

Checking Einstein's general theory of relativity

Was Einstein Right?—Putting General Relativity to the Test

Clifford M. Will

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Reviewed by Bernard F. Schutz

General relativity occupies a unique place in physics. Surely no other theory has, on the one hand, inspired such respect and even awe among physicists and, on the other, spawned so many serious attempts to replace it with alternative theories. These twin attitudes of physicists are reflected and even exaggerated in the response of the general public. Einstein, with his rumpled clothes, wild hair, and impish grin, is everyone's idea of the brilliant scientist, and popular books explaining his work outsell books on any other physical theory. At the same time, any working relativist will receive distressingly many monographs, written and published by members of the public who believe they have found the logical inconsistency in relativity and have cured it with a better theory. Where does this dualism come from?

I would trace it to the fact that the creation of general relativity broke all the rules. If our naive idea of how physics progresses is that experiment leads and theory follows, then relativity doesn't fit. When Einstein began to develop the theory, there were no anomalous experiments pushing him for an explanation; he was motivated solely by a *theoretical* difficulty, namely that Newton's theory of gravity was inconsistent with special relativity. Einstein had no tight experimental constraints to guide his choice of theory; criteria of simplicity and elegance led to general relativity. Remarkably, experimental support for the theory was not long in coming, but it was little enough until recently. That Einstein did so well is awe-inspiring. But is



Laser shot to the Moon from the University of Texas's McDonald Observatory. The photograph (reproduced by permission of the University of Texas) appears in *Was Einstein Right?*

there not room for alternative theories? For the serious physicist, it is important to question the esthetic criteria that guided Einstein, to see what changing them might produce. For too many laymen, unfortunately, there is the delusion that if Einstein could do it all while working in a patent office, so can they.

But if experiments played little role in the birth of general relativity, the theory could not remain aloof from experiment forever. Its recent history is radically different from its inception. From the mid 1950s, physicists began to take a new interest in the theory. Led by people such as S. Chandrasekhar, John Wheeler, and Yakov Zel'dovich, all of whom had established their reputations in other branches of physics, physicists began asking pragmatic questions of the theory: How do we

describe its predictions in terms of measurements, which of these measurements can be performed by experimenters directly, and which of its predicted phenomena can be observed somewhere in the universe? Their answers led to our present understanding of, for example, black holes, neutron stars, the Big Bang, and gravitational waves as predictions of the theory. Astronomy, blooming in the technology of the space age, found ready use for these ideas. General relativity is an intimate part of our present understanding of quasars, pulsars, x-ray binaries, jets, giant radio galaxies, the abundance of helium, gravitational lensing, the dynamics of the binary pulsar PSR 1913 + 16, and many other observed systems. So today the stakes are much higher than in Einstein's day: If the theory is wrong,

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astrophysics has a real problem. What, then, is the experimental picture?

That is the question Clifford Will asks and answers in this readable and at times fascinating account of the modern history of experimental relativity. While theorists were sharpening their understanding of the theory, experimenters were busy too. Leading experimenters such as Robert Dicke, Leonard Schiff, Irwin Shapiro, and Robert Vessot—again, people who had established their names in other fields—turned the new tools of modern technology to the job of testing relativity and its foundations. They and their colleagues have tested some predictions of the theory to extraordinary precision, and they have come up with new kinds of tests that Einstein never dreamed of. The list of effects tested is long: gravitational redshift, deflection of light, perihelion shift, time delay, the Nordtvedt effect, the constancy of G , gravitational waves and the binary pulsar, dragging of inertial frames.

Learning the results of these experiments, however, is only part of the appeal of this book, and perhaps not the largest part. What impressed me most was its narrative style: Each experiment is a story, each experimenter a personality. Will gives us a sense of their motives, their feelings during crises, and their satisfaction when the experiment finally goes right. Take Einstein himself as an example. Will brings the man alive when he tells us that after explaining the "anomalous" perihelion precession of Mercury, Einstein "later wrote, 'for a few days, I was beside myself with joyous excitement,' and told a colleague that the discovery had given him palpitations of the heart." As another example, it is a bit of light relief to be told that the Stanford gyroscope experiment—one of the most difficult, time-consuming, and expensive that NASA has ever supported—"can be said to have been conceived by three naked men basking in the noonday California sun..." This story-telling style does more than entertain. It helps nonscientists to understand what practicing scientists know, sometimes too well: Science is a human undertaking, pursued for human motives, and limited by human failings.

The book has another commendable feature. Aimed as it is at the "popular" market, Will has to make sure he describes general relativity well enough to allow his reader to know what the tests are testing. He does this remarkably well in places, as in his explanation of why the curvature of time is responsible for the Newtonian gravitational effects, and in his analogy between the dragging of inertial frames

and water draining from a pool. By taking advantage of the fact that he is describing real experiments rather than theoretical imaginings, Will is able to guide the nonspecialist reader through some difficult ground very elegantly indeed.

Will is well qualified to write on this subject. With Kip Thorne and Ken Nordtvedt, he provided a theoretical framework within which the tests of relativity could be understood and quantitative comparisons made between competing theories. He knows the people he is writing about and has first-hand experience of many of the experiments.

The book will appeal to a wide spectrum of readers. Since it contains little mathematics, it will be accessible to interested laymen and high-school physics students, and I can recommend it wholeheartedly. But even professional physicists have something for them, because it is the only book I know that describes the experiments and their results without too much technical detail. If you want to know how relativity has fared experimentally, this is a good place to start.

But I almost forgot to give the answer to the question, "Was Einstein right?" Well, the question doesn't have a definitive answer: Every generation has to renew the tests with greater precision and invent some more, and at any time the theory could be found wanting. As Will points out, one must never take any physical theory for granted. But today, our confidence in general relativity is stronger than ever. Astronomers know this better than most; black holes would not be the "standard model" for active galaxies if the theory were in doubt. Competitor theories, such as the Brans-Dicke scalar-tensor theory, are no longer serious contenders. Einstein's esthetic criteria have provided us with a remarkably robust theory. And there is a modern lesson here, one that is well understood by high-energy theorists. We may hope that elegance, simplicity, and mathematical consistency may yet guide us to a good "theory of everything," even if some of the energies of interest are well beyond the reach of experiment today.

General Relativity

Robert M. Wald

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More than twenty years ago, general relativity reentered the mainstream of physics and there it has remained, thanks largely to problems posed in astrophysics, cosmology, and the

search for a consistent unification with quantum theory. Such a venerable and beautiful theory has naturally also developed its own set of "internal" problems that have in turn enriched other areas of theoretical physics and mathematics. Einstein's theory has withstood every observational challenge and has survived in its original form for over 70 years. Relativity theorists have made great progress in understanding both qualitative and quantitative implications of the classical theory. Furthermore, the so far unsuccessful searches for a quantum theory of gravity or a more comprehensive theory including gravity have been strongly influenced by the ideas and techniques of general relativity. One has only to think of the Kaluza-Klein theories or the currently fashionable string theories to see that more than a nodding acquaintance with metrics, connections, and curvature is required to understand the results of the fervent efforts devoted to these grand problems.

Robert Wald has given us in his truly excellent *General Relativity* a sophisticated text of manageable size that will probably be read by every student of relativity, astrophysics, and field theory for many years to come. Experienced researchers and teachers, especially the mathematically inclined, will also find it valuable—if not indispensable. The level of mathematical rigor and precision is consistently high throughout. Yet it is accessible to students largely because Wald uses an "abstract index" notation rather than the overly abbreviated notation often used in modern differential geometry. The introductory material on tensors and the mathematical appendices are of special value in bridging the gap between what is commonly taught in "mathematical physics" courses and what is required to understand the results of the past two decades on horizons, singularities, and global space-time geometry.

Besides the mathematical appendices, the book is divided successfully between "Fundamentals" and "Advanced topics." The advanced topics include black holes, quantum effects in curved space-time and many other morsels, among which almost anyone will find something to feast upon. The excellence of the expositions reflects that Wald himself has contributed significantly to the modern understanding of many of these topics. The section on fundamentals is also generally strong. I confess some disappointment in the treatment of linearized gravity, but only because I found it too brief. The treatment would be enhanced by more detail on the nuts and