100 years of General Relativity—Part Three

By Bryan Dyne
9 December 2015

This is the last part of a three-part series examining the history, science and implications of Einstein's general theory of relativity. Part one was published December 7. Part two was published December 8.

The present revolution of scientific thought follows in natural sequence on the great revolutions at earlier epochs in the history of science.
-Arthur Eddington, 1922

When Einstein revealed his finished work on general relativity in 1915, it was met with mixed reactions. On one hand, the contradictions that arose from considering an accelerating observer had been resolved with the unity of special relativity with gravity and geometry. On the other, there had yet to be empirical evidence confirming the theory.

This was not for a lack of trying. In 1911, Einstein had developed his understanding of general relativity enough to know that light rays curve in the presence of a massive object like the Sun and predicted that this would be a noticeable effect looking at starlight during a total solar eclipse. Einstein reasoned that light from stars behind the Sun would bend enough to be seen and measured on Earth.

A team of astronomers was assembled in 1914 to measure this effect, going to Russia to observe the eclipse happening that year. However, with the outbreak of World War I, they were arrested and became prisoners of war. Though they were released within weeks of their capture, they missed the opportunity to test general relativity.

Ironically, a test then would have shown the theory to be incorrect, as Einstein's 1911 calculations had an error. When he published the completed theory of general relativity in 1915, he included the corrected estimate for the deviation of stars as would be seen by a solar eclipse. Four years later, British physicist Arthur Eddington proved these predictions correct .

Einstein proposed one further test, the last of the three classical tests of general relativity he put forward in 1916 (the first two being calculating the offset in Mercury's orbit and the deviation in starlight caused by the Sun). One of the consequences of the equivalence principle (Einstein's postulate that an accelerating frame of reference and a gravitational field are indistinguishable) is that as light moves away from a gravitational field, its wavelength elongates. We see this on Earth as the light coming from a star being redder than what would be expected, knowing the star's composition and temperature. (This phenomenon is distinct from the famous "red shift" associated with the overall expansion of the universe, first measured by astronomer Edwin Hubble).

This effect was first observed by astronomer Walter Sydney Adams, who specialized in looking at the color composition of the light, or spectra, coming from stars. As part of his research, he found in 1915 that the companion of the star Sirius, dubbed Sirius B, is a white dwarf, a very dense object about the size of Earth but as massive as the Sun. Knowing the predicted properties of this type of star let him calculate what the spectra of Sirius B should be and to see if any gravitational red shift would show up in his results. He performed his test in 1925, and reported that he did indeed see the stretching of light predicted by general relativity.

Perhaps the most dramatic test of general relativity comes from the field of cosmology, the study of the large-scale structure of the universe. In the 1920s, astronomers Alexander Friedman and Georges Lemaître showed that general relativity forces the universe to be unstable, that it must either expand or contract. Lemaître made the explicit prediction that the universe should expand. This did not sit well with Einstein, who envisioned a static universe and introduced a "cosmological constant" to make this possible.

However, experimental evidence proved Einstein incorrect. In 1929, Edwin Hubble observed that distant galaxies are moving away from our own, and that the further away they are, the faster they move. The explanation that best fit the data was that Friedman and Lemaître were correct and that general relativity causes an expanding universe. In the face of the evidence, Einstein retracted his effort to artificially insert the cosmological constant, calling it "the biggest blunder of my life."

The corollary of an expanding universe is to look back at what the universe looked like in its infancy, when the now widely distributed matter was compacted into a singularity, a tiny and very hot, very dense, high-energy unit. In this singularity everything was in the same place and at the same time. For reasons as yet unknown, in a tiny fraction of a second, the singularity began its expansion, "exploding." Astrophysicists term this the Big Bang—one of the few concepts associated with general relativity that has wide popular awareness, albeit in a highly simplified form.

Studying the rate at which distant galaxies are receding from our own remains a key component of modern cosmology, and an important source of knowledge about the nature of the Big Bang. One of the primary tasks of the Hubble Space Telescope was to measure this expansion with extreme accuracy.

General relativity also predicts a phenomenon known as gravitational waves, ripples in spacetime propagating outward from matter in motion. The effect is most noticeable in bodies orbiting one another as the energy transported away by these waves eventually causes the bodies to crash into each other. While the effect is too small to observe with the Earth and Sun, it can be seen when the very dense remnants of dead stars, neutron stars and white dwarfs, orbit each other in close proximity. The most recent study of such a system was undertaken by a team of international astronomers in 2013 and agrees very strongly with predictions made using general relativity. Direct detection of gravitational waves is the next step and is currently being undertaken by the LIGO and GEO 600 experiments. Other experiments, such as NANOGrav and LISA, are being developed.

Other tests of general relativity include measuring the distance to objects in the solar system with radar and lasers, looking at how the light from distant galaxies is curved as that light passes by other galaxies on its way to Earth, and observing the slight distortions in spacetime caused by the rotation of massive objects. All of these show to a high degree of accuracy that general relativity, and not other theories of gravity subsequently developed, is the correct way to describe gravity.

Though general relativity became more and more accepted amongst the scientific community as it was tested, some of the predictions it made were the source of a great deal of controversy. The most famous of these surrounds the existence of black holes. According to general relativity, it is possible to have a region of spacetime with such strong gravity that once entered, not even light can escape. Gravity is so strong in this area that, locally, it infinitely warps spacetime. Such objects cannot be seen, their existence inferred only through the effect they have on surrounding matter.

One of the main points of contention centered around how such an object would come into existence. Even though the equations allowed for a solution, there was no evidence in the 1920s for a physical process that could squeeze matter to such a degree. Part of the solution came from Subrahmanyan Chandrasekhar in 1931 when he showed that white dwarfs would collapse if they became at least 1.4 times the mass of the Sun. Further work showed that above this, white dwarfs collapse into neutron stars rather than black holes, but in 1939 Robert Oppenheimer concluded that, above three times the mass of the Sun, there is no physical process that would prevent a neutron star from collapsing into a black hole.

A question still remained: how to detect these invisible objects? The easiest way would be to watch the x-rays being emitted off matter accreting around some region of space and then seemingly disappearing. As Earth's atmosphere blocks x-rays, it wasn't until an x-ray detector was launched aboard a rocket in 1964 that a black hole was discovered using this method. An effort to directly detect a black hole was started by MIT in 2012 with encouraging initial results.

The existence of black holes has provided new insights into many areas of astrophysics. It is now understood that when a massive star dies in a supernova explosion, there is a possibility that the event is so violent as to produce a black hole. In galactic astronomy, black holes several million (or even billion) times the mass of the Sun are the most likely candidates for being the seed around which galaxies form.

Black holes also provide a way to test theories of general relativity other than gravity. While no test to date has proven general relativity wrong, black holes are among the most extreme tests and have yet to be fully explored. In addition, some theories predict black holes in strange shapes that, if detected, would provide a serious challenge to the validity of general relativity.

One interesting aspect of general relativity is its use in studying dark matter. More than seventy years ago, astronomer Fritz Zwicky noticed aberrant motions of the galaxies composing the Coma Cluster caused by what seemed to be a great deal of some sort of invisible matter, which he dubbed "dark matter." Vera Rubin, in the 1970s, studied this deficit more systematically, as the known structure and motion of galaxies and groups of galaxies could not be explained by the quantity of visible matter they contained, which was seemingly too small. This became known as the "missing mass" problem.

Originally, it was hypothesized that a more detailed inventory of the contents of galaxies would balance the books, but investigations to find the mass in comparatively "invisible" forms, such as inert "brown dwarfs" between stars, black holes, or similar hiding places, all failed to account for the discrepancy.

What has since been determined is that galaxies are surrounded by halos of "dark matter" which does not emit light but does interact with the gas and dust of galaxies gravitationally. General relativity has helped astronomers to observe this dark matter indirectly by looking at how light is bent around galactic clusters, providing estimates for just how much dark matter there is in the universe.

In the future, general relativity may also allow researchers to directly observe events closer to the Big Bang than what is currently possible. As a result of everything being extremely hot and dense for some time after the universe began, we can only see back to 380,000 years after the Big Bang. There is no light that comes from an earlier time. Gravitational waves, on the other hand, do not suffer this restriction and, if the necessary detection equipment can be developed, could provide direct insight into the early universe.

As it stands today, however, there is one major theory that general relativity has yet to reconcile itself with: quantum mechanics. As well as developing the theory of special relativity, Einstein and his contemporaries were grappling with the nature of matter on the smallest scale. For some time, it was assumed that the elements on the periodic table were the most fundamental building blocks of matter. However, experiments by J.J. Thomson in 1897, Earnest Rutherford in 1911 and James Chadwick in 1932 showed that the elements have an internal structure and consist of electrons, protons and neutrons.

The study of the inner workings of the atom took the first quarter of the 20th century and involved essentially every physicist of the time. (See: One hundred years since Albert Einstein 's annus mirabilis) In 1926, when the comprehensive theory of quantum mechanics was finally developed, one of the first tasks of physicists was to integrate this framework with relativity.

Combining special relativity with quantum mechanics proved to be difficult. In 1928, Paul Dirac and others successfully worked out the mathematics to combine the two fields of physics, but it left a glaring philosophical problem. The mathematics allowed for both positive and negative energy values for elementary particles. How could energy, the quantity which measures matter's motion, be negative?

With assistance from Robert Oppenheimer, Dirac realized that an electron with negative energy can be better described as one with positive energy and positive electric charge. A year later, experiments by Carl Anderson would prove that the anti-electron, the positron, exists. The successful synthesis of quantum mechanics and special relativity is the basis for modern particle physics.

General relativity, however, has proven fundamentally incompatible with quantum mechanics. In the former, spacetime is described as a smooth, continuous fabric that is warped by the presence of mass and energy. In the latter, all matter is fundamentally quantized with a clear demarcation between one point and the next. While both theories are proven in their particular spheres, they cannot both be right as they currently stand. There have been many attempts to find a greater synthesis into which general relativity and quantum mechanics can be incorporated. These are the myriad theories of "quantum gravity," such as string theory, but after nine decades of searching there is no strong evidence that any of them are correct.

The new contradiction reminds one of the old. One hundred and fifty years ago, Maxwell wrote down a set of equations that fundamentally disagreed with the established Newtonian mechanics. It took another half century and two generations of physicists to resolve the issue, developing the theories of special and general relativity. The current struggle to unify general relativity and quantum mechanics into Einstein's elusive "Unified Field Theory" has gone on for nearly a century and has remained the foremost problem in theoretical physics. At the same time, this pursuit has simultaneously helped drive and been driven by the technological developments of the 20th and 21st centuries. No matter the outcome, the basic human desire to understand nature will keep us exploring.

Concluded