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Volume 199

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Silvia De Bianchi · Claus Kiefer  
Editors

# One Hundred Years of Gauge Theory

Past, Present and Future Perspectives

 Springer

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# Preface

The origin of gauge theory has been studied by scientists and historians of science in recent decades, but a complex outlook taking into account the historical and philosophical implications is still missing. The aim of this volume is to celebrate hundred years of gauge theory, by considering as seminal starting point of its history the publication of Hermann Weyl's *Raum-Zeit-Materie*. In 1918 Hermann Weyl published the first edition of his masterpiece in which he draws the conceptual underpinnings of gauge invariance later reframed within the context of relativistic quantum mechanics in 1929. This volume aims at stimulating the reflection upon the origin and development of gauge theory and its scientific and philosophical importance. Taking into account one of the central concepts of Weyl's work, symmetry, this volume sheds light on several aspects of Weyl's work and gauge theory and connects theoretical physics with other fields, including mathematics, history and philosophy. The multidisciplinary approach proposed by the volume makes it a unique in the landscape of previous books on the history of gauge theory. Indeed, our scope is to discuss not only the historical and philosophical underpinnings of gauge theory, but also to put forward a discussion about future perspectives of gauge theory taking into account the state of art in both theoretical and experimental physics.

Before resuming the content of the contributors, it is worth mentioning that our aim is to stimulate the interaction and future collaborations among philosophers, physicists and historians in order to grasp from a fresh perspective both Weyl's work and the development and rationale behind gauge theory. This is pretty much in the spirit of Weyl's thought. As it emerges in the contributions, Weyl strongly supported the interaction between philosophical reflection and scientific research, especially in the light of the great revolutions introduced by relativity theory and Quantum Mechanics. For this reason, we decided to group the contributions in this volume to constitute three parts focused on the historical and philosophical underpinnings of gauge theory inspired by Weyl's work, those devoted to Weyl's *Raum-Zeit-Materie* and the philosophical underpinning of his approach, and finally those exploring the theoretical and mathematical physics of gauge theory.

The first part of the volume is introduced by Norbert Straumann's contribution titled "[Hermann Weyl's Space-Time Geometry and the Origin of Gauge Theory 100 Years Ago](#)". It focuses on the historical roots of gauge theory by describing the gradual recognition that a common feature of the known fundamental interactions is their gauge structure. Central to his reconstruction is the work of Hermann Weyl and Wolfgang Pauli's early construction in 1953 of a non-Abelian Kaluza-Klein theory. In "[Gauging the Spacetime Metric—Looking Back and Forth a Century Later](#)", Erhard Scholz reviews Weyl's 1918 proposal for generalizing Riemannian geometry by local scale gauge, its mathematical foundations, as well as his philosophical and physical implications. Scholz reviews in detail Weyl's disillusion with this research programme and the rise of a convincing alternative for the gauge idea by translating it to the phase of wave functions and spinor fields in quantum mechanics. In mid-20th century years the question of conformal and/or local scale gauge transformation were reconsidered in high energy physics (Bopp, Wess, et al.) and, independently, in gravitation theory (Jordan, Fierz, Brans, Dicke). As Scholz underlines, it is in this context that Weyl geometry attracted new interest among different groups of physicists (Omote-Utiyama-Kugo, Dirac-Canuto-Maeder, Ehlers-Pirani-Schild). The merit of Scholz's contribution is to show that, albeit modified, Weyl's first proposal of his basic geometrical structure finds new interest in present day studies of elementary particle physics, cosmology and philosophy of physics. On the philosophical aspects that Weyl's 1918 proposal implies, Sebastian De Haro proposes an analysis regarding empirical equivalence and duality. In "[On Empirical Equivalence and Duality](#)", he argues that theories can be taken to be empirically equivalent on the ground of the judicious reading: very different-looking theories can have equivalent empirical content. The last two contributions regarding this first part of our collection both mark the relevance of gauge symmetry and the necessity of not taking it as mathematical redundancy. This topic is briefly exposed in Carlo Rovelli's contribution "[Gauge Is More Than Mathematical Redundancy](#)" and largely debated from a conceptual standpoint by Gabriel Catren in "[Homotopic Identities and the Limits of the Interpretation of Gauge Symmetries](#) as 'surplus structure'".

In the second part of the volume, we grouped contributions that can fall under the approach of integrating the history and philosophy of science. They are devoted to Weyl's *Raum-Zeit-Materie*, its conceptual roots and implications, as well as the reconstruction of the debates surrounding philosophical debates. In Dennis Dieks' contribution titled "[Reichenbach, Weyl, Philosophy and Gauge](#)", Weyl's approach and phenomenologist stance is compared and contrasted with Reichenbach's logical empiricism. By following the guideline of the reflection upon the nature of space and time and the revolution introduced by relativity, Dieks assesses the nature of Weyl's phenomenological stance, mostly influenced by Husserl's philosophy. In Dieks' view, Weyl's use of phenomenology should be seen as a case of personal heuristics rather than as a systematic modern philosophy of physics. Also in Thomas Ryckman's contribution, Weyl's philosophical views are taken into account. In "[Hermann Weyl, the Gauge Principle, and Symbolic Construction from the 'Purely Infinitesimal'](#)", Ryckman reconstructs the history of the development of

Weyl's 1918 formal unification of Einstein's theory and electromagnetism. Then he focuses on its consequences and Weyl's purely mathematical turn in 1925–6 to Lie theory and of course Lie groups and Lie algebras that played prominent roles in the subsequent development of the gauge principle leading up to the Standard Model of particle physics. In Ryckman's view, Weyl's predominant interest in Lie theory stems from two complementary philosophical interests, phenomenology and an epistemologically driven assumption of the "*Nahewirkungsphysik*". Both inform Weyl's notion of symbolic construction, a pillar in his works from 1927 onward. In Silvia De Bianchi's "[Weyl's \*Raum-Zeit-Materie\* and the Philosophy of Science](#)" the philosophical underpinning of Weyl's interpretation of Relativity as emerging from the pages of *Raum-Zeit-Materie* is analysed in detail. In particular, the distinction between the philosophical and the mathematical methods is underlined. De Bianchi underscores the dichotomy and relationship between time and consciousness that is identified by Weyl as the conceptual engine moving the whole history of Western philosophy, and the revolutionary relevance of relativity for its representation is investigated together with the conceptual underpinning of Weyl's philosophy of science. In identifying the main traits of Weyl's philosophy of science in 1918, this paper also offers a philosophical analysis of some underlying concepts of unified field theory.

In the third part of our collection, the reader will find a number of contributions exploring past and current perspectives of gauge theory in different branches of physics, including cosmology, quantum gravity and high energy physics.

Claus Kiefer in "[Space, Time, Matter in Quantum Gravity](#)" investigates the role that the three central concepts of Weyl's book play in a quantum theory of the gravitational field. He focuses on quantum geometrodynamics where the key concept is a wave functional on the configuration space of all three geometries and matter fields (Wheeler's superspace). At the most fundamental level, time is absent; the standard notion of time (and spacetime) only emerges in an appropriate semi-classical limit. He reviews ideas about the origin of matter from topology and from a unified quantum theory of interactions—problems which so far remain unsolved.

Friedrich Hehl and Yuri Obukhov in "[Conservation of Energy-Momentum of Matter as the Basis for the Gauge Theory of Gravitation](#)" give a concise overview of gauge theories of gravity. These are constructed by starting from a rigid symmetry that is made local. Of great relevance is the Poincaré gauge theory of gravity for which the global Poincaré symmetry of special relativity is employed. Therefore, they emphasize the role that Gauge theories of gravity may play in the construction of a unified field theory.

Christian Steinwachs in "[Higgs Field in Cosmology](#)" investigates features of the Standard Model when applied to cosmology. A central role in this is played by the Higgs field, and Steinwachs entertains the idea that this field could lead to the inflationary expansion of the early universe. This is, in fact, a promising idea because no new speculative field is needed in this case. Steinwachs also elaborates on the role of Higgs inflation in quantum cosmology and the quantum equivalence (or non-equivalence) of different field parametrizations.

In “[The Gauge Theoretical Underpinnings of General Relativity](#)”, Thomas Schücker compares various structural approaches to general relativity: the field theoretic approach, chrono- and geometric approaches and, in more detail, the gauge theoretic approach. The latter approach exhibits many similarities with the gauge theory underlying the Standard Model, although important differences remain.

Finally, we decided to close our volume with a contribution by Gerard 't Hooft, titled “[Past and Future of Gauge Theory](#)”. 't Hooft is himself one of the key figures in the historic development of gauge theories. In his contribution, he gives a colourful and personal account of this development and of the main scientists who were involved in it. He makes a strong case for the importance of gauge theories in the future and speculates in particular about the fundamental role that conformal symmetry might play in the unification of the Standard Model with gravity. Whatever the future will bring, gauge theories will continue being of interest for another hundred years.

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April 2020

Silvia De Bianchi  
Claus Kiefer

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