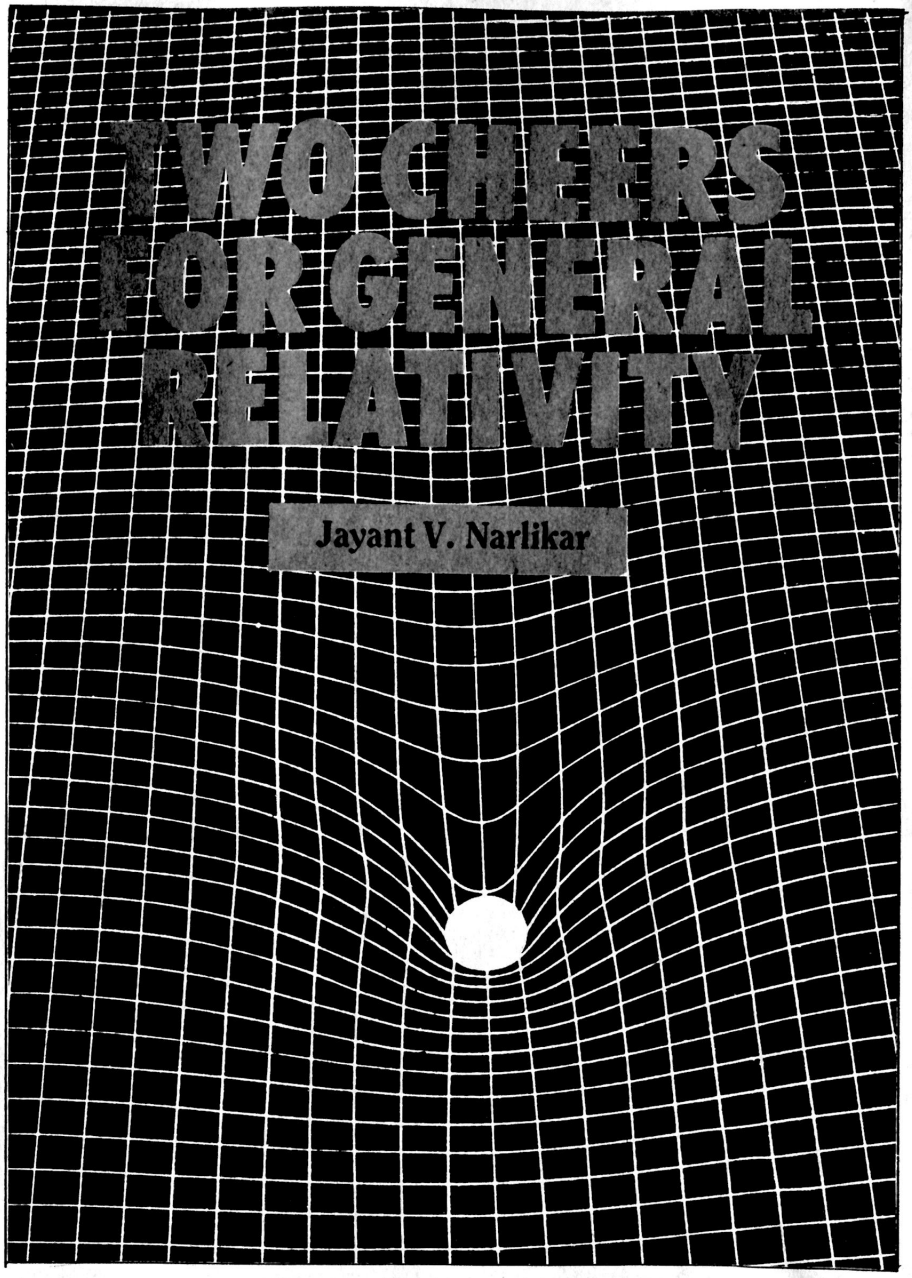
How has the theory of general relativity fared in the seventy years since it was propounded?



IN 1915, Albert Einstein proposed the general theory of relativity. The theory was the outcome of intense thinking on the part of its creator on problems of space, time, motion and gravitation. It is unusual for a physical theory to be born this way. Generally, a theory is born when experiments and observations show up some unexplained phenomena. Newton's law of gravitation (which general relativity was meant to supplant), for instance, came out of efforts to explain the observed motions of planets and the Moon. The electromagnetic theory took shape through constant interactions of theory and experiments. Even ideas on the special theory of relativity (Einstein's first major achievement of a decade earlier) were 'in the air' since the days of the Michelson-Morley experiment. But there were no such challenges which motivated general relativity.

Theories born in such isolation from the observational situation often turn out to be sterile and are soon forgotten. This year, general relativity enters its seventieth year. How has the theory fared in this interval which has seen dramatic advances in science on all fronts? What is left of it if we subtract away all the charisma and mystique built round it in Einstein's life time? To what extent has the theory contributed to the growth of theoretical physics at the fundamental level? And then the 'bread and butter question': 'how has the theory stood up to observational tests?' Let us try to answer these questions from the modern standpoint. But first, what is relativity all about?

In 1686-87, Isaac Newton published his famous treatise, *Principia* (The long title translates to *Mathematical Principles of Natural Philosophy*). This work laid solid foundations for physics—foundations that survived for two centuries. Of the several aspects that Newton covered, the two fundamental ones, the laws of motion and the law of gravitation, are of concern here.

The laws of motion describe how and why things move. Newton's laws tell us that all bodies in the universe possess the property of inertia because of which they resist any externally imposed changes of their state. Thus a body will continue to be in a state of rest or of uniform speed in a straight line if no external force acts on it. And if such a force does act on it, the resulting change of state is measured by the acceleration of the body. This acceleration, for a given external force, is large for a body of small inertia and small for a body of large inertia. You can lift a cat and move it around, but any force you exert cannot budge an elephant which has far greater inertia than the cat.

Now acceleration is the rate of change of velocity while velocity is the rate of change of position of the body. Naturally, to quantify these notions, Newton needed the concept of space and time. After spending an agonising time over these basic issues, Newton finally arrived at the concept of absolute space and absolute time. The idea

of absolute time is visualised by imagining a unique clock of nature which serves as the timekeeping device for all events and all observers. Likewise, absolute space provides the backdrop against which all velocities and accelerations are measured. These laws of motions worked well and thereby generated confidence, bordering on total faith, in the Newtonian system. What was forgotten was the fact that in the last analysis the Newtonian laws were based on concepts of spacetime that were assumptions, not absolute truths.

It was these assumptions that Einstein challenged when he proposed the special theory of relativity in 1905. Einstein argued that in concrete terms there was no unique backdrop that could serve as absolute space and so, in principle, all observers with uniform velocities relative to each other were equivalent in status.

He made a distinction between two types of observers: the *inertial* ones on whom no external force acts and the rest, *non-inertial* ones. Observers of the former category should, according to Einstein, have the same formal physical description of the universe. The basic laws governing the electromagnetic phenomena do exhibit this feature, for example—provided we are willing to give up the Newtonian concepts of absolute space and time.

For a person, who is standing on a platform, the express train appears to move very fast as it rushes through the station. However, the same train, when viewed by a motor car driver moving along a parallel road, does not appear to move so fast; the observed speed of the train in the two cases is different. In the case of light, however, the same speed is measured by all observers even though they are moving relative to one another. This required a new rule of addition of velocities. Special relativity, in fact, provided the new rules on how spacetime measurements are to be made. And these rules required giving up the notions of absolute space and time. The resulting changes in the laws of motion were stated by Einstein in the 1905 paper and out of these

Isaac Newton

Albert Einstein

emerged the famous general relation $E = mc^2$ between energy and mass.

So much for special relativity. Where does general relativity come in? The general theory provided an alternative to the law of gravitation. According to Newton, gravitation is a property of nature that generates a *force* of attraction between any two material bodies. It is this force that drives the planets round the Sun and the satellites round the planets. Had there been no force of attraction between the Earth and the Sun, the Earth would have continued on a straight path with uniform speed as per Newton's first law of motion, instead of following an elliptical orbit.

Einstein's way of looking at the phemenon of gravitation was radically different. Einstein noted that since

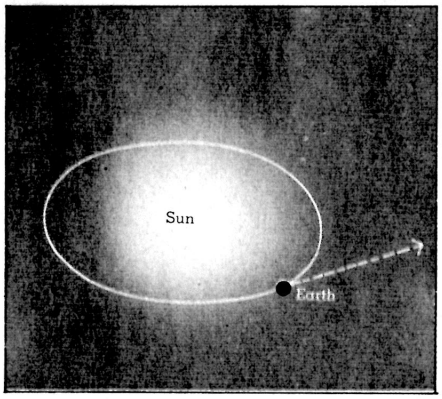


Fig. 1 According to Newton, gravitation is a property of nature that generates a force of attraction between any two material bodies. It is this force that drives the planets round the Sun; had there been no force of attraction between the Earth and the Sun, the Earth would have continued on a straight path with uniform speed. According to Einstein, however, the Earth is not going round the Sun because of any "force" of attraction between them but because the spacetime round the Sun is curved (see opposite page). Einstein calculated that the geometry round the Sun is so different from that of Euclid that planetary motion indeed is "straightline motion with uniform speed"

gravity as an interaction operates between all material bodies, there is no part of space that is free from it. Nor can gravity be "switched off" in a given region, as electricity can be. This omnipresence of gravity can be understood if it is linked to another omnipresent physical entity: space and time. Einstein achieved this link by means of geometry.

Geometry as a subject deals with the measurements of spatial distances and angles. At school we learn Euclid's geometry not just because it is the simplest geometry but also because it has practical applications in everyday life. But there are other geometries, which do not follow Euclid's basic postulates. Theorems based on these non-Euclidean geometries can be quite different from those we are familiar with. For example, the theorem that the three angles of a triangle add up to 180^0 does not hold in non-Euclidean geometries.

Using these non-Euclidean geometries, Einstein proposed the hypothesis of "curved spacetime" that holds the key to general relativity. The basic idea can be illustrated with the Sun-Earth example. Why do planets go round the Sun in elliptical orbits? Not, according to Einstein, because of any "force" of attraction between them, but because the spacetime round the Sun is curved (p. 20). New rules of geometry apply here. The criterion of deciding "what is a straight line?" of course depends on what geometry we use. Einstein calculated that the geometry around the Sun is so different from that of Euclid's that planetary motion indeed is "straight-line motion with uniform speed" according to the new geometry! To anyone looking at Fig. 1 this statement will appear incredible. But it happens to be correct. So general relativity "eliminated" gravity as a force but instead argued that the effects of gravity are manifested through the non-

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attempts at grand unification aim at unifying three of the four basic forces of nature, leaving apart (ironically) the force of gravity. For it is realised that gravity as presented through general relativity does not quite fit into the present scheme of unification. The present attempts at unification are nevertheless indirect tributes to Einstein's vision: for he embarked upon his unification work at a time when all other leading physicists were sceptical.

Two alternatives are thought of to remedy the situation. One is to construct a quantum theory of gravity, a task that is immensely difficult. The difficulty lies both in relativity and in quantum theory. Quantum theory describes the properties of nature at a very small (microscopic) level. Just as matter looks continuous and unbroken at the "everyday" macroscopic level but is in fact made of discrete particles like atoms and molecules, so it is with the general description of physics. For example, electromagnetic radiation appears to be a continuous flow of waves at the macroscopic level, but at the microscopic level it is also made of particles of light called "photons". Likewise physicists believe that gravitational radiation is made of "gravitons"—particles like photons. But remember, according to general relativity, gravity is a manifestation of spacetime geometry. So how do we stretch a geometrical meaning to the "graviton"? Does it imply that the spacetime structure is not continuous but is discrete? These questions are conceptually hard to answer. Just as at the classical level gravitational radiation proved to be much more complex in nature than electomagnetic radiation, so has quantum gravity turned out to be much more intractable than quantum electrodynamics. But it is essential to quantise the general theory of relativity if gravity is to be united with other forces of nature.

Perhaps the difficulties of this path have prompted some physicists to take another route of *supergravity*. This is a new approach to gravity somewhat akin to the particle physicists' way of looking at basic interactions. It is too early to say whether this path will lead us to the desired goal.

To sum up then, we may judge the performance of general relativity to date on three criteria: (1) Did the theory introduce a dramatic input of new ideas into fundamental physics? (2) Has it passed all the possible experimental tests to date? (3) Has it interacted with other branches of physics to stimulate further advances? To me the answer is "yes" on the first two counts but "no" on the last.

I can therefore raise only two cheers for general relativity today.

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