevator" and "bucket" in particular and of the traditions of field theory and mechanics in general in order to build up a considerable "machinery" consisting of formalisms, mathematical techniques, and conceptual insights (such as Poisson's equation as model for a gravitational field equation, the recognition that a metric tensor represents the gravitational potential, etc.). This machinery eventually developed a dynamics of its own and led to a "conceptual drift," i. e. to results that were not always compatible with Einstein's heuristic starting points - whether they were rooted in field theory or in the mechanistic generalization of the relativity principle. In the following, I will selectively discuss some examples of this peculiar effect in order to illustrate that Mach's Principle, too, belongs to its victims.

One of the first indications of this effect was a revision of the theory of the static gravitational field published in 1912 which ran into conflict with the "heuristics of the elevator," and also with an expectation raised by traditional field theory.[82] The revision of Einstein's first static theory became necessary after he had found out that his theory violated the principle of the equality of action and reaction. The gravitational field equation of his original theory was constructed in accordance with the model of Poisson's equation in classical physics, that is, a linear second order differential operator applied to the (scalar) gravitational potential was equated to a term involving the density of the masses representing the source of the field.

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[81] See p. 66 of Einstein’s Scratch Notebook 1900-1914? (Appendix A in Klein et al. 1994a) and Castagnetti et al. 1994.

[82] For Einstein's first theory, see Einstein 1912a, for his second, revised theory, see Einstein 1912b.

The revision of this theory induced by the requirement of momentum conservation led to a new field equation which now was no longer linear and which contained a term that Einstein interpreted as the energy density of the gravitational field acting as its own source.[83] The introduction of this correction term was plausible in the light of the relationship between mass and energy established by Special Relativity from which it follows that the energy represented by the masses of bodies and the energy represented by the gravitational field should both act as sources of the gravitational field there being no difference in principle between them. But on the other hand, the non-linearity of the revised field equation turned out to be incompatible with the equivalence principle as Einstein had formulated it in 1907. The homogeneous static gravitational field which Einstein had replaced by a uniformly accelerated frame of reference was simply no longer a solution of the revised non-linear field equation.[84] In other words, after the revision Einstein's theory of the static gravitational field contradicted its own heuristic starting point. As a consequence, Einstein had to restrict the Principle of Equivalence to infinitesimally small regions. From our perspective on the heuristic roots of General Relativity in classical physics, the most significant implication of this episode was, however, that the gravitational field had entered the scene in its own right, on a par with the material bodies acting as its source. It became hence, at least in principle, conceivable that non-trivial gravito-inertial fields could exist without being caused by material bodies. But as it turned out, Einstein remained hesitant to accept this conclusion - which is in obvious contradiction to the Machian requirement that all inertial effects are due to ponderable masses - even after he had formulated the final theory of General Relativity.

During the development of Einstein's generalized theory of relativity in the years 1912 and 1913 the "heuristics of the bucket" did not fare much better. It is true that in Einstein's research notes from this period one encounters again and again the metric tensor representing the Minkowski space as seen from a rotating frame of reference.[85] But, first of all, the physical situation represented by this metric tensor did not quite correspond to that envisaged by Mach in his discussion of Newton's bucket because there the inertial forces acting on the water in the bucket were speculatively related to the masses of the universe in relative rotation with respect to the water, while the metric

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[83] See Einstein 1912b, p. 457.

[84] For an extensive evaluation of Einstein's Principle of Equivalence, see Norton 1989a; and, in particular, p. 18 for the present discussion.

[85] See, e. g., pp. 42R, 43L, 11L, 12L, 12R, 24R, and 25R of Research Notes on a Generalized Theory of Relativity (dated ca. August 1912) in Klein et al. 1994b.

of Minkowski space does not represent the presence of such cosmic masses, being a solution of the field equation for empty space. This means that the original Machian argument had effectively been replaced by the aim to formulate a theory which remains invariant under the transformation to a rotating frame of reference, an observation that we could have made already above when we considered the role of Ehrenfest's paradox for the insight into the relevance of non-Euclidean geometry.

Secondly, it remained unclear for some time whether or not the field equation of the preliminary theory of gravitation which Einstein published in 1913 together with his mathematician friend Marcel Grossmann[86] satisfied even this transformed requirement of incorporating the Machian bucket. In this situation the original heuristics played the ambivalent role of providing not only the misleading reassurance that what should be true is actually true but also the orientation marks for the further search leading to the theory of 1915. When Einstein found that his "Entwurf" theory is invariant only under a restricted class of transformations which he could not easily specify and which possibly did not even include any transformations to accelerated frames of reference,[87] he at first looked for arguments that could justify the restriction on the basis of the original heuristics. He found, for instance, that he could infer a restriction of the admissible coordinate frames from the transformational properties of an equation he had identified as the expression for the conservation of energy and momentum covering both matter and the gravitational field. By interpreting this conclusion as the assertion that matter determines the choice of coordinate systems by way of the conservation laws he was able to interpret even his abandonment of general covariance from the perspective of his Machian heuristics.[88] Einstein's argument crucially depended on the identification of an "energy-momentum tensor" of the gravitational field as a constituent of his conservation laws. It quickly turned out, however, that this identification was not justified as the mathematical object in question does actually not have the properties of a tensor.[89] Einstein thus encountered another instance in which a conceptually new aspect of his emerging theory of gravitation - here the non-localizability of the gravitational energy corresponding to the

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[86] Einstein and Grossmann 1913.

[87] See Einstein to H. A. Lorentz, 14 August 1913 (Klein et al. 1993, p. 547).

[88] See Einstein to H. A. Lorentz, 16 August 1913 (Klein et al. 1993, pp. 552-553), Einstein 1913, p. 1258, and Einstein to Ernst Mach, second half of December 1913 (Klein et al. 1993, pp. 583-584). For a discussion the relationship of this argument to Einstein's Machian heuristics, see Hoefer 1994.

[89] See note 1 on p. 218 of Einstein and Grossmann 1914.

difficulty of identifying a gravitational energy-momentum tensor - undermined his original heuristics and even prevented its adaptation to his new findings.[90]

Apart from the general question of the nature of the restricted covariance class of the 1913 "Entwurf" theory of the gravitational field, the specific problem of whether or not this class included transformations to rotating coordinate systems was of the utmost importance to Einstein in view of his Machian aim to conceive rotation as rest. He at first believed that the "Entwurf" field equation does not actually hold in a Minkowski metric described in rotating coordinates and then erroneously convinced himself that it does.[91] It is an amazing fact that in spite of the crucial status in Einstein's conceptual framework of the question of whether or not the gravitational field equation holds for rotating coordinate systems he never explored this question in any depth.[92] On several occasions he performed calculations amounting to a check of this question without pursuing this relatively simple matter to the point of discovering that the "Entwurf" field equations do not hold for a Minkowski metric in rotating coordinates. Only in 1915 was Einstein forced to notice, practically by accident, that his field theory of 1913 fails this crucial test. It seems that, after he had found in 1913 that the "Entwurf" theory embraces accelerated frames of reference without however being able to specify which frames exactly, Einstein had simply assumed that rotating coordinates must be included among those accelerated frames. Apparently, it was difficult for him to imagine that what had been a crucial building block for constructing his theory, the rotating frame of reference, should not also be included in its range of application. In any case, Einstein's eventual discovery that the "Entwurf" theory is in conflict with this expectation was a principle motive for discarding this theory and for beginning anew the search for a theory that promised to become a better fulfilment of his original

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[90] After this attempt to justify a restriction of the covariance group had failed Einstein formulated another argument by which he aimed to show that generally covariant gravitational field equations are impossible as a matter of principle, the so-called "hole argument." For a discussion the relationship of this argument to Einstein's Machian heuristics, see Hoefer 1994.

[91] See Einstein to Michele Besso, ca. 10 March 1914 (Klein et al. 1993, pp. 603-604) and Einstein to Joseph Petzold, 16 April 1914, a letter recently discovered by Giuseppe Castagnetti in Berlin (GStA PK, I HA, Rep. 76 Vb, Sekt. 4, Tit. III, Nr. 37, Bd. 1, ; Bl. 135r-v).

[92] This fact and its significance was first noticed by Michel Janssen and will be discussed at length in a forthcoming publication. I am grateful to him for making a preliminary version of his paper available to me.

goals.[93] In this way, the "heuristics of the bucket" again played a crucial role in the discovery of the General Theory of Relativity.

Attempts at a Machian interpretation of General Relativity in the period 1915 - 1917

After Einstein had formulated this theory in 1915, the tension between his original heuristics and the implications of what he had found were, however, not resolved but continued to characterize the further development of General Relativity at least until 1930. It may appear that, initially, a motive behind Einstein's emphasis on epistemological arguments based on the relationship between the new theory and its Machian heuristics was his desire to make his achievement acceptable to the scientific community because an important element of the empirical confirmation of the theory was only supplied when the eclipse expedition of 1919 spectacularly confirmed the bending of light by a gravitational field. In 1913 Einstein had written to Mach that the agreement which he had found between the consequences of his then preliminary theory of gravitation and the latter's critique of Newtonian mechanics was practically the only argument he had in its favor;[94] and also in his early publications on the final theory he insisted again and again on its epistemological advantages, which provided additional arguments for its claim of superiority with regard to competing theories.[95]

But as a matter of fact Einstein's insistent pursuit of the Machian aspects of General Relativity in these early years after its formulation was determined less by tactical motives than by the need of a physical interpretation of the technical features of the new theory in the light of the heuristics that had made its formulation possible. For instance, the insight, that as a rule specific boundary conditions are required in addition to the distribution of matter in order to determine the gravitational field by the field equations had to be brought together with Einstein's intention to realize a generally relativistic theory and his Machian hopes of explaining inertial behavior by material bodies only.[96] For some time in 1916 and early 1917 he attempted to formulate boundary conditions that would somehow comply with his original

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[93] See, e. g., Einstein to Arnold Sommerfeld, 28 November 1915.

[94] See Einstein to Ernst Mach, second half of December 1913 (Klein et al. 1993, pp. 583-584).

[95] See, e. g., Einstein 1916a, pp. 771-772.

[96] See Einstein to Lorentz, 23 January 1915, and the extensive historical discussion in Kerszberg 1989a and b, as well as in Hoefer 1994, on which the following account is based.

intentions.[97] He searched, for example, for boundary conditions in which the components of the metric tensor would take on degenerate values as he assumed that a singular metric tensor would remain invariant under general coordinate transformations and thus allow to maintain the requirement of General Relativity even in the boundary region of the space-time. Or he searched for a way to define a boundary region outside the system of masses constituting the physical universe in which a test body would not display any inertial behavior so that he might then be able to claim that inertia is indeed created by the physical system circumscribed by this empty boundary region.[98] It is noteworthy that in the course of these attempts the expectation that General Relativity was to provide a Machian explanation of inertia began to be silently transformed from a requirement concerning the nature of the theory to a criterion to be applied to specific solutions of the theory. As a matter of fact, since Minkowski's flat space-time with its inertial properties familiar from classical mechanics and Special Relativity was a solution to the field equations of General Relativity for the absence of matter, it simply could not be true in general that in this theory inertial effects are explained by the presence of matter.

After Einstein's failure to find a satisfactory treatment of the supposed Machian properties of General Relativity along the road of singular boundary conditions, he published in February 1917 a completely different proposal to deal with the cosmological aspects of the theory.[99] He had found that it seemed possible to formulate a space-time satisfying all his expectations concerning the constitution of the universe, including the explanation of its inertial properties by the masses acting as sources of the gravitational field, but at the price of modifying the field equations to which this space-time was a solution. As Einstein's cosmological paper of 1917 has been discussed a number of times, I can confine myself here to briefly emphasizing its place in the development of the tensions between Einstein's Machian heuristics and the implications of the new theory.[100] The solution to the field equations - modified by the introduction of a "cosmological constant" - which Einstein considered in 1917 describes a spatially closed and static universe with a uniform distribution of matter. It therefore avoided the problem of boundary conditions and at the same time was believed by him to correspond to a more or less realistic picture of the universe as it

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[97] See, e. g., Einstein to Michele Besso, 14 May 1916.

[98] See Einstein to de Sitter, 4 November 1916 and Einstein to Gustav Mie, 8 February 1918.

[99] Einstein 1917.

[100] See in particular Hoefer 1994 for a detailed discussion of this paper from the point of view of Mach's influence on Einstein.

was then known. In fact, however, Einstein rather tended to neglect the relationship between the new theory and astronomy, as well as the exploration of the properties of the solutions to its field equations, in contrast in particular to Willem de Sitter who in these years was his principal opponent in the discussion about whether or not Mach's explanation of inertia made sense on the background of the cosmological implications of General Relativity.[101] In any case, Einstein not only hoped that his radical step of modifying the field equations of General Relativity had allowed him to find at least one acceptable solution to the field equations but he also assumed that he had succeeded in getting rid altogether of empty space solutions in which inertial properties are present in spite of the absence of matter.[102] It was therefore an unpleasant surprise to him - which he found difficult to digest and at first attempted to refute - when de Sitter demonstrated shortly after the publication of Einstein's paper that even the modified field equations admit of just such an empty space solution.[103] In 1918 Einstein published a critical note on de Sitter's solution in which he wrote: "If de Sitter's solution were valid everywhere, then it would be thereby shown that the purpose which I pursued with the introduction of the λ-term [the cosmological constant J. R.] has not been reached. In my opinion the General Theory of Relativity only forms a satisfactory system if according to it the physical qualities of space are *completely* determined by matter alone. Hence no $g_{\mu\nu}$-field must be possible, i. e., no space-time-continuum, without matter that generates it."[104]

The introduction of "Mach's Principle" in 1918

The increasing tension between Einstein's original intentions and the ongoing exploration of consequences of the new theory was accompanied by attempts to rephrase the criteria of what it meant to satisfy the philosophical requirements corresponding to the heuristics which had guided the discovery of the theory. Characteristically, in 1918 Einstein introduced and defined the very term "Mach's Principle" in the context of a controversy on whether or not the General Theory of

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[101] See, e.g., Einstein to Willem de Sitter, 12 March 1917, where he referred to his solution as a "Luftschloss," having the principal purpose of showing that his theory is free of contradictions. See also Einstein to Besso, 14 May 1916, for the Machian motivations of Einstein's construction. For a historical account of the controversy between Einstein and de Sitter on the implementation of Machian ideas and cosmological considerations in General Relativity, see Kerszberg 1989a and b.

[102] See Einstein to de Sitter, 24 March 1917.

[103] See de Sitter to Einstein, 20 March 1917.

[104] Einstein 1918b, p. 271.

Relativity in fact represented a realization of his intention to implement a generalization of the relativity principle of classical mechanics and Special Relativity.[105] His paper of 1918 was a response to the argument by Kretschmann that the general covariance of the field equations of General Relativity does not imply such a generalization of the relativity principle but are to be considered as a mathematical property only. Einstein argued that he had so far not sufficiently distinguished between two principles which he now introduced as the Principle of Relativity and Mach's Principle.[106]

The first principle defined by Einstein states that the only physically meaningful content of a relativistic theory in the sense of this principle are coincidences of physical events in points of space and time. Since the occurrence of these point coincidences is independent of whether they are described in one or the other coordinate frame, their most appropriate description is by a generally covariant theory. This principle had, of course, not been the starting point of Einstein's search for a generally relativistic theory of gravitation but rather constitutes a result of his reflection on complications encountered in a long but eventually successful search for such a theory.[107] For our purpose here it is particularly remarkable that this formulation of the Principle of Relativity no longer appeals to the intuition of a world of isolated bodies distributed in an otherwise empty space whose physical interactions should only depend on their relative distances, velocities, etc., an intuition which is characteristic of the mechanistic generalization of the relativity principle and which was at the root of Einstein's search for a generalized theory of relativity.

This original intuition had in fact included Mach's suggestion to conceive of inertial effects as the result of physical interactions between the bodies of such a world. Now, however, the further development of Einstein's theory had enforced a separate clarification of what could be meant by a causal nexus between inertial effects and matter. In fact, the idea of such a causal link suggested by Mach's critical analysis of the foundations of classical mechanics needed to be reinterpreted in the light of the newly developed formalism of General Relativity. According to this formalism inertial effects are described by the metric tensor representing the gravito-inertial field, while matter is described by the

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[105] See Einstein 1918a, pp. 241-242.

[106] For historical discussions of this paper and its context, on which the following account is based, see Norton 1992a, in particular pp. 299-301, and Norton 1993b, pp. 806-809.

[107] See the various discussions of Einstein's "hole argument" in the recent literature, e. g. in Norton 1989b, section 5.

energy-momentum tensor representing the source term of the field equations for the gravitational field. It was therefore natural for Einstein to translate the supposed causal nexus between inertial forces and matter into the requirement that the gravitational field is entirely determined by the energy-momentum tensor. It is this requirement which he chose to call in 1918 "Mach's Principle."[108] Certainly this was not a mathematically concise criterion allowing one to examine either General Relativity as a theory or particular solutions of it in order to decide whether they do or do not satisfy Mach's Principle. Two aspects of this principle are, nevertheless, clear: The translation of Mach's original suggestion into the language of General Relativity transferred it from the conceptual world of mechanics into the conceptual world of field theory, as both terms in Einstein's 1918 definition of Mach's Principle are basically field theoretical concepts, the gravitational field as well as the energy-momentum tensor. Secondly, it is obvious from the context of this definition - which we have discussed in part above - that, whatever was precisely intended, Einstein considered empty space solutions of the gravitational field equations, that is, solutions in which a gravitational field is present even in the absence of matter, as a violation of this principle.

The conceptual drift from Mach's Principle to "Mach's ether" (1918-1920)

Ironically, both of these aspects of Einstein's first explicit definition of Mach's Principle in his writings contributed to preparing the ground for its eventual rejection. As a first step towards this rejection, which we have already considered above, de Sitter established that not only Einstein's gravitational field equations of 1915 but even the equations modified by the introduction of the cosmological constant admit of empty space solutions. As a consequence, Mach’s Principle now definitely took on the role of a selection principle for solutions to the field equations. It seems that one interpretative reaction by Einstein to this serious defeat of his principle was to extend the field theoretical interpretation of General Relativity at the expense of the emphasis on the mechanical roots of his original heuristics. By 1920 the attempt of 1918 to define Mach's Principle in terms of the conceptual building blocks of his theory had been complemented by the introduction of a

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[108] "*Mach's principle*: The *G*-field is *completely* determined by the masses of bodies. Since mass and energy are identical in accordance with the results of the special theory of relativity and the energy is described formally by means of the symmetric energy tensor ($T_{\mu\nu}$), the *G*-field is conditioned and determined (*bedingt und bestimmt*) by the energy tensor of the matter." See Einstein 1918a, pp. 241-242, quoted from Barbour 1992, p. 138.

"Machian ether" as a means to capture its conceptual implications.[109] In a lecture given 1920 in Leiden, Einstein exploited the time honored concept of an ether, to which Lorentz had given the definitive form for the realm of electrodynamics, in order to explain the new concept of space which had emerged with General Relativity.[110] He now directly turned against Mach's interpretation of inertial effects as caused by cosmic masses because this interpretation presupposed an action at a distance, a notion incompatible with both field theory and relativity theory. Instead and contrary to his original heuristics, Einstein associated these inertial effects with the nature of space, which he now conceived as equipped with physical qualities and which he hence appropriately called ether.[111] Contrary to Lorentz's ether, however, Mach's ether, which Einstein thought of as being represented by the metric tensor, was supposed not only to condition but also to be conditioned, at least in part, by matter. This capacity of being influenced by the presence of matter was, apparently, the last resort which the Machian idea of the generation of inertial effects by the interaction of material bodies had taken in Einstein's conceptual framework.

Two aspects of the relationship between matter and space remained, however, open problems for the time being: With space - under the name of a Machian ether - taking on the role of an independent physical reality, the question presented itself of whether matter had not lost all claims to primacy in a causal nexus between space and matter. In his Leiden lecture Einstein noted that it was possible to imagine a space without an electromagnetic field but not without a gravitational field, as space is only constituted by the latter; he concluded that matter - which for him was represented by the electromagnetic field - appears to be only a secondary phenomenon of space.[112] In 1919 he had made an attempt at a derivation of the properties of matter from the gravitational and the electrodynamic field, an attempt which he considered as still being unsatisfactory but which, for him, constituted the beginning of a new line of research in the

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[109] For historical discussions, see Illy 1989, Kox 1989, and Kostro 1992. Probably under the influence of Lorentz, Einstein had begun to reconsider the concept of ether already in 1916. On 17 June of this year he had written to H. A. Lorentz: "I admit that the General Theory of Relativity is closer to the ether hypothesis than the special theory." (transl. in Kostro 1992, p. 262). At that time, however, as the same letter suggests, Einstein took it for granted that the ether is entirely determined by material processes. The transition to the ether concept as explained in the following seems to be complete by the end of 1919, see Einstein to Lorentz, 15 November 1919.

[110] See Einstein 1920.

[111] See Einstein 1920, pp. 11-12.

[112] See Einstein 1920, p. 14.

tradition of the electrodynamic or rather field theoretical world view.[113] It lay in fact in the perspective of such a research program not only to reintroduce the concept of an ether in order to represent the physical qualities of space but also to provide a theoretical construction of matter as an aspect of this ether. The other question concerning the relationship between matter and space which was left unclarified even after Einstein's introduction of a Machian ether was the astronomical problem of the distribution of masses and of the large-scale spatial structure of the universe. Both questions, the theoretical as well as the empirical one turned out to be significant not only for Einstein's further exploration of General Relativity but, along the way, for the fate of Mach's Principle as well.

Mach's Principle from the Backburner to Lost in Space (1920-1932)

The program to interpret General Relativity along the lines of Mach's philosophical critique of classical mechanics ceased to play a significant role in Einstein's research after 1920. In addition to the difficulty of implementing Machian criteria in the elaboration of the theory, his exploration during the twenties of the heuristic potential which General Relativity offered to the formulation of a unified theory of gravitation and electrodynamics was probably responsible for this shift of interest.[114] As this heuristic potential for a further unification of physics was associated with the field theoretic aspects of General Relativity, the relationship of the theory to the foundational problems of mechanics naturally stepped into the background. Nevertheless, on several occasions during his ongoing research on a unified theory of gravitation and electromagnetism, Einstein hoped that he was able to link the program of a unified field theory with a satisfactory solution of the cosmological problem in the sense of his Machian heuristics. In 1919, for example, he emphasized that his new theory had the advantage that the cosmological constant appears in the fundamental equations as a constant of integration, and no longer as a universal constant peculiar to the fundamental law; he made a point of showing that again a spherical world results from his new equations.[115] An additional reason for not definitely rejecting Mach's Principle may have been Einstein's awareness in a period which saw the triumph of quantum mechanics that, after all, not the field theoretical but rather the corpuscular foundation of physics might prevail in the end, so that

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[113] See Einstein 1919.

[114] See Pais 1982, pp. 287-288; see also the extensive discussion in Vizgin 1994.

[115] See Einstein 1919, p. 353, see also Einstein 1923b, p. 36.

fields would indeed have to be conceived as epiphenomena of matter, just as the gravitational field is according to Mach's Principle.[116]

There also was a rather mundane reason for why Mach's Principle did not figure prominently in Einstein's publications of this period and yet was not entirely dismissed by him: more than its definition in 1918, its association with the cosmological model of 1917 had brought the principle to an end point of its theoretical development, to a point where the question of whether or not Mach's Principle could be implemented in General Relativity had become a question of its confirmation or refutation by astronomical data. In 1921 Einstein remarked with reference to the possibility of explaining of inertia in the context of his cosmological model: "Experience alone can finally decide which of the two possibilities is realised in nature."[117] In any case, for the time being, he remained convinced that astronomical research on the large systems of fixed stars could not but bear out a model of the universe compatible with his Machian expectations. Also in 1921 he wrote: "A final question has reference to the cosmological problem. Is inertia to be traced to mutual action with distant masses? And connected with the latter: Is the spatial extent of the universe finite? It is here that my opinion differs from that of Eddington. With Mach, I feel that an affirmative answer is imperative, but for the time being nothing can be proved."[118] In other words, although Einstein invested his hopes and his research efforts in the period between 1920 and 1930 mainly into the creation of a unified field theory, he nevertheless kept Mach's Principle on the backburner as long as it was not contradicted by astronomical data.

Einstein's firm conviction made him sceptical with respect to the possibility of alternative cosmological models. In 1922 he criticized, among other proposals, Friedmann's paper on solutions to the original field equations which correspond to a dynamical universe.[119] He believed to have identified a calculational error in Friedmann's solution, which he had looked upon with suspicion from the beginning. In another

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[116] See, in particular, Einstein's views expressed in connection with theoretical and experimental studies of radiation in this period, for example: "It is thus proven with certainty that the wave field has no real existence, and that the Bohr emission is an instantaneous process in the true sense." (Einstein to Max Born, 30 December 1921, my transl.; see also the discussion in Vizgin 1994, p. 176.)

[117] Einstein 1922a, p. 42; the German original was published in 1921 (Einstein 1921a).

[118] Einstein 1921b, p. 784. Einstein's astronomical views in this period were strongly under the influence of his Machian belief, see, e. g., Einstein 1922b, p. 436.

[119] See Einstein 1922d; for Einstein's criticism of other proposals, see Einstein 1922b and Einstein 1922c.

paper of the same year, he explicitly criticized a cosmological model for its incompatibility with "Mach's Postulate."[120] In 1923, however, Einstein recognized that he had committed an error in rejecting the dynamical solutions of Friedmann. He published a retraction of his earlier criticism and henceforth no longer expected an astronomical confirmation of his Machian cosmology with the same certainty as before.[121] The change of Einstein's attitude is already apparent from a comparison between the published retraction of his criticism with a manuscript version that has been preserved. In the manuscript version Einstein wrote: "It follows that the field equations, besides the static solution, permit dynamic (that is, varying with the time coordinate) spherically symmetric solutions for the spatial structure, to which a physical significance can hardly be ascribed." In the published paper, on the other hand, Einstein omitted the last half-sentence.[122] In another paper of the same year, Einstein referred with scepticism to "Mach's Postulate" and to the modification of the field equations which it requires because the introduction of the cosmological constant was not founded on any experience; he concluded: "For this reason the suggested solution of the 'cosmological problem' can, for the time being, not be entirely satisfactory."[123]

Nevertheless, until the end of the twenties Einstein did not give up his hope that Mach's Principle could be maintained as a feature of a cosmologically plausible solution of the field equations of General Relativity. When he discussed the "ether" of General Relativity in 1924 he added that it is determined by ponderable masses and that this determination is complete if the world is spatially finite and closed in itself.[124] In the same paper he dealt both with the possibility that a unification of gravitation and electrodynamics can be achieved by field theory and with the possibility that an understanding of the quantum problem can be achieved without field theoretical components.[125] As suggested above, it is conceivable that this ambivalence as to which of the foundational concepts - field or corpuscle - would eventually prevail may have reinforced the role of Mach's Principle in Einstein's thinking. In 1926 he discussed the cosmological implications of General Relativity

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[120] See Einstein 1922b, p. 437.

[121] Einstein 1923c.

[122] This has been noted by John Stachel, see, also for the translation of the passage, Stachel 1986, p. 244.

[123] Einstein 1923a, p. 8., my transl. He also modified an earlier version of an attempt to formulate a unified field theory by omitting the cosmological constant, see Vizgin 1994, pp. 192-193.

[124] See Einstein 1924, p. 90.

[125] See Einstein 1924, in particular, pp. 92-93.

in line with his earlier arguments in favor of a finite static universe.[126] In 1929 he wrote: "Nothing certain is known of what the properties of the space-time continuum may be as a whole. Through the general theory of relativity, however, the view that the continuum is infinite in its time-like extent but finite in its space-like extent has gained in probability."[127]

Around 1930, however, things began to change. Primarily driven by his strong intellectual engagement in the program to formulate a unified field theory Einstein expressed himself even more definitely than earlier in favor of a causal primacy of space in relation to matter - in sharp contrast to his original Machian heuristics. He would still ask the question "If I imagine all bodies completely removed, does empty space still remain?" and suggest a negative answer.[128] But now this question is not so much intended as referring to the constitution of the universe than rather as an epistemological enquiry regarding the construction of the concept of space. In fact, the entire passage which I have partly quoted reads: "But how is the concept of space itself constructed? If I imagine all bodies completely removed, does empty space still remain? Or is even this concept to be made dependent on the concept of body? Yes, certainly, I reply." While Einstein develops at length, in the sequel of the paper, his reasons for suggesting a *cognitive* primacy of the concept of physical object with respect to the concept of space, he concludes his discussion of the state of research on the foundations of physics with the remark quoted as a motto of this paper: "Space, brought to light by the corporeal object, made a physical reality by Newton, has in the last few decades swallowed ether and time and seems about to swallow also the field and the corpuscles, so that it remains as the sole medium of reality."[129] In a lecture given in 1930 Einstein formulated his view even more drastically: "The strange conclusion to which we have come is this - that now it appears that space will have to be regarded as a primary thing and that matter is derived from it, so to speak, as a secondary result. Space is now turning around and eating up matter. We have always regarded matter as a primary thing and space as a secondary result. Space is now having its revenge, so to speak, and is eating up matter."[130]

In the course of his work on unified field theory and assisted by his epistemological reflections Einstein had come a long way from

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[126] See Einstein 1926-1927 and, for historical discussion, Vizgin 1994, pp. 212-213.
[127] Einstein 1929, p. 107.
[128] Einstein 1930a, p. 180.
[129] Einstein 1930a, p. 184.
[130] Einstein 1930b, p. 610.

believing that a successful implementation of Mach's Principle would entail a synthesis of physics in which the concept of matter would play a primary and the concept of space a secondary role. Nevertheless, as the development of Mach's Principle in his thinking had become so closely associated with his cosmological ideas, the question of Mach's Principle remained open exactly to the extent that the decision about Einstein's static universe was left open by observational cosmology. In the period between 1917 and 1930 a dominant issue debated by researchers in this field was whether de Sitter's or Einstein's static universe is a better model of reality, while the question of expanding universes, raised by Friedmann in 1922 and by Lemaître in 1927, largely remained outside the horizon of observational cosmology.[131] The range of theoretical alternatives taken into account by contemporary researchers testifies to the persistent role of Einstein's Machian interpretation of General Relativity for cosmology, even if this interpretation gradually became a mere connotation of one of the cosmological alternatives rather than being the primary issue.

With the stage thus set for an observational decision on Mach's Principle, a definitive blow to Einstein's belief in it came with the accumulation of astronomical evidence in favor of an expanding universe, the decisive contribution being Hubble's work published in 1929.[132] Einstein became familiar with these results early in 1931, during a stay at CalTech. As is suggested by an entry in his travel diary of 3 January 1931, Richard Tolman convinced Einstein that his doubts about the correctness of Tolman's arguments in favor of the role of nonstatic models for a solution of the cosmological problem were not justified.[133] In March of the same year Einstein wrote to his friend Michele Besso: "The Mount Wilson Observatory people are excellent. They have recently found that the spiral nebulae are spatially approximately uniformly distributed and show a strong Doppler effect proportional to their distance, which follows without constraint from the theory of relativity (without cosmological constant)."[134] Almost immediately after his return to Berlin Einstein published a paper on the cosmological problem in which he stated that the results of Hubble had made his assumption of a static universe untenable.[135] As it was even easier for General Relativity to account for Hubble's results than to

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[131] See Ellis 1989, pp. 379-380.

[132] For historical discussion, see Ellis 1989, pp. 376-378.

[133] "Doubts about correctness of Tolman's work on cosmological problem. Tolman, however, was in the right." Quoted from Stachel 1986, p. 249, note 53; for a discussion of Tolman's contribution, see Ellis 1989, pp. 379-380.

[134] Einstein to Michele Besso, 1 March 1931, quoted from Stachel 1986, p. 245.

[135] Einstein 1931b.

construe a static universe - because no modification of the field equations by the introduction of a cosmological constant was required - his earlier solution now appeared to Einstein as remote from empirical evidence.[136]

In a lecture given in October of 1931 he still mentioned his static solution in connection with the implementation of Mach's ideas in General Relativity but, in spite of the numerous remaining difficulties of the dynamical conception of the universe, he now had definitely given up his belief in a Machian world.[137] In 1932 Einstein published himself an expanding universe solution to the unmodified field equations of General Relativity, in a joint paper with de Sitter - the main opponent of his earlier controversy about a Machian explanation of inertia.[138] In this paper the original Machian motivation for Einstein's static universe solution is no longer even mentioned: "Historically the term containing the “cosmological constant” λ was introduced into the field equations in order to enable us to account theoretically for the existence of a finite mean density in a static universe. It now appears that in the dynamical case this end can be reached without the introduction of λ."[139] In other words, in the course of the evolution of Einstein's cosmological views from his adherence to a static world to his acceptance of an expanding universe, Mach's Principle had disappeared from his perspective without any noise.

Reflections in the aftermath of Mach's Principle

Although Einstein continued to acknowledge the role of Mach's critique of classical mechanics for the emergence of General Relativity even after 1930, one can nevertheless notice a tendency to reinterpret even the heuristics which had originally guided his formulation of the theory. In his later accounts of the conceptual foundations of General Relativity he used the concept of field in order to point out those weaknesses of classical physics which he had earlier discussed in the spirit of Mach's critique of mechanics. He emphasized, for instance, that it was due to the introduction of the concept of field that the standpoint of considering space and time as independent realities had been surmounted.[140] Or he argued that already the Principle of Equivalence, which had originally motivated the extension of the relativity principle

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[136] Einstein 1931b, p. 5.

[137] See Einstein 1932.

[138] Einstein and de Sitter 1932.

[139] Einstein and de Sitter 1932, p. 213.

[140] See, e. g., Einstein 1961, Appendix V, p. 144.

beyond the Special Theory of Relativity, demonstrated the existence of the field as a reality in its own right, that is, independent of matter, since for the field experienced by an observer in an accelerated frame of reference the question of sources does not arise.[141]

But when the occasion presented itself, Einstein also became quite explicit about his rejection of his earlier Machian heuristics. In a letter to Felix Pirani, for instance, he explains with reference to Mach's Principle, as he himself had earlier defined it, that he no longer finds it plausible that matter represented by the energy-momentum tensor could completely determine the gravitational field, since the specification of the energy-momentum tensor itself already presupposes knowledge of the metric field. In the same letter Einstein explicitly revokes Mach's Principle: "In my view one should no longer speak of Mach's Principle at all. It dates back to the time in which one thought that the "ponderable bodies" are the only physically real entities and that all elements of the theory which are not completely determined by them should be avoided. (I am well aware of the fact that I was myself influenced by this *idée fixe* for a long time.)"[142] He similarly explains in his Autobiographical Notes: "Mach conjectures that in a truly reasonable theory inertia would have to depend upon the interaction of the masses, precisely as was true for Newton's other forces, a conception that for a long time I considered in principle the correct one. It presupposes implicitly, however, that the basic theory should be of the general type of Newton's mechanics: masses and their interaction as the original concepts. Such an attempt at a resolution does not fit into a consistent field theory, as will be immediately recognized."[143]

In summary, this section has shown that Mach's critique of classical mechanics was a crucial element in the heuristics guiding Einstein's way to the formulation of the General Theory of Relativity. It played this role as one among several aspects of the tradition of classical physics and was, just as many of these other elements, eventually superseded by the development of General Relativity. At the outset it opened up Einstein's perspective towards a generalization of the relativity principle and towards an explanation of inertial effects, and hence of the physical properties of space, by material bodies. By conceptualizing inertial forces as an interaction of bodies in motion, it provided a decisive complement to the prospect of a dynamical theory of gravitation which was suggested by the conceptual tradition of field

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[141] See Einstein 1961, Appendix V, p. 153.

[142] Einstein to Felix Pirani, 2 February 1954 (my transl.).

[143] Einstein 1992, p. 27.

theory but which lacked an empirical substantiation that could offer orientation among a variety of possible research directions. The results which Einstein accumulated in the course of his search for a General Theory of Relativity enforced several adjustments and reformulations of his original heuristics. Eventually, it became impossible for him to bring the progress of General Relativity into agreement with this heuristics.[144] Here we have seen that this is the case for those aspects of his heuristics which were founded on the stimulation received from Mach's critique of mechanics. It seems, however, plausible that the incompatibility between the conceptual framework that shaped Einstein's original heuristics and that which emerged from the final theory can be demonstrated more generally.[145]

5. Einstein’s Philosophical Perspective on the Foundational Problems of Physics

Einstein's route to General Relativity between physics and philosophy

The account given in the previous section of the impact of Mach's critique on the development of General Relativity seems to provide a strong case in point for an influence of philosophy on physics. Einstein himself confirms in many contemporary comments as well as in later recollections that he conceived the emergence of General Relativity at least in part as a response to Mach's analysis of the foundations of classical mechanics.[146] He indeed continued his search for such a response even when more simple alternative approaches to the problem of gravitation seemed to be available and when only epistemological arguments could motivate the continuation of his search for a generalization of the relativity principle.[147] The fact that also the followers of a mechanistic generalization of the relativity principle could refer to Mach's analysis as to the philosophical background of their enterprise, however, raises some doubts as to how significant the

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[144] See also the systematic discussions of the relationship between Mach's Principle and the progress of General Relativity in Goenner 1970 and 1981, and Torretti 1983, pp. 199-201.

[145] See Renn 1993 for the sketch of a theory of conceptual development in science accounting for this feature; see Castagnetti et al. 1994 for a discussion of the emergence of General Relativity along these lines.

[146] For contemporary evidence, see, e. g., Einstein's correspondence with Mach quoted above, for a later recollection, see, e. g., Einstein 1954a, pp. 133-134. The significance of Mach's philosophical critique of mechanics for Einstein is exhaustively treated in Wolters 1987, Chapter 1.

[147] See Einstein 1914, p. 344, where Einstein commented on Nordström's competing theory.

contribution of philosophy to Einstein's particular approach actually was. The starting point of Einstein's revision of the foundations of mechanics was in fact, as we have seen in the previous section, in contrast to that of these "Machians" not a general philosophical concern but a concrete problem which he encountered in the course of his research. It was not that the Principle of Equivalence had been formulated as a consequence of Einstein's search for a generalization of the principle of relativity but vice versa, that the introduction of the equivalence principle in the context of a problem of "normal science" had opened up the perspective towards the foundational questions of mechanics. In a recollection from 1919 Einstein laconically states with reference to the emergence of General Relativity: "The epistemological urge begins only in 1907."[148]

There is, however, a crucial distinction between the reaction of Einstein and that of the adherents of a mechanistic generalization of the relativity principle to Mach's critique of the foundations of mechanics. In Einstein's view, the primary philosophical attack of Mach's critique was directed precisely against what seemed to be for the "Machian relativists" - at least within the context of this particular research problem - an undisputed presupposition of their thinking, namely the mechanistic ontology on the basis of which they attempted a generalization of the relativity principle. Einstein himself later remembered that the questioning of the self-evident character of the concepts of mechanics was one of the principal effects which the philosophy of Mach had upon him: "We must not be surprised, therefore, that, so to speak, all physicists of the previous century saw in classical mechanics a firm and definitive foundation for all physics, indeed for the whole of natural science, and that they never grew tired in their attempts to base Maxwell's theory of electromagnetism, which, in the meantime, was slowly beginning to win out, upon mechanics as well. ... It was Ernst Mach who, in his *History of Mechanics*, upset this dogmatic faith; this book exercised a profound influence upon me in this regard while I was a student."[149] In other words, in contrast to those physicists whose reception of Mach's critique of mechanics was shaped only by the perspective of this one subdiscipline of physics, Einstein read Mach as a philosopher and hence understood the central philosophical intention behind Mach's historical and critical account of mechanics which was

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[148] See Einstein to Paul Ehrenfest, 4 December 1919 (my transl.). See also Wheeler 1979, p. 188, for a later recollection by Einstein, according to which he recognized the significance of the equality of inertial and gravitational mass only as a consequence of his failure to formulate a special relativistic theory of gravitation. For a different interpretation, see Barbour 1992, p. 130, p. 133.

[149] Einstein 1992, p. 19. See also Holton 1986, Chapter 7, pp. 237-277, in particular p. 241; Holton 1988, Chapter 4, pp. 77-104, and Wolters 1987, Chapter 1, pp. 20-36.

directed against the special status which mechanics had had for a long time among the subdisciplines of physics.

We may therefore ask whether it was this philosophical sensibility with regard to the epistemological character of some of the foundational problems of classical physics which protected Einstein from the temptation to attempt a solution of these problems within one of the subdisciplines of classical physics as did, for instance, the adherents of a mechanistic generalization of the relativity principle. There can be little doubt indeed that Einstein's thinking was characterized by such a sensibility which was in addition educated by his philosophical reading including such authors as Kant, Hume, Helmholtz, Mach, and Poincaré.[150] But it seems, on the other hand, doubtful whether a philosophical scepticism alone with regard to false pretensions of a conceptual system is sufficient to overcome its limitations. The philosophical critics at the turn of the century of the claim of a privileged status of classical mechanics, often associated as it was with the pretension of an *a priori* character, may themselves serve as counter examples. Neither Mach nor Poincaré built on the basis of their epistemological critique the foundations of a new mechanics, let alone the foundations of a new conceptual framework for all of physics. Poincaré who had emphasized the conventional character of scientific concepts was nevertheless as late as 1910 of the opinion that the principles of mechanics may turn out to be victorious in their struggle with the new theory of relativity and that it was hence possibly unjustified prematurely to abandon these principles.[151] Mach had left it open, as we have seen, that new empirical evidence may require a modification of the principles of mechanics.[152] Contrary to Einstein, he speculated that an electromagnetic world view may provide a new universal conceptual framework for the entire body of physics, while his own contributions to such a unity remained rather on the level of a metatheoretical reflection on science.[153] Einstein, in any case, was convinced that one should not attempt to identify Mach's crucial contribution in what can also be found in the works of Bacon, Hume, Mill, Kirchhoff, Hertz, or Helmholtz but rather in his concrete analysis of scientific content.[154]

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[150] For a list of some of Einstein's philosophical readings, see the introduction to Stachel et al. 1989a.

[151] See Poincaré 1911 (see also Cuvaj 1970, p. 108, for a historical discussion).

[152] See Mach 1960, pp. 295-296.

[153] For an extensive discussion of Mach's attitude with respect to the electromagnetic world view, see Wolters 1987, pp. 29-36. For Mach's attempt to integrate mechanics into the body of physics on the level of methodological reflections, see Mach 1960, Chapter 5.

[154] See his remarks to this effect in his obituary for Mach, Einstein 1916b, pp. 154-155.

It can, in addition, be historically documented that Einstein's scepticism with respect to the competing world views based on mechanics, electrodynamics, or thermodynamics was rooted in his precise knowledge of their respective scientific failings and not only in his epistemological awareness.[155] Shortly after the turn of the century, for instance, when the electromagnetic world view still appealed to many physicists as the most promising starting point for a new conceptual foundation of physics, Einstein had already recognized the devastating consequences which the discovery by Planck of the law of heat radiation had for classical electrodynamics and hence for the conceptual backbone of a world view based on traditional field theory. But does this observation not imply that what I have called "Einstein's philosophical perspective on the foundational problems of physics" simply dissolves, in the end, into technical competence in physics? This conclusion would only be justified if one accepted the conceptual distinction between philosophy of physics and physics as it is accepted today, that is, as a distinction between a methodological, epistemological, or metaphysical, in any case, a metatheoretical study of physics and the concrete occupation with its scientific problems. In order to respond to the question of the philosophical character of Einstein's perspective we have therefore briefly to examine the historical situation of the relationship between physics and philosophy at the time of Einstein.

The historical context of Einstein's philosophical perspective on physics

At the turn of the century the separation between philosophy of science and science in the sense accepted today had been complete for a long time. The more recent history of this separation can be understood as a consequence of the failure of traditional philosophy to integrate the natural sciences into its reflective enterprise. This failure is partly due to the explosive growth of the body of knowledge of the various disciplines and partly to the change of the cultural and political role which philosophy, and philosophy of science in particular, underwent in the nineteenth century. In German academic philosophy of the second half of the nineteenth century, for instance, Neokantianism, which saw itself as a critical reaction to the philosophy of German idealism played a weighty role.[156] Its gesture was that of a politically neutral epistemology which - in contrast to the natural philosophy of German

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[155] See, in particular, Einstein's own account in his autobiographical notes, Einstein's 1992, in particular, pp. 42-45, which is confirmed by recently found contemporary evidence such as Einstein's letters to Mileva Maric´ (see Renn and Schulmann 1992).

[156] For this and the following, see the detailed study by Köhnke (Köhnke 1986).

idealism, which often was anything but politically neutral - no longer issued any prescriptions for science but just attempted to capture the epistemological and methodological structures which made scientific progress possible. As much as Neokantianism and the tradition of philosophy of science which continued to pursue its metatheoretical concerns took the natural sciences as their orientation mark, they did not offer, on the other hand, a theoretical framework which allowed them to reflect upon the body of scientific knowledge in its totality, let alone for discussing the social and cultural conditions and implications of science.

The intrinsic necessity of dealing with science also as a social and cultural phenomenon had, on the other hand, since the middle of the nineteenth century been approached primarily on a pragmatic level, as is witnessed by the increasing role which science and education policy by the state and the creation of funding agencies and scientific organizations such as the Kaiser-Wilhelm-Gesellschaft in Germany played for the development of the large-scale structure of science. Attempts to achieve an intellectual integration of scientific knowledge, for instance in the form of a scientific world view, remained in the shadow of this development towards a practical control of the sciences as a social system, which only later was supplemented also by theoretical studies of science policy and the sociology of science.[157] As a consequence of this diverse dynamics of the social and the intellectual development of science, the transfer of knowledge beyond disciplinary boundaries and the establishment of connections between disparate branches of the body of knowledge remained a process largely left to chance and to the initiative of the individual researcher. Only to a small degree was this process systematically furthered by the requirements of the intellectual integration of science for the purposes of education, to mention one extreme, and in the context of a few, themselves highly specialized interdisciplinary research projects, to mention the other extreme. The lack of a global intellectual synthesis of scientific knowledge was, on the other hand, only poorly compensated by a popular scientific literature whose aim was often less the distribution and mediation of scientific knowledge than its mystification.

The lack of a systematic place in the social system of the sciences and of academic philosophy for a reflection on the contents of science beyond the narrow requirements of disciplinary specialization lent a particular importance to the philosophical efforts by scientists

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[157] For an attempt to assess this historical situation from the point of view of a systematic historical epistemology, see Damerow and Lefèvre 1994.

themselves. For Einstein's intellectual development it is in fact clear that the writings of scientists such as Mach, Duhem, Poincaré, and Helmholtz had a greater impact on his philosophical reflection on science than the works of contemporary academic philosophers, precisely because they often dealt with the philosophical implications of concrete problems at the forefront of research. Nevertheless, it would be misleading to consider Einstein's own philosophical contribution only as a continuation of the tradition of epistemological and methodological reflections by nineteenth century philosopher-scientists. Although this view is naturally suggested by the separation of physics and philosophy as it is understood today, it is too restrictive to capture the peculiar way in which research in physics and philosophical reflection are intertwined in Einstein's work. In fact, Einstein's scientific contributions to many branches of physics, from thermodynamics to statistical mechanics, from the theory of relativity to quantum physics, cannot be understood without assuming the background of a scientific world picture holding together otherwise disparate chunks of knowledge. Already as a student, Einstein possessed an extraordinary overview over the state of physics of his time, which enabled him to recognize foundational questions of physics in problems which others preferred to see only from the point of view of their area of specialization.[158] In comparison to Einstein's perception of the entire body of physics and its conceptual incongruences the claim of those who undertook the construction of, say, an electromagnetic world picture almost appears as an attempt to conceal the limitations of a specialist outlook. In any case, Einstein's perspective distinguished itself profoundly and with significant consequences from the mutual ignorance which characterized the field theoretical approach to the problem of gravitation and the approach of a mechanistic generalization of the relativity principle, as we have seen in section 3.

Einstein and the "culture of scientific mediation"

From my sketch of the historical situation of the relationship between physics and philosophy it should be clear that the roots of the scientific world view which shaped Einstein's perception of physics at the beginning of his career could only have been of a highly eclectic and backward character. What is known about his early biography allows the conclusion that his reading of popular scientific books, together with his exposure to the technical culture associated with the business activities of his family, played a crucial role for the early development

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[158] For a reconstruction of Einstein's discoveries of 1905 on this background, see Renn 1993. See also Holton 1988, Chapter 4.

of his scientific world view.[159] The popular scientific books which he devoured as an adolescent combined an easily accessible and conceptually organized overview of scientific knowledge with the claim that the enterprise of science also serves as a model for the development of moral and political standards.[160] These works represented an attempt to transmit the values of democracy, and of political and technological progress, which had been defeated on the political scene with the failure of the revolution of 1848, in the medium of popular science.[161] Einstein's scientific world view, which apparently had some of its roots in his early fascination with these popular scientific books, has indeed much in common with their image of science as a substitute for religion, with their appeal to the moral and also political ideals of science, and with their effort to achieve a conceptual unification of scientific knowledge beyond its disciplinary boundaries.[162]

The conceptual framework which formed the basis of this effort was a rather primitive combination of remnants of the old natural philosophy from the beginning of the nineteenth century and of scientific results roughly on the level of the state of knowledge at the middle of the century. It was, however, apparently sufficient to provide the young Einstein with a global perspective on science to which he could then assimilate a broad array of detailed knowledge without committing himself to a premature specialization. In any case, during his entire scientific career he pursued the idea of a conceptual unity of physics, whose first primitive image he may have encountered in his early reading of popular scientific literature. The history of Einstein's formulation of the Special Theory of Relativity, for instance, illustrates not only that he, already at the beginning of his career, saw in the conceptual diversity of mechanics and field theory a challenge to this unity of physics but also that he was aware that neither of the two subdisciplines alone could provide the basis for a solution of this conflict. On the contrary, the foundation of the Special Theory of Relativity on the principle of relativity from classical mechanics and on

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[159] For evidence, see Einstein 1992, as well as the documents collected in Stachel et al. 1987; for historical discussion, see Pyenson 1985, Renn 1993, Lefèvre 1994, and the unpublished paper by Gregory referred to below.

[160] See, in particular, Bernstein 1867-1869.

[161] The biographical background of Bernstein, the author of the book which apparently played a key role for Einstein's early intellectual development, has been extensively studied by Frederick Gregory to whom I am grateful for making a preliminary version of his paper accessible to me. For more on the relationship between popular scientific literature and political developments in the nineteenth century, see Gregory 1977; see also Lefèvre 1990.

[162] For a systematic analysis of the role of "images of science" as a mediator between science and its external influences, see Elkana 1981.

the principle of constancy of the speed of light rooted in the tradition of field theory makes it clear that the conceptual innovation represented by this theory presupposed an integration of the knowledge accumulated in these two branches of classical physics.

It is now possible to recognize in Einstein's reaction to the clash between classical mechanics and field theory in the case of gravitation, which I have reconstructed in detail in the previous sections, an intellectual attitude that was deeply rooted in his scientific world view and shaped by his experience with the creation of the Special Theory of Relativity.[163] The line of thinking of a mechanistic generalization of the relativity principle had a function for the emergence of General Relativity which is indeed similar to that which mechanics had for the development of Special Relativity: It provided the Principle of Relativity with the support of a network of arguments which reached outside the narrow scope of the specific questions under examination, be it the electrodynamics of moving bodies or the integration of Newton's theory of gravitation into a relativistic field theory. Similarly, in the case of Special Relativity, Einstein had taken the relativity principle as an almost self-evident starting point inherited from and "globally" supported by the entire building of classical mechanics, whereas Lorentz, for instance, dealt with the violation of the principle of relativity, which his assumption of a stationary ether entailed, only as a "local" problem, in the context of specific problems such as those posed by the Michelson-Morley experiment. Accordingly, Lorentz only had to handle the effects of the motion of the earth with respect to the ether in such a way that the violation of the Principle of Relativity was suppressed, step by step, beyond the reach of measurability, in the context of each particular problem area which he had to confront. Contrary to Lorentz's electrodynamics, Einstein's solution, the Special Theory of Relativity, treated the principles of mechanics as just as foundational as those of electrodynamics, at the price of a revision of the concepts of classical physics. As I have extensively shown above, the same characterization applies to Einstein's early work on General Relativity.

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[163] Einstein himself compared the heuristics which motivated his search for a general theory of relativity with that guiding his formulation of Special Relativity: "The theory has to account for the equality of the inertial and the gravitational mass of bodies. This is only achieved if a similar relationship is established between inertia and gravitation as that [which is established] by the original theory of relativity between Lorentz's electromotive force and the action of electrical field strength on an electrical mass. (Depending on the choice of the frame of reference, one is dealing with one or the other.)" See Einstein to H. A. Lorentz, Einstein to Lorentz, 23 January 1915 (my transl.).

Although Einstein's perspective on the foundational problems of physics encompassed the entire range of classical physics, there can be no doubt that it was dominated by the tension between its two major conceptual strands, field theory and mechanics. In 1931, for instance, he wrote: "In a special branch of theoretical physics the continuous field appeared side by side with the material particle as the representative of Physical Reality. This dualism, though disturbing to any systematic mind, has to-day not yet disappeared." He then added with specific reference to Lorentz's Theory of Electrons, as well as with respect to the Special and General Theories of Relativity: "The successful physical systems that have been set up since then represent rather a compromise between these two programmes, and it is precisely this character of compromise that stamps them as temporary and logically incomplete, even though in their separate domains they have led to great advances."[164] For Einstein, the insight into the need of overcoming the dualism of matter and field was not a matter of lip service to the conceptual unity of physics but one of the principal determinants of his research program. While his perspective was broader than that of many contemporary physicists, it was, however, also limited by this same program. To what extent Einstein's intellectual horizon was actually circumscribed by the problem of reconciling the fundamental conceptual conflict which he perceived at the heart of classical physics can be seen from his role in the exploration of the consequences of the theory of General Relativity up to the twenties. Contrary to other researchers who took part in this history, Einstein's interest focused almost exclusively on what might be called the "philosophical closure" of the new theory. Whether the problem of boundary conditions for the gravitational field or the question of exact solutions to the field equations was concerned, his interest in these emerging topics of research in General Relativity was not primarily guided either by a program of exploring new features of the theoretical structures he had created or by that of comparing these structures with the empirical results of astronomy but by the question of whether or not a deeper understanding of General Relativity would reveal its agreement with the heuristics that had guided its discovery. This interest merely reflects the perspective which had accompanied Einstein's work on General Relativity since its beginning: he had indeed not searched for a theoretical foundation of cosmology but for a contribution to the conceptual unification of classical physics and in particular a synthesis of the field theoretical and mechanical aspects of gravitation.

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[164] Einstein 1931a, pp. 69-70, and p. 72.

In spite of these limitations of Einstein's perspective and in spite of the conflict between his heuristic expectations and the conceptual implications of what he had found, it is remarkable that in the course of his work on General Relativity he was nevertheless gradually able to overcome his own preconceived expectations and to adapt the interpretation of his theory to his new results. This is in contrast to many other cases of conceptual innovation in science in which the crucial step of conceptual innovation takes place at a generational transition, in the transmission of knowledge from "master" to "disciple," so to say, as was actually the case in the transformation of Lorentz's electrodynamics into Einstein's Special Theory of Relativity.[165] Einstein's own significant contribution to the conceptual understanding of General Relativity is related to the fact that, from his earliest efforts to formulate such a theory to the end of his life, he did not cease to expound the conceptual presuppositions and consequences of his research in accounts accessible also to the non-specialist. Einstein was himself one of the great authors of popular scientific literature whose writings made the intellectual core of his scientific problems accessible to his readers with only a minimal technical component. The fact that the function of Einstein's general accounts of the theory of relativity was not only to disseminate expert knowledge to the layman but that these writings formed a medium for his own reflection on the conceptual aspects of scientific problems is usually overlooked by philosophers of science. But the gradual adaptation of Einstein's Machian heuristics to the implications of General Relativity and finally its definitive abandonment in the light of these implications provide a vivid illustration for the impact of these reflective accounts on the understanding of General Relativity by Einstein himself.

It is hardly possible to overlook the significance which the effort to explain scientific knowledge to laymen had for Einstein's intellectual biography in general and in particular for his capacity to address foundational questions beyond the limits imposed by disciplinary specialization. In Bern as well as in Zurich he shared his ideas with a group of friends most of whom were not physicists. In one case, that of Michele Besso, we know with certainty that Einstein was indebted to him for a decisive inspiration which made the breakthrough to the formulation of the Special Theory of Relativity possible.[166] Also in Bern as well as in Zurich he was part of amateur science societies which offered an institutional framework for an exchange of ideas which transgressed the usual academic and social boundaries. Even before his

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[165] See Renn 1993.

[166] See the acknowledgement in Einstein 1905 as well as the recollection in Ishiwara 1971.

study of physics in Zurich Einstein had the chance in Aarau of attending an unusual high school in whose intellectual atmosphere there was no sharp demarcation between research and education, and in which he could experience the spirit of a *res publica litterarum*. Teachers who were at the same time scientists, such as the physicists Conrad Wüest and August Tuchschmid or the linguist Jost Winteler, must have confirmed Einstein's conviction that science could offer the foundation for making a life, and not only intellectually.[167]

To conclude: a culture of science which includes the effort of explanation as well as the search for conceptual unity in the diversity of scientific knowledge, that is, a "culture of scientific mediation," forms an essential background for Einstein's philosophical perspective on the foundational problems of physics. The historical preconditions which made this perspective possible were fragile already at the time: Evidently, neither popular scientific literature nor societies of amateur scientists could halt the disciplinary fragmentation of scientific knowledge and the loss of the possibility for a single individual to achieve a comprehensive overview. In spite of the claim by many physicists of Einstein's generation to a proximity of their field to philosophy, Einstein was in fact already part of a small minority with his ceaseless attempts to reflect upon the whole of physics and search for its conceptual unity. The isolation in which he worked on his later attempts to create a unified field theory testify to his failure to achieve a unity of physics along these lines. Are therefore, in this historical sense, modern physicists right after all when they claim that only a dead physicist, better even a physicist who has been dead for a long time, can be a good philosopher? They would be right if we would expect from a single philosopher or physicist the kind of integrative achievement which even Einstein was no longer able to deliver. But considering how much a single individual could accomplish even on the basis of inadequate presuppositions, we can read the history of Einstein's contributions also as the challenge and the encouragement to work on a culture of scientific mediation which responds to the needs of today.

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[167] See the documents collected in Stachel et al. 1987 and Klein et al. 1993. For historical discussion, see Pyenson 1985 and the introduction to Renn and Schulmann 1992.

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