Springer Handbook of Spacetime

Ashtekar
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Editors

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With 190 Figures and 9 Tables

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Preface

In his *Principia Mathematica*, Isaac Newton formalized the notions of space and time, thereby laying the foundations of a new, revolutionary science. The sweeping success of celestial mechanics firmly established the power of Newton's spacetime paradigm. Soon it became firmly rooted in scientific thought and it gradually came to be an integral part of human consciousness itself. It became commonplace to assume that space is a three-dimensional Euclidean continuum and time flows eternally and uniformly, indifferent to everything else. This view reigned for over 200 years.

However, it was dramatically toppled at the beginning of the twentieth century by the even more revolutionary theories of special and general relativity. First, Albert Einstein taught us that the flow of time is not so indifferent after all; time intervals depend on the state of motion of the observer. Hermann Minkowski completed this scenario by showing us that space and time, in fact, fuse together to form a genuinely four-dimensional spacetime continuum. As he put it,

> *the whole world presents itself as resolved into such worldlines, and I want to say in advance, that in my understanding the laws of physics can find their most complete expression as interrelations between these worldlines.*

This fusion served as the point of departure for Einstein's discovery of general relativity. In this theory, spacetime geometry is no longer flat. Its curvature encodes the gravitational field. Spatial distances and time intervals between events are replaced by the proper time elapsed between them along worldlines of observers. This duration is sensitive not only to the motion of those observers but also to the gravitational field in the region. Space and time are no longer inert, background entities, a canvas on which the dynamics of particles and fields is painted. Spacetime *itself* is now dynamical, an active player in the drama of evolution. This new conceptual framework is truly compelling. As Hermann Weyl said,

> *It is as if a wall that separated us from truth has collapsed. Wider expanses and greater truths are now exposed to the searching eye of knowledge, regions of which we had not even a pre-sentiment.*

Soon after his discovery of general relativity, Einstein wrote to Arnold Sommerfield:

> *Of the general theory of relativity, you will be convinced, once you have studied it. Therefore, I am not going to defend it with a single word.*

This Springer Handbook of Spacetime is dedicated to the ground-breaking paradigm shifts embodied in the two relativity theories and describes in detail the profound reshaping of the physical sciences that they ushered in. In a single volume it includes chapters on the foundations, the underlying mathematics, physical and astrophysical implications, experimental evidence and cosmological predictions, as well as chapters on efforts to unify general relativity and quantum physics. The presentation is at an introductory level in that each chapter provides a bird's-eye view of a sub-area in which notable advances have occurred, especially in the past 30 years. Therefore, the Handbook can be used as a ready reference by researchers in a wide variety of fields, not only by specialists in relativity but also by researchers in related areas that either grew out of, or are deeply influenced by, the two relativity theories: cosmology, astronomy and astrophysics, high-energy physics, quantum field theory, mathematics, and the philosophy of science. It should also serve as a valuable resource for graduate students and young researchers entering these areas, and for instructors who teach courses on these subjects.

The Springer Handbook of Spacetime is divided into six parts. The first part deals with the historical origins of the spacetime notion that emerged from special relativity and introduces the basic ideas of special and general relativity. It ends with an emphasis on the intrinsic link between physics and spacetime geometry revealed by the two relativity theories. The second part is devoted to a number of foundational issues, most of which are concerned with the nature of time and gravity. This part also discusses some subtle issues in special and general relativity. The third part introduces the reader to mathematical structures that have served as powerful tools to unravel numerous implications of the two relativity theories. Here, the emphasis is on theoretical frameworks that are widely used in the contemporary research on spacetime structures, and on the

qualitatively new results that have emerged naturally. Because they are unrelated to the initial motivations used by Einstein, these unexpected advances bring out the amazing depth of general relativity and, more generally, the richness of the interplay between physics and mathematics. The fourth and the fifth parts summarize the observational status of the two relativity theories and the deep influence general relativity has had on our understanding of the cosmos as a whole. Here, one finds another amazing synergy, namely that between advanced technology and predictions of general relativity. One cannot be but deeply impressed by the fact that not only is the theory exceptional in its aesthetic beauty – its supreme conceptual economy and mathematical elegance – but it has also withstood some of the most stringent and imaginative observational tests to which any physical theory has been subjected. The sixth and final part illustrates various approaches to the unification of general relativity and quantum physics. They provide a flavor of the new science that could lead us to the next paradigm shift, taking us well beyond our present notion of spacetime.

This Springer Handbook is the outcome of the dedicated effort and commitment of many individuals. Authors accepted the difficult task of pitching their chapters at a level that is suitable for beginning researchers in the field and readily incorporated suggestions for improvements made by the referees. Numerous referees sent very detailed and helpful comments on manuscripts. Angela Lahee coordinated a smooth and delightful collaboration with Springer. This project could never have been completed without the generous support of all these individuals. We are grateful to them all. This work was supported in part by the NSF grant PHY-1205388 and the Eberly Research Funds of Penn State.

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Vesselin Petkov received a graduate degree in physics from Sofia University, a doctorate in philosophy from the Institute for Philosophical Research of the Bulgarian Academy of Sciences, and a doctorate in physics from Concordia University in Montreal. He taught at Sofia University and Concordia University, and also had a stint at the Physics Department of the Johannes Kepler University of Linz, Austria, before coming to Montreal in 1990. He is one of the founding members of the Institute for Foundational Studies *Hermann Minkowski*.

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