APPROACHES TO QUANTUM GRAVITY

Toward a New Understanding of Space, Time and Matter

The theory of quantum gravity promises a revolutionary new understanding of gravity and spacetime, valid from microscopic to cosmological distances. Research in this field involves an exciting blend of rigorous mathematics and bold speculations, foundational questions and technical issues.

Containing contributions from leading researchers in this field, this book presents the fundamental issues involved in the construction of a quantum theory of gravity and building up a quantum picture of space and time. It introduces the most current approaches to this problem, and reviews their main achievements. Each part ends in questions and answers, in which the contributors explore the merits and problems of the various approaches. This book provides a complete overview of this field from the frontiers of theoretical physics research for graduate students and researchers.

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Preface

Quantum Gravity is a dream, a theoretical need and a scientific goal. It is a theory which still does not exist in complete form, but that many people claim to have had glimpses of, and it is an area of research which, at present, comprises the collective efforts of hundreds of theoretical and mathematical physicists.

This yet-to-be-found theory promises to be a more comprehensive and complete description of the gravitational interaction, a description that goes beyond Einstein's General Relativity in being possibly valid at all scales of distances and energy; at the same time it promises to provide a new and deeper understanding of the nature of space, time and matter.

As such, research in Quantum Gravity is a curious and exciting blend of rigorous mathematics and bold speculations, concrete models and general schemata, foundational questions and technical issues, together with, since recently, tentative phenomenological scenarios.

In the past three decades we have witnessed an amazing growth of the field of Quantum Gravity, of the number of people actively working in it, and consequently of the results achieved. This is due to the fact that some approaches to the problem started succeeding in solving outstanding technical challenges, in suggesting ways around conceptual issues, and in providing new physical insights and scenarios. A clear example is the explosion of research in string theory, one of the main candidates to a quantum theory of gravity, and much more. Another is the development of Loop Quantum Gravity, an approach that attracted much attention recently, due to its successes in dealing with many long standing problems of the canonical approach to Quantum Gravity. New techniques have been then imported to the field from other areas of theoretical physics, e.g. Lattice Gauge Theory, and influenced in several ways the birth or growth of even more directions in Quantum Gravity research, including for example discrete approaches. At the same time, Quantum Gravity has been a very fertile ground and a powerful motivation for developing new mathematics as well as alternative ways of thinking about spacetime and matter, which in turn have triggered the exploration of other promising avenues toward a Quantum Gravity theory.

I think it is fair to say that we are still far from having constructed a satisfactory theory of Quantum Gravity, and that any single approach currently being considered is too incomplete or poorly understood, whatever its strengths and successes may be, to claim to have achieved its goal, or to have proven to be the only reasonable way to proceed.

On the other hand every single one of the various approaches being pursued has achieved important results and insights regarding the Quantum Gravity problem. Moreover, technical or conceptual issues that are unsolved in one approach have been successfully tackled in another, and often the successes of one approach have clearly come from looking at how similar difficulties had been solved in another.

It is even possible that, in order to achieve our common goal, formulate a complete theory of Quantum Gravity and unravel the fundamental nature of space and time, we will have to regard (at least some of) these approaches as different aspects of the same theory, or to develop a more complete and more general approach that combines the virtues of several of them. However strong faith one may have in any of these approaches, and however justified this may be in light of recent results, it should be expected, purely on historical grounds, that none of the approaches currently pursued will be understood in the future in the same way as we do now, even if it proves to be the right way to proceed. Therefore, it is useful to look for new ideas and a different perspective on each of them, aided by the the insights provided by the others. In no area of research a "dogmatic approach" is less productive, I feel, than in Quantum Gravity, where the fundamental and complex nature of the problem, its many facets and long history, combined with a dramatically (but hopefully temporarily) limited guidance from Nature, suggest a very open-minded attitude and a very critical and constant re-evaluation of one's own strategies.

I believe, therefore, that a broad and well-informed perspective on the various present approaches to Quantum Gravity is a necessary tool for advancing successfully in this area.

This collective volume, benefiting from the contributions of some of the best Quantum Gravity practitioners, all working at the frontiers of current research, is meant to represent a good starting point and an up-to-date support reference, for both students and active researchers in this fascinating field, for developing such a broader perspective. It presents an overview of some of the many ideas on the table, an introduction to several current approaches to the construction of a Quantum Theory of Gravity, and brief reviews of their main achievements, as well as of the many outstanding issues. It does so also with the aim of offering a comparative perspective on the subject, and on the different roads that Quantum Gravity researchers are following in their searches. The focus is on non-perturbative aspects of Quantum Gravity and on the fundamental structure of space and time. The variety of approaches presented is intended to ensure that a variety of ideas and mathematical techniques will be introduced to the reader.

More specifically, the first part of the book (Part I) introduces the problem of Quantum Gravity, and raises some of the fundamental questions that research in Quantum Gravity is trying to address. These concern for example the role of locality and of causality at the most fundamental level, the possibility of the notion of spacetime itself being emergent, the possible need to question and revise our way of understanding both General Relativity and Quantum Mechanics, before the two can be combined and made compatible in a future theory of Quantum Gravity. It provides as well suggestions for new directions (using the newly available tools of category theory, or quantum information theory, etc.) to explore both the construction of a quantum theory of gravity, as well as our very thinking about space and time and matter.

The core of the book (Parts II–IV) is devoted to a presentation of several approaches that are currently being pursued, have recently achieved important results, and represent promising directions. Among these the most developed and most practiced are string/M-theory, by far the one which involves at present the largest amount of scholars, and loop quantum gravity (including its covariant version, i.e. spin foam models). Alongside them, we have various (and rather different in both spirit and techniques used) discrete approaches, represented here by simplicial quantum gravity, in particular the recent direction of causal dynamical triangulations, quantum Regge calculus, and the "consistent discretization scheme", and by the causal set approach.

All these approaches are presented at an advanced but not over-technical level, so that the reader is offered an introduction to the basic ideas characterizing any given approach as well as an overview of the results it has already achieved and a perspective on its possible development. This overview will make manifest the variety of techniques and ideas currently being used in the field, ranging from continuum/analytic to discrete/combinatorial mathematical methods, from canonical to covariant formalisms, from the most conservative to the most radical conceptual settings.

The final part of the book (Part V) is devoted instead to effective models of Quantum Gravity. By this we mean models that are not intended to be of a fundamental nature, but are likely to provide on the one hand key insights on what sort of features the more fundamental formulation of the theory may possess, and on the other powerful tools for studying possible phenomenological consequences of any Quantum Gravity theory, the future hopefully complete version as well as the current tentative formulations of it. The subject of Quantum Gravity phenomenology is a new and extremely promising area of current research, and gives ground to the hope that in the near future Quantum Gravity research may receive experimental inputs that will complement and direct mathematical insights and constructions.

The aim is to convey to the reader the recent insight that a Quantum Gravity theory need not be forever detached by the experimental realm, and that many possibilities for a Quantum Gravity phenomenology are instead currently open to investigation.

At the end of each part, there is a "Questions & Answers" session. In each of them, the various contributors ask and put forward to each other questions, comments and criticisms to each other, which are relevant to the specific topic covered in that part. The purpose of these Q&A sessions is fourfold: (a) to clarify further subtle or particularly relevant features of the formalisms or perspectives presented; (b) to put to the forefront critical aspects of the various approaches, including potential difficulties or controversial issues; (c) to give the reader a glimpse of the real-life, ongoing debates among scholars working in Quantum Gravity, of their different perspectives and of (some of) their points of disagreement; (d) in a sense, to give a better picture of how science and research (in particular, Quantum Gravity research) really work and of what they really are.

Of course, just as the book as a whole cannot pretend to represent a complete account of what is currently going on in Quantum Gravity research, these Q&A sessions cannot really be a comprehensive list of relevant open issues nor a faithful portrait of the (sometimes rather heated) debate among Quantum Gravity researchers.

What this volume makes manifest is the above-mentioned impressive development that occurred in the field of Quantum Gravity as a whole, over the past, say, 20–30 years. This is quickly recognized, for example, by comparing the range and content of the following contributed papers to the content of similar collective volumes, like *Quantum Gravity 2: a second Oxford symposium*, C. Isham, ed., Oxford University Press (1982), *Quantum structure of space and time*, M. Duff, C. Isham, eds., Cambridge University Press (1982), *Quantum Theory of Gravity, essays in honor of the 60th Birthday of Bryce C DeWitt*, S. D. Christensen, ed., Taylor and Francis (1984), or even the more recent *Conceptual problems of Quantum Gravity*, A. Ashtekar, J. Stachel, eds., Birkhauser (1991), all presenting overviews of the status of the subject at their time. Together with the persistence of the Quantum Gravity problem itself, and of the great attention devoted, currently just as then, to foundational issues alongside the more technical ones, it will be impossible not to notice the greater variety of current approaches, the extent to which researchers have explored beyond the traditional ones, and, most important, the enormous amount of progress and achievements in each of them. Moreover, the very existence of research in Quantum Gravity phenomenology was un-imaginable at the time.

Quantum Gravity remains, as it was in that period, a rather esoteric subject, within the landscape of theoretical physics at large, but an active and fascinating one, and one of fundamental significance. The present volume is indeed a collective report from the frontiers of theoretical physics research, reporting on the latest and most exciting developments but also trying to convey to the reader the sense of intellectual adventure that working at such frontiers implies.

It is my pleasure to thank all those that have made the completion of this project possible. First of all, I gratefully thank all the researchers who have contributed to this volume, reporting on their work and on the work of their colleagues in such an excellent manner. This is a collective volume, and thus, if it has any value, it is solely due to all of them. Second, I am grateful to all the staff at the Cambridge University Press, and in particular to Simon Capelin, for supporting this project since its conception, and for guiding me through its development. Last, I would like to thank, for very useful comments, suggestions and advice, several colleagues and friends: John Baez, Fay Dowker, Sean Hartnoll, Chris Isham, Prem Kumar, Pietro Massignan, and especially Ted Jacobson.

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