reviews

General Relativity after Einstein

Robert Wald

General Relativity: An Einstein Centenary Survey. Edited by S. W. Hawking and W. Israel. Pp. 831. (Cambridge University Press: Cambridge, 1979.) £37.50.

MARCH 14, 1979, marked the one hundredth anniversary of the birth of Albert Einstein and numerous activities commemorating this event have taken place or are planned for the near future: the erection of a statue, the convening of conferences and the publication of memorial volumes, such as this book. I do not wish to speculate on how Einstein would have viewed all these activities; in any case, in the final analysis their value must be judged on their own scientific (or other) merits, not on their proclaimed connection to Einstein. Judged in this light, the Hawking-Israel volume is, in all respects, a marvellous book.

When two distinguished scientists edit a book consisting of sixteen articles contributed by other distinguished scientists, it is almost impossible for a bad book to be produced. But the Hawking-Israel volume is quite a bit more than merely "not a bad book". The articles cover the complete spectrum of progress in relativity theory in the past decade, and almost all are very well written. Most of them should be accessible to graduate students in relativity and yet almost all contain some new results or new points of view that should be of interest to the specialised researcher. Of course, no book is perfect and in this volume there is some disparity from article to article in the technical expertise expected of the reader. But this fault — which is almost unavoidable in a book of this nature — is about the only one important enough to be worthy of mention.

Very little work on general relativity was done during the 1940s and 1950s, but there has been a great deal of activity and progress since then, both in development of the theory and in experimental (or observational) verification of its predictions. With regard to the latter, for many years the empirical basis of general relativity rested on the fact that its predictions were in accord with observations in the three classical tests: the gravitational redshift, the bending of light, and the precession of Mercury's orbit. In recent years, however, the use of techniques such as long baseline radio interferometry (to measure the gravitational deflection by the Sun of radio signals from a quasar) and radar (and laser) ranging (to measure gravitational time delay of signals and determine orbits of bodies) have greatly improved measurement accuracy; and the discovery of a pulsar in a close binary orbit has given us an apparently clean system where effects of strong gravity are important and can be studied. In the meantime, a theoretical frame has been developed for analysing alternative theories of gravitation and determining which aspects of each theory the various experiments and observations actually test. All these developments are comprehensively reviewed in the chapter by Will, who concludes that, so far, general relativity has passed all empirical tests, but more stringent tests will confront it in the near future.

One important prediction of general relativity that has not yet been directly confirmed (although it can now be inferred from changes in the orbit of the binary pulsar) is the existence of gravitational radiation. The chapter by Douglass and Braginsky estimates the charactertistics of gravitational radiation expected from the various possible astrophysical sources and discusses the schemes for detecting this radiation. The problems of detection are formidable, as even the radiation from a supernova within our galaxy is estimated to produce fractional relative displacements of only $\sim 10^{-17}$. Nevertheless, the authors are optimistic that an unambiguous discovery of gravitational radiation will occur in the near future.

A key ingredient in the renaissance of theoretical work in general relativity beginning in the 1960s was the use of techniques of modern differential geometry. These techniques were used to prove theorems about the global structure of spacetime, in particular the inevitability of singularities in certain conditions and important results in the theory of black holes. These 'global methods' are reviewed in the chapter by Geroch and Horowitz. Their review focuses on the basic ideas and issues and illustrates how a theorist goes about proving a theorem or constructing a counterexample. The 'expert' who wants complete proofs of the strongest known theorems would be best off consulting other sources, such as the textbook of Hawking and Ellis. But the non-expert — or the graduate student who wishes to become an expert — should find this article to be the best available introduction to the subject.

Progress in the analysis of Einstein's equation is the subject of the chapter by Fischer and marsden. The main topics of their review are the initial value formulation of general relativity, linearisation stability (that is, the question of whether a linear perturbation corresponds to an exact solution), and other issues involving the manifold structure of the space of solutions. In contrast to the Geroch-Horowitz chapter, this chapter *is* written for the expert and is rather demanding of the reader. Most relativity theorists will also have difficulties following the notation, as index notation for tensors is not used.

One of the most exciting areas of progress in the past decade has been the full development of the theory of the black hole, the "region of no escape" which results from the gravitational collapse of a body. Among the marvellous results that have been obtained are the proof of uniqueness of black hole stationary states, the theory of energy extraction, and the analogy between the laws of black hole mechanics and the laws of thermodynamics. These and other results are reviewed in the chapter by Carter.

The marvellous properties of black holes do not end with the above general theory. Studies of the equations governing gravitational, electromagnetic, and other perturbations of the Kerr solution — the unique stationary black hole — have shown that decoupled equations can be obtained and can be solved by separation of variables. Furthermore, numerous differential identities exist between solutions. The chapter by Chandrasekhar provides a thorough introduction and summary of his work on this problem.

The role of black holes in astrophysics is the subject of a very well written review by Blandford and Thorne. These authors summarise the theoretical scenarios where black holes may occur and the astrophysical effects they would produce, as wel as the observational evidence for them. In addition, Blanford and Thorne do a good job in conveying a sense of the nature of the assumptions which go into the various models. Thus, the relativity theorist or other non-astrophysicist who wants to known how seriously to take reports of discoveries of black holes will find this chapter to be a valuable source.

The other area besides black holes where the effects of general relativity play a dominant role is cosmology. A brief chapter by Dicke and Peebles presents some interesting — though rather sketchy — speculations on issues related to the apparently finite origin of our Universe. Zel'dovich describes the history of the early Universe, including discussions of primordial black holes, quantum effects, and implications of particle physics for cosmology (and *vice versa*). The chapter by MacCallum provides a thorough review of homogeneous, anisotropic cosmological models as well as the rather meagre known results concerning inhomogeneous cosmology.

One of the highlights of the book is Penrose's beautifully written, thought provoking chapter on time asymmetry. Penrose considers the much discussed question of the origin of the arrow of time, but his ideas are quite original, though, as he continually points out, well within the realm of conventional physics. Penrose's main thesis is that at least some, and possibly all, of the various arrows of time — such as entropy increase and the retardation of radiation — can be explained by assuming the initial state of the Universe is one of low entropy. He speculates that this conclusion should be incorporated into physical law, perhaps in the form: The Weyl tensor vanishes at all initial singularities. (The Weyl tensor is a rough measure of gravitational clumping, so the intent of the proposed law is to state that initial gravitational entropy is small.) Whether or not this speculation is correct, the reader should find Penrose's discussion of cosmic censorship, his criticisms of Hawking's "black hole is a white hole" hypothesis and his fundamental criticism of chaotic cosmology, as well as numerous other side discussions, to be of great interest.

The final four chapters of the book deal with quantum aspects of general relativity. Virtually all researchers agree that classical general relativity cannot be an exact description of nature; that the gravitational field, like all other fields, must be quantised. But major conceptual issues arise when one attempts to do so, resulting mainly from the fact that the quantity which describes the gravitional field — the spacetime metric — also describes the background structure of spacetime. If one ignores this issue and tries to quantise gravity by procedures analogous to those used for other fields, one finds that the theory is non-renormalisable, that is, in perturbation theory new terms must be introduced in order to cancel the ultraviolet divergences. Presumably, an infinity of new, undetermined, parameters would appear if one went to arbitrarily high order in perturbation theory.

These difficulties have been known for a long time, but two recent developments have made theorists considerably more optimistic that they can be overcome. The first is the success achieved in particle physics in quantising gauge theories and unifying the fundamental interactions. Gravity would fit very naturally into further developments of this programme. The second is Hawking's calculation of thermal particle creation by black holes due to quantum effects. The beauty of this result has provided the psychological equivalent of experimental verification that the theory is on the right track.

Almost all of the solidly grounded results on quantum effects in strong gravitational fields have been obtained in the approximation where the metric can still be treated classically. These results include calculations of particle creation (such as Hawking's black hole calculation) and 'back-reaction' of the particles on the gravitational field. This work is nicely reviewed from the Cambridge viewpoint by Gibbons. The chapter by DeWitt also contains an extensive review of this work, including a good discussion of the observer dependence of particle detection. Proposals for dealing with gauge problems in full quantum gravity are also discussed by DeWitt.

The chapter by Hawking is probably the best available introduction to his current ideas on quantum gravity. Hawking uses the path integral approach and proposes a solution to the problem of the indefiniteness of the gravitational action (which causes convergence problems in the path integral). His ideas for going beyond the lowest approximation lead him to a picture of "spacetime foam", a highly complex topological structure of spacetime on Planck length (10^{-33} cm) scales. Much of this work is highly speculative and the logic is not always airtight; but the beauty of many of the ideas should convince the reader that there must be much fundamental truth contained in this work.

The chapter by Weinberg takes a much more conventional viewpoint on quantum gravity. Weinberg reviews the evidence that quantum gravity is non-renormalisable, but points out that if the condition of "asymptotic safety" (defined and discussed in the chapter) holds for the theory, then all but a finite number of the infinity of parameters occuring because of non-renormalisability could be fixed in a natural way. This would tame the non-renormalisability problem and could make the theory acceptable without further modifications. Some evidence that quantum gravity might be asymptotically safe is provided by a model calculation in $2 + \varepsilon$ dimensions.

As the above discussion should indicate, the Hawking-Israel volume provides a dramatic demonstration of recent progress and future prospects of general relativity theory. The time is ripe for a book of this kind, and it is fortunate that the anniversary of Einstein's birth has provided the impetus for publishing it.

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Control of prokaryotic gene expression

The Operon. Edited by J. H. Miller and W. S. Reznikoff. Pp. 449. (Cold Spring Harbor Laboratory: Cold Spring Harbor, New York, 1978.) $42.

The Operon is a collection of review articles that summarise much of what is known about the control of prokaryotic gene expression. The first half of the book describes aspects of regulation in the *Escherichia coli* lactose operon: the system that is best understood. The remainder of the book focuses on other systems which contrast with the *lac* operon: regulation by temperate phage λ repressor, the regulation of λ repressor synthesis, dual control of the galactose operon, the synthesis of 3′,5′ cyclic AMP, positive regulation of the arabinose operon, attenuation control of the tryptophan biosynthetic operon, autogenous regulation of the histidine degradation operon, and the mechanism of phase variation in *Salmonella*. The book is highly successful in that the articles are well written and provide a very broad education. It would be suitable for graduate courses and useful as a source of information for instructors in molecular genetics.

Jonathan Beckwith's first article describes the genetic methods used to study the *lac* operon. This chapter is sufficiently clear and general to allow the reader to understand microbial genetics in a broader sense. Beckwith provides a second chapter on methods for fusing the β-galactosidase gene into foreign regulatory units, so that the simplicity of the β-galactosidase assay can be used to probe very complex regulatory systems as well as the mechanism by which proteins are exported from the cytoplasm to the cell membrane and into the medium.

Jeffrey Miller's chapter gives a concise history of genetic studies on the lactose repressor (*lacI*) gene. It also contains a detailed description of the genetic methods used to create mutant repressors with interesting physical and chemical properties. An extra attraction of this article is its summary of how the mechanism of mutagenesis was worked out, using the known DNA sequence of the *lacI* gene, in combination with a variety of genetic manipulations.

The chemical properties of normal and mutant *lac* proteins are thoroughly discussed by I. Zabin and K. Beyreuther. I was interested to learn that both the specific and nonspecific DNA-binding properties of the *lac* repressor are