Preface

Einstein presented the field equations of general relativity to the journal of the Prussian Academy of Sciences, Berlin on 25 November 1915. How he arrived at these equations after a heroic effort lasting eight years, is one of the most fascinating stories of the process of research.

Subsequent to publishing his great work on special relativity in 1905, Einstein wondered as to how the principle of relativity could be extended to include observers in non-uniform motion. He did not figure how to make progress on this, until 1907, when during the preparation of a review article on special relativity he had the 'happiest thought of my life'. The realization came that an observer falling freely in a gravitational field will not experience his/her own weight, and will perceive him/herself to be in an inertial frame. Einstein raised this realization to the level of a principle, namely that physics in a uniformly accelerating frame cannot be distinguished from physics in an inertial frame with a corresponding gravitational field (Principle of Equivalence). Gravitation became the clue for extending relativity to non-uniform motion. He used the principle to already deduce, using kinematics, the gravitational redshift, equivalence of energy and gravitational mass, and the bending of light rays (this last result being off by a factor two from the final correct result). An early goal Einstein set for himself was to explain the anomaly of 43 seconds of arc in the precession of Mercury's perihelion, using the new theory he hoped to arrive at.

The major task now was to find out the field equations of gravitation, which would make Newtonian gravitation consistent with special relativity. It was clear to Einstein that this cannot be done by making a special relativistic generalization of the Newton–Poisson equation, because accelerating frames, and hence gravity, cannot be brought within the framework of special relativity. In 1912, he proposed a tentative scalar theory of gravitation, based on the variable speed of light in a gravitational field. While this was only a transitory model, Einstein learnt some important physics from it, which was to shape further development. He deduced the equation of motion from extremizing the path length in a non-Minkowski spacetime. Because gravitational energy produces gravity, the field equations must be nonlinear. Equivalence principle holds only locally.

Einstein attached great significance to physics of the rotating frame. Already in 1912, he inferred that the geometry in a rotating frame must be non-Euclidean. From evidence such as this came the great leap of thought that gravitation must be described using invariants of the ten metric functions that appear in the fundamental quadratic line-element introduced by Gauss. Gravitational field equations must be generally covariant field equations which relate matter energy–momentum to constructs from the metric. Spacetime geometry in the presence of gravitational fields must be non-Euclidean.

From his mathematician friend Marcel Grossman, Einstein learnt in 1913 that Riemannian geometry would be suitable for their purpose. Together they started a collaboration to seek and find the field equations, using the geometry of Riemann. Their 1913 paper, known as the Entwurf paper, begins with an exposition of Riemann's geometry and tensor analysis for physicists. The Riemann curvature tensor and the Ricci tensor are introduced, and it is proposed that the gravitation tensor should be constructed from differential operations on the metric. Then they drop a bombshell. They somehow conclude that the Ricci tensor cannot be used to construct the gravitation tensor, because it does not yield the desired Newton's law of gravitation in the weak field, static limit! How and why they arrived at this (incorrect) conclusion is not quite spelt out fully in the paper, and the unravelling of this mysterious inference has kept historians of relativity busy for many decades.

For the time being, Einstein gave up his cherished dream of a generalized principle of relativity, and was convinced that is how it must be. Instead, in the same paper, Einstein–Grossman proposed the Entwurf field equations, in which the gravitation tensor constructed from the metric is invariant under linear coordinate transformations, and has the correct Newtonian limit.

By mid-1915, Einstein became dissatisfied with the Entwurf theory. For one, it did not give the correct precession of Mercury's perihelion. He discovered other problems also, with the theory. Perhaps the longing for general covariance persisted too. In typical Einstein style, there was a sudden dawning of light, an outburst of genius, and in a series of four brief papers in November 1915, Einstein arrived at the final field equations which bear his name. The 4 November paper presented a form of the field equations using a part of the Ricci tensor, something which was considered (and rejected) in the *Zurich Notebook*, but now brought back with an improved understanding of coordinate conditions. The 11 November paper proposed, for the first time, the Ricci tensor as the gravitation tensor. The 18 November paper correctly obtained the anomalous precession of Mercury, a great triumph for Einstein, which gave him immense joy and conviction. Finally, the Einstein field equations were presented in the 25 November paper. Eight years down the road, the new edifice had been successfully constructed.

If Einstein were to come back today, a hundred years later, he would be tremendously delighted as to how far his theory has reached. He lived for forty years after the discovery of his theory, but during that period research in the subject progressed rather slowly, remaining largely confined to study of solutions and properties of the field equations. Mention should of course be made of the momentous 1919 solar eclipse expedition led by Eddington to look for the bending of light, and the discovery of the expansion of the Universe in 1929. But the first interntional conference on General Relativity was held only in 1955, in Bern, three months after Einstein's death. Today the triennial meeting of the International Society of General Relativity and Gravitation is attended by nearly a thousand scientists. Quite a few countries have their own Gravitation Society/Association.

General Relativity (GR) came into its own in the 1960s, with the discovery of pulsars and neutron stars, and subsequently, black holes (candidates). The discovery of the Cosmic Microwave Background Radiation (CMBR) put hot Big Bang cosmology on a firm footing, firmed up furthermore by detection of temperature anisotropies in the CMBR in 1992. The sixties and seventies saw also great strides in theory, via the singularity theorems, black hole themodynamics, and Hawking radiation. The Hulse–Taylor binary pulsar provided resounding confirmation for GR through the indirect deduction of gravitational waves, whose direct detection by LIGO seems imminent.

Yet, great challenges remain. We do not know for sure what dark energy and dark matter are made up of. Was there indeed a period of inflation in the very early universe? Did the universe start with a Big Bang, or was there a prior phase too? Why is the cosmological constant so small? Is the modification to Einstein's gravity required to understanding certain astronomical phenomena? And perhaps the greatest challenge of them all: the merger of GR and quantum theory, and the unification of gravitation with other interactions. Einstein would perhaps be pleased that GR stands strong after hundred years, and yet extraordinary efforts are afoot to apply it to address the remaining challenges.

At *Current Science*, we have made a modest effort to put together this special section on GR. We requested our distinguished contributors to put together the history and science of their topic from the time of discovery of GR, leading up to their own current research work. Narlikar and Dadhich have written about the growth of GR research in India. Advances in classical GR and in thermodynamic gravity are described in the respective articles of Iyer and of Padmanabhan. Loop quantum gravity has been reviewed by Ashtekar, and string theory by Gopakumar. Moreover, the aspects of relativistic astrophysics and quantum gravity are covered by, respectively, Mukhopadhyay and Singh. Our sincere thanks go out to all our contributors for accepting our invitation. We deeply regret that this special section does not have articles on Experimental Gravitation, Cosmology, and Modified Gravity (although the last one is briefly touched upon by Mukhopadhyay). Because of their busy schedule, authors who were preparing articles on these topics could not get them ready in time for this issue. Our thanks go out to them too, for their efforts.

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–Guest Editors
Special Section: 100 Years of General Relativity