Introduction

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The year 1915 saw one of the most momentous events in the history of science: on 25 November of that year, Einstein completed his decade long search for a general theory of relativity by presenting his final gravitational field equations to the Prussian Academy for publication in its Proceedings. But despite Einstein's alleged "heart palpitations" that he said he experienced when he succeeded to compute the correct value of Mercury's perihelion, the quest for a new theory of gravitation was hardly answered yet. No solutions to the field equations were known, and the implications of the theory both for physics proper and for our philosophical understanding of physics were largely in the dark.

The publication of Einstein's field equations immediately gave rise to pioneering research. Only a few weeks after publication of Einstein's field equations, Karl Schwarzschild found the first non-trivial solution to these equations. Einstein himself continued to ponder the question of whether the theory faithfully reflected his underlying heuristic ideas, in particular, concerning what he began to call "Mach's Principle". During an exchange with the Dutch astronomer Willem de Sitter, he developed the first relativistic world model and thus laid the foundations for modern theoretical cosmology. And in 1919, Sir Arthur Eddington confirmed Einstein's prediction for the reflection of light during an eclipse, a feat that immediately proved decisive for Einstein's popularity in the broader public.

Since the theory had deep and far-reaching implications for our understanding of space and time, the discovery of the field equations was also followed by intense philosophical debate. Prominent proponents of positivism and neo-Kantianism, e.g. Moritz Schlick, Rudolf Carnap, and Ernst Cassirer made contributions of lasting importance.

In view of these developments, it seems just to say that, in November 1915, the theory had only just arrived but was not fully developed, yet; what we know and value as the theory of general relativity really only came into being in the aftermath of the discovery of the field equations, triggered by this event and building on it.

The aim of this volume therefore is to reconsider Einstein's theory from the perspective of its immediate and later reception in physics and philosophy. We aim at an integrated understanding of Einstein's theory by combining perspectives from both history and philosophy.

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Since many contributions to this volume integrate historical and philosophical perspectives (which we take to be very fruitful), they do not divide themselves naturally into categories that stress the viewpoint of one of either discipline, respectively. Nevertheless, some contributions are more historically oriented, while others focus more on philosophical aspects. We have thus organized the volumes by starting with the more historical contributions and then moving forward towards more philosophically oriented chapters.

The first chapter of the volume puts our very own conference into a historical perspective. **Claus Kiefer** takes a look back at another conference held in 1955 in Bern, which in some ways marks the beginning of the renaissance of the theory. Taking place only weeks after Einstein's death, the 1955 Bern conference can be considered the true beginning of a regular international conference series "General Relativity and Gravitation", which is still ongoing and which led to the institutionalization of an ever growing and active research community in general relativity. Kiefer, himself a physicist working in general relativity and quantum gravity, offers an assessment of the scientific content of the 1955 Bern conference. He comments on the papers given then and puts them into a larger perspective of later developments, singling out developments in classical general relativity, cosmology, and the very early work on quantum gravity.

John Norton goes further back in time and traces Einstein's path from the special theory of relativity to the discovery of the general theory. The story of Einstein's discovery of the gravitational field equations has been subject of intensive scrutiny and the story has been told many times, also in pioneering work by Norton himself. Nevertheless, neither has consensus been reached about all aspects of this nor have some notorious dark points been fully clarified yet. Norton addresses one such point which actually pertains to the heart of Einstein's intellectual journey. His point of departure is the unclear role that the principle of equivalence played in Einstein's thinking at the time, given the fact that the precursor theory of general relativity did not play out well on this explicit heuristics. Norton goes back to Einstein's early steps towards a static theory of gravitation and shows how a second tier of heuristics, viz. energy-momentum conservation, emerges as a powerful constraint that for some time overruled the more explicit demands of general equivalence.

One of the most important early applications of general relativity pertained to cosmology. Einstein's 1917 landmark paper "Cosmological Considerations in the General Theory of Relativity" ("Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie") established the first relativistic model of the Universe. In his chapter, **Cormac O'Raifeartaigh** examines Einstein's model from both a historical and a philosophical perspective. He stresses the important role that Mach's principle played for the introduction of the model.

Einstein had relied on the principle when introducing his very theory, and used it to rule out certain boundary conditions since he took them to be incompatible with the principle. Einstein finally came up with a spatially closed model of the Universe, the static character of which could only be maintained by introducing a cosmological constant in the field equations. In this respect, O'Raifeartaigh notes a slight mathematical inaccuracy that may have influenced Einstein's understanding of the new term. As O'Raifeartaigh further stresses, in his 1917 paper Einstein did not test his models against observations, although he could have done so; nor did he consider the stability of his world model.

The instability of his world model later became one of the prime reasons for Einstein to give it up. As **Casey McCoy** points out, considerations of stability have also played an important role in inflationary cosmology. One reason to believe that the early Universe was inflated by more than twenty orders of magnitude is that the Universe would otherwise be unstable with respect to its flatness: Small deviations from flatness would increase and lead to a Universe that is curved at large scales. It thus seems that stability is a key standard on cosmological models. In his chapter, McCoy spells doubts on this idea. After a close analysis of the instability of the Einstein world and of a flat cosmological model, he discusses stability from the perspective of dynamical systems theory. He argues that there are pragmatic reasons for assuming stability, but that an outright rejection of any unstable model is not justified.

A decisive application of any theory of gravity is the two-body problem; in general relativity it plays a particularly important role because of its connection to the problem of motion. **Galina Weinstein**'s chapter turns to Einstein's work on the two-body problem, which resulted in a particular solution to the gravitational field equations, the so-called Einstein-Rosen bridge, published in 1935. At the same time, he did also research on the thought experiment of the famous "EPR"-paper by Einstein, Rosen and Podolsky (1935). So might the Einstein-Rosen bridge have served as a heuristic guide for Einstein in developing the quantum mechanical thought experiment? Weinstein lays out the historical evidence for this conjecture and contends that, although we have no conclusive evidence for the claim that the EPR paradox would have been inspired by the Einstein-Rosen bridge, it is not an unlikely scenario.

With the formulation of non-Euclidean geometry in the 19th century, and with renewed urgency once general relativity came to be accepted, the "problem of space", i.e., the challenge of determining the geometrical structure of physical space, arose. **Neil Dewar** and **Joshua Eisenthal** present Weyl's solution to the problem of space, which he presented in 1922 in a series of lectures in Barcelona. Weyl started from the idea that the demand for free motion by a rigid body to be "localized" implied that acceptable geometries would just be those described by a metric whose form is infinitesimally Pythagorean, i.e., can be written as some positive-definite quadratic form. These "Riemannian" metrics have unique symmetric affine connections compatible with them, and so are associated with a unique notion of parallel transport. Dewar and Eisenthal then show how Weyl's insight and the concepts he introduced can be used to illuminate the contemporary debate of whether spacetime is represented in general relativity just by the bare topological manifold (while the metric counts as additional physical field) or by the manifold together with the metric field defined on it. Weyl offers a via media between these poles: the "nature" of the metric is part of spacetime's intrinsic, fixed essence, while its "orientation" is only a posteriori given and contingently determined by the material content of the world and consequently not part of spacetime. Dewar and Eisenthal feature Weyl's view as a contribution that is still significant to the question of what it is to be physical space or spacetime.

In the following chapter, **Ryan Samaroo** addresses the status of the principles underlying general relativity, among them the principle of equivalence. According to Michael Friedman, who has adopted a broadly Kantian perspective, physical theories have several layers. Some principles of a theory are constitutive because they open the conceptual space for certain possibilities and thus define a framework for empirical investigation. Other principles presuppose this framework and shrink the possibilities on empirical grounds. This outlook echoes the Kantian distinction between a priori and a posteriori and contrasts with a Quinean picture in which the principles of a theory do not admit of a principled distinction in e.g. a priori and a posteriori. Friedman has prominently illustrated his approach to physical theories using Einstein's general relativity. For Friedman, the principle of equivalence is a constitutive one, while the field equations are of the other type. Samaroo's main aim in his contribution is to defend a broadly Friedmanian account of general relativity against objections. One objection, for instance, has it that there is no unique way to make the distinction between both kinds of principles. Samaroo argues that some of the objections are based upon misunderstandings. But he concedes to the critics that the principle of equivalence should not be regarded as constitutive.

In the next contribution, **Niels Linnemann** addresses the question to what extent the theory of general relativity is in need of interpretation. That question famously arises for the theory of quantum mechanics where the measurement problem makes a straightforward interpretation of the theory impossible. Taking as his starting point work by Erik Curiel who distinguished between three kinds of interpretation, concrete, categorical, and meta-linguistic, Linnemann proposes a further refinement of this analysis, suggesting a new category of interpretation which he calls "qualificatory interpretation". His claim is that the general theory is, in fact, in need of this kind of interpretation, and his two key arguments pertain to the question of chronometric interpretation and the problem of what it means to assign thermodynamic notions like entropy to solutions of the gravitational field equations like the surface area of a black hole. In his chapter, Linnemann also explores how a concrete or a categorical interpretation of GR can guide the search after a successor theory.

James Read's contribution discusses the so-called "dynamical" view of spacetime theories, which is contrasted with the more standard "geometric" view. In his characterization, the geometric view takes the metric field to be an autonomous physical entity, which constrains the dynamics of matter fields. The geometric view is thus a brand of substantivalism. In contrast, Read defines the dynamical view as relegating the metric field from the status of an ontologically autonomous entity to a mere codification of the symmetry properties of the dynamics of present matter fields, and so a form of relationalism. This holds at least at the level of special relativity; once we move to general relativity, advocates of the dynamical view must concede that the metric is an independent entity, which cannot be reduced to matter fields and their dynamics because of the gravitational degrees of freedom postulated in general relativity. This is ultimately the reason why defensible versions of the dynamical view collapse into a form of the geometric view, at least of the “qualified” kind, at the level of general relativity. Using Jim Weatherall’s recent writings on the geodesic principle as a foil, Read closes in arguing that viable versions of the dynamical and the geometric views on general relativity not only converge, but also naturally lead to a form of spacetime functionalism.

In analogy to Newton’s first law, the geodesic principle of general relativity identifies the possible trajectories of free, i.e., “inertially” moving, massive point particles with time-like geodesics. Following a long tradition of debating the status of the geodesic principle in general relativity as either an independent postulate or a theorem following from basic assumptions, **James Weatherall** investigates the possibility of finding a formulation of the geodesic principle that does not make problematic reference to point particles and analyses the extent to which such a reformulated principle could obtain the status as theorem in general relativity. Weatherall first discusses two ways in which one might prove a geodesic principle, none of which is satisfactory from a physical point of view. He then proposes a new approach based on “tracking”, which combines the two approaches and permits overcoming, to a significant degree, the shortcomings of both. Tracking uses constructions allowing us to capture the idea that matter fields as encoded in the stress-energy tensor T_{ab} are as concentrated as one likes for a finite duration as long as one likes near a given curve. It also permits a reformulation of the geodesic principle according to which the energy-momentum tensors associated with solutions to source-free matter field equations only track time-like or null geodesics. As intended, the reformulated principle, which can be established (almost, i.e., modulo the satisfaction of the dominant energy condition) as a theorem in general relativity, associates certain “inertial” motions of physical bodies with a geometrically elite class of curves—the geodesics.

As mentioned before, one of the principles that led Einstein to his theory, was Mach’s principle. According to the principle, roughly, inertial motion is not determined by the nature of some absolute space, but rather by the distribution of matter. But what exactly does it mean to say that the distribution of matter determines how inertial motion is like? This is the question that **Antonio Vassallo** and **Carl Hoefer** address in their chapter. Their focus is on so-called rotational frame-dragging effects that manifest the Machian nature of general relativity. One example is the Einstein-Lense-Thirring effect in which the rotation of a gyroscope is determined by the surrounding mass distribution. As Vassallo and Hoefer point out, it is not attractive to conceive of this determination in terms of causation. The reason is that a change in the mass distribution affects inertial motion in an immediate way; while causal influence is most often thought to propagate with the speed of light at most. To develop an alternative metaphysical picture of the dependence relation, Vassallo and Hoefer use structural equation modeling and develop a precise model of the way in which the matter distribution impacts on the inertial motion. The question of how the determination relation is best understood then turns on the understanding of the structural equation framework. One answer that they suggest is that the relation is halfway between causation and grounding.

How does general relativity explain the success of special relativity in dealing with physical phenomena not involving gravity? One would surely expect general relativity—a more encompassing theory than special relativity—to subsume special relativity and explain both its success as well as its shortcomings. In his contribution, **Samuel Fletcher** uses the notion of an "approximate local spacetime symmetry" he developed elsewhere in order to offer central aspects of such an explanation. Applying this notion, it can be shown that every general-relativistic spacetime is approximately locally Poincaré symmetric. Since Minkowski spacetime is (precisely and globally) Poincaré symmetric, the approximate symmetry of relativistic spacetimes connects general relativity to special relativity. Fletcher notes that, although a keystone, this fact is insufficient by itself as it does not in general account for why the observable behavior of matter fields in generic spacetimes is well approximated by those of corresponding fields in Minkowski spacetime.