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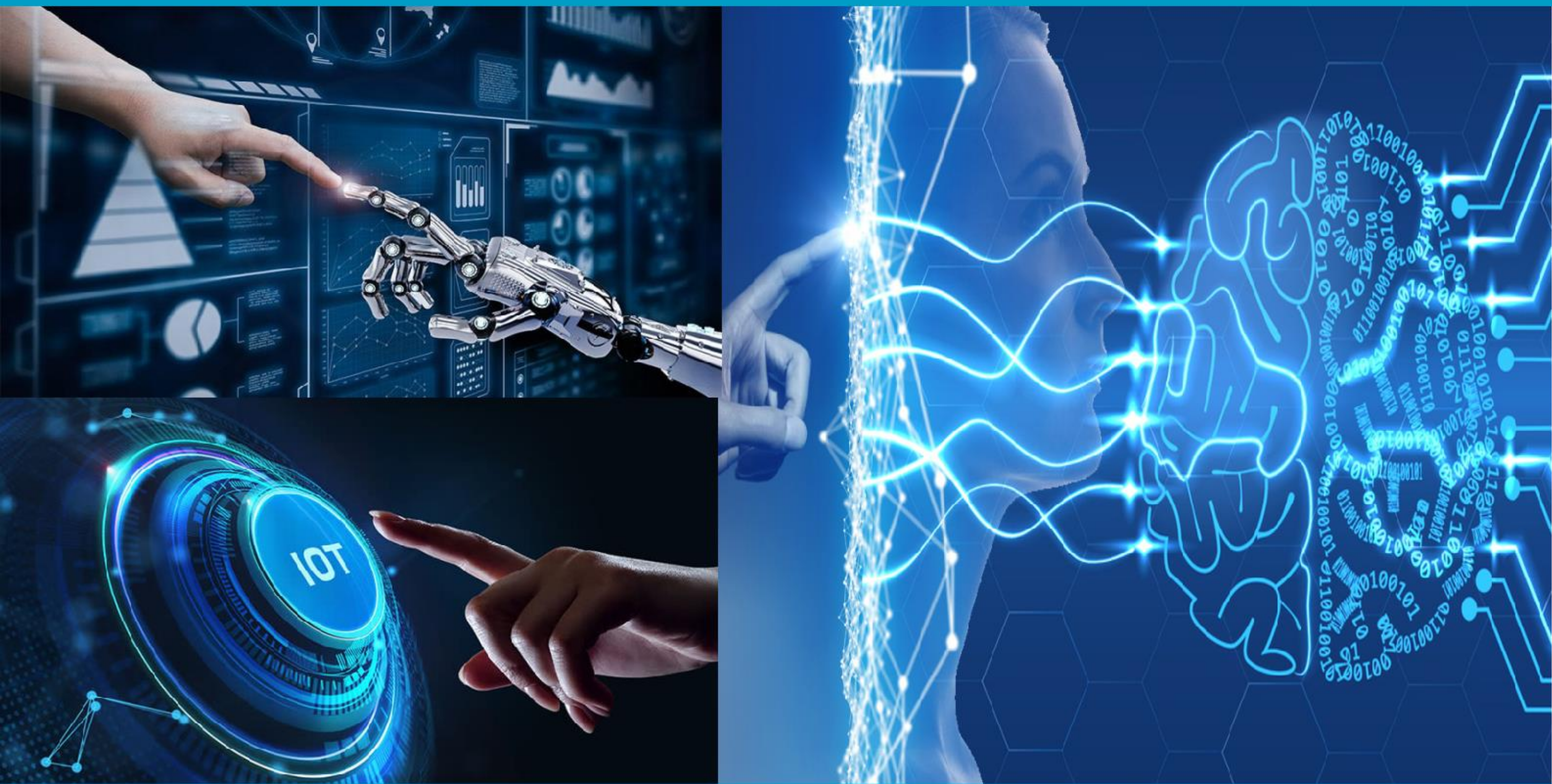

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An Abridged Study on the Einstein's General Relativity

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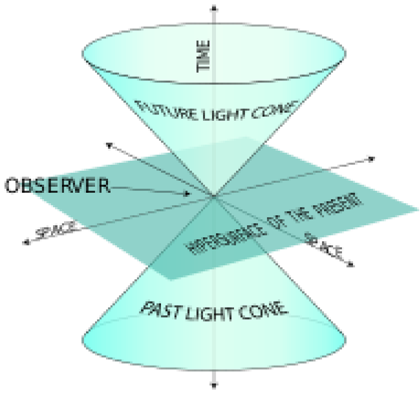
ABSTRACT: Einstein's General relativity postulates that the globalLorentz covariance of special relativity becomes a local Lorentz covariance in the presence of matter. The presence of matter'curves'spacetime, and this curvature affects the path of free particles (and even the path of light). General relativity uses the mathematics of differential geometry and tensors in order to describe gravitation as an effect of the geometry of spacetime. Einstein based this new theory on the general principle of relativity, and he named the theory after the underlying principle.

KEYWORDS: General, Relativity, Einstein, Inertial Non-inertial, Frame of reference.

I. INTRODUCTION

General relativity was developed by Einstein in the years 1907 - 1915. The general principle of relativity states: All systems of reference are equivalent with respect to the formulation of the fundamental laws of physics. That is, physical laws are the same in all reference frames—inertial or non-inertial.



A diagrammatic representation of space-time

In physics, the principle of relativity is the requirement that the equations describing the laws of physics have the same form in all admissible frames of reference.

For example, in the framework of special relativity the Maxwell equations have the same form in all inertial frames of reference. In the framework of general relativity the Maxwell equations or the Einstein field equations have the same form in arbitrary frames of reference.

Several principles of relativity have been successfully applied throughout science, whether implicitly (as in Newtonian mechanics) or explicitly (as in Albert Einstein's special relativity and general relativity).

General principle of relativity

The general principle of relativity states:

All systems of reference are equivalent with respect to the formulation of the fundamental laws of physics.

That is, physical laws are the same in *all* reference frames—inertial or non-inertial. An accelerated charged particle might emit synchrotron radiation, though a particle at rest does not. If we consider now the same accelerated charged particle in its non-inertial rest frame, it emits radiation at rest.

Physics in non-inertial reference frames was historically treated by a coordinate transformation, first, to an inertial reference frame, performing the necessary calculations therein, and using another to return to the non-inertial reference frame. In most such situations, the same laws of physics can be used if certain predictable fictitious forces are added into consideration; an example is a uniformly rotating reference frame, which can be treated as an inertial reference frame if one adds a fictitious centrifugal force and Coriolis force into consideration.

The problems involved are not always so trivial. Special relativity predicts that an observer in an inertial reference frame does not see objects he would describe as moving faster than the speed of light. However, in the non-inertial reference frame of Earth, treating a spot on the Earth as a fixed point, the stars are observed to move in the sky, circling once about the Earth per day. Since the stars are light years away, this observation means that, in the non-inertial reference frame of the Earth, anybody who looks at the stars is seeing objects which appear, to them, to be moving faster than the speed of light.
Since non-inertial reference frames do not abide by the special principle of relativity, such situations are not self-contradictory.

Basic concepts
Certain principles of relativity have been widely assumed in most scientific disciplines. One of the most widespread is the belief that any law of nature should be the same at all times; and scientific investigations generally assume that laws of nature are the same regardless of the person measuring them. These sorts of principles have been incorporated into scientific inquiry at the most fundamental of levels.
Any principle of relativity prescribes a symmetry in natural law: that is, the laws must look the same to one observer as they do to another. According to a theoretical result called Noether's theorem, any such symmetry will also imply a conservation law alongside. For example, if two observers at different times see the same laws, then a quantity called energy will be conserved. In this light, relativity principles make testable predictions about how nature behaves.

Special principle of relativity
According to the first postulate of the special theory of relativity:
Special principle of relativity: If a system of coordinates K is chosen so that, in relation to it, physical laws hold good in their simplest form, the *same* laws hold good in relation to any other system of coordinate’s K' moving in uniform translation relatively to K.
— *Albert Einstein: The Foundation of the General Theory of Relativity, Part A, §1*
This postulate defines an inertial frame of reference.
The special principle of relativity states that physical laws should be the same in every inertial frame of reference, but that they may vary across non-inertial ones. This principle is used in both Newtonian mechanics and the theory of special relativity. Its influence in the latter is so strong that Max Planck named the theory after the principle.
The principle requires physical laws to be the same for any body moving at constant velocity as they are for a body at rest. A consequence is that an observer in an inertial reference frame cannot determine an absolute speed or direction of travel in space, and may only speak of speed or direction relative to some other object.
The principle does not extend to non-inertial reference frames because those frames do not, in general experience, seem to abide by the same laws of physics. In classical physics, fictitious forces are used to describe acceleration in non-inertial reference frames.

In Newtonian mechanics
Galilean invariance
The special principle of relativity was first explicitly enunciated by Galileo Galilei in 1632 in his *Dialogue Concerning the Two Chief World Systems*, using the metaphor of Galileo's ship.
Newtonian mechanics added to the special principle several other concepts, including laws of motion, gravitation, and an assertion of an absolute time. When formulated in the context of these laws, the special principle of relativity states that the laws of mechanics are *invariant* under a Galilean transformation.

In special relativity
Joseph Larmor and Hendrik Lorentz discovered that Maxwell's equations, used in the theory of electromagnetism, were invariant only by a certain change of time and length units. This left some confusion among physicists, many of whom thought that a luminiferous aether was incompatible with the relativity principle, in the way it was defined by Henri Poincaré:
The principle of relativity, according to which the laws of physical phenomena should be the same, whether for an observer fixed, or for an observer carried along in a uniform movement of translation; so that we have not and could not have any means of discerning whether or not we are carried along in such a motion.
Henri Poincaré, 1904, in their 1905 papers on electrodynamics, Henri Poincaré and Albert Einstein explained that with the Lorentz transformations the relativity principle holds perfectly. Einstein elevated the (special) principle of relativity to a postulate of the theory and derived the Lorentz transformations from this principle combined with the principle of the independence of the speed of light (in vacuum) from the motion of the source. These two principles were reconciled with each other by a re-examination of the fundamental meanings of space and time intervals.

The strength of special relativity lies in its use of simple, basic principles, including the invariance of the laws of physics under a shift of inertial reference frames and the invariance of the speed of light in vacuum. (See also: Lorentz covariance.)

It is possible to derive the form of the Lorentz transformations from the principle of relativity alone. Using only the isotropy of space and the symmetry implied by the principle of special relativity, one can show that the space-time transformations between inertial frames are either Galilean or Lorentzian. Whether the transformation is actually Galilean or Lorentzian must be determined with physical experiments. It is not possible to conclude that the speed of light c is invariant by mathematical logic alone. In the Lorentzian case, one can then obtain relativistic interval conservation and the constancy of the speed of light.

Often Questionable Points about Einstein's general relativity theory

More than 100 years after Albert Einstein published his iconic general theory of relativity, it is beginning to fray at the edges, said Andrea Ghez, UCLA professor of physics and astronomy. Now, in the most comprehensive test of general relativity near the monstrous black hole at the center of our galaxy, Ghez and her research team report in the journal Science that Einstein's theory holds up.

"Einstein's right, at least for now," said Ghez, a co-lead author of the research. "We can absolutely rule out Newton's law of gravity. Our observations are consistent with Einstein's general theory of relativity. However, his theory is definitely showing vulnerability. It cannot fully explain gravity inside a black hole, and at some point we will need to move beyond Einstein's theory to a more comprehensive theory of gravity that explains what a black hole is."

Einstein's 1915 general theory of relativity holds that what we perceive as the force of gravity arises from the curvature of space and time. The scientist proposed that objects such as the sun and the Earth change this geometry. Einstein's theory is the best description of how gravity works, said Ghez, whose UCLA-led team of astronomers has made direct measurements of the phenomenon near a supermassive black hole — research Ghez describes as "extreme astrophysics."

The laws of physics, including gravity, should be valid everywhere in the universe, said Ghez, who added that her research team is one of only two groups in the world to watch a star known as S0-2 make a complete orbit in three dimensions around the supermassive black hole at the center of the Milky Way. The full orbit takes 16 years, and the black hole's mass is about 4 million times that of the sun.

The researchers say their work is the most detailed study ever conducted into the supermassive black hole and Einstein's general theory of relativity.

The key data in the research were spectra that Ghez's team analyzed last April, May and September as her "favorite star" made its closest approach to the enormous black hole. Spectra, which Ghez described as the "rainbow of light" from stars, show the intensity of light and offer important information about the star from which the light travels. Spectra also show the composition of the star. These data were combined with measurements Ghez and her team have made over the last 24 years.

Spectra — collected at the W.M. Keck Observatory in Hawaii using a spectrograph built at UCLA by a team led by colleague James Larkin — provide the third dimension, revealing the star's motion at a level of precision not previously attained. (Images of the star the researchers took at the Keck Observatory provide the two other dimensions.) Larkin's instrument takes light from a star and disperses it, similar to the way raindrops disperse light from the sun to create a rainbow, Ghez said.

"What's so special about S0-2 is we have its complete orbit in three dimensions," said Ghez, who holds the Lauren B. Leichtman and Arthur E. Levine Chair in Astrophysics. "That's what gives us the entry ticket into the tests of general relativity. We asked how gravity behaves near a supermassive black hole and whether Einstein's theory is telling us the full story. Seeing stars go through their complete orbit provides the first opportunity to test fundamental physics using the motions of these stars."

Ghez's research team was able to see the co-mingling of space and time near the supermassive black hole. "In Newton's version of gravity, space and time are separate, and do not co-mingle; under Einstein, they get completely co-mingled near a black hole," she said.

"Making a measurement of such fundamental importance has required years of patient observing, enabled by state-of-the-art technology," said Richard Green, director of the National Science Foundation's division of astronomical sciences. For more than two decades, the division has supported Ghez, along with several of the technical elements critical to the research team's discovery. "Through their rigorous efforts, Ghez and her collaborators have produced a high-significance validation of Einstein's idea about strong gravity."

Keck Observatory Director Hilton Lewis called Ghez "one of our most passionate and tenacious Keck users." "Her latest groundbreaking research," he said, "is the culmination of unwavering commitment over the past two decades to unlock the mysteries of the supermassive black hole at the center of our Milky Way galaxy."

The researchers studied photons — particles of light — as they traveled from S0-2 to Earth. S0-2 moves around the black hole at blistering speeds of more than 16 million miles per hour at its closest approach. Einstein had reported that in this region close to the black hole, photons have to do extra work. Their wavelength as they leave the star depends not only on how fast the star is moving, but also on how much energy the photons expend to escape the black hole's powerful gravitational field. Near a black hole, gravity is much stronger than on Earth.
Ghez was given the opportunity to present partial data last summer, but chose not to so that her team could thoroughly analyze the data first. "We're learning how gravity works. It's one of four fundamental forces and the one we have tested the least," she said. "There are many regions where we just haven't asked, how does gravity work here? It's easy to be overconfident and there are many ways to misinterpret the data, many ways that small errors can accumulate into significant mistakes, which is why we did not rush our analysis."

Ghez, a 2008 recipient of the MacArthur "Genius" Fellowship, studies more than 3,000 stars that orbit the supermassive black hole. Hundreds of them are young, she said, in a region where astronomers did not expect to see them.
It takes 26,000 years for the photons from S0-2 to reach Earth. "We're so excited, and have been preparing for years to make these measurements," said Ghez, who directs the UCLA Galactic Center Group. "For us, it's visceral, it's now — but it actually happened 26,000 years ago!"

This is the first of many tests of general relativity Ghez's research team will conduct on stars near the supermassive black hole. Among the stars that most interest her is S0-102, which has the shortest orbit, taking 11 1/2 years to complete a full orbit around the black hole. Most of the stars Ghez studies have orbits of much longer than a human lifespan.

Ghez's team took measurements about every four nights during crucial periods in 2018 using the Keck Observatory — which sits atop Hawaii's dormant Mauna Kea volcano and houses one of the world's largest and premier optical and infrared telescopes. Measurements are also taken with an optical-infrared telescope at Gemini Observatory and Subaru Telescope, also in Hawaii. She and her team have used these telescopes both on site in Hawaii and remotely from an observation room in UCLA's department of physics and astronomy.
Black holes have such high density that nothing can escape their gravitational pull, not even light. (They cannot be seen directly, but their influence on nearby stars is visible and provides a signature. Once something crosses the "event horizon" of a black hole, it will not be able to escape. However, the star S0-2 is still rather far from the event horizon, even at its closest approach, so its photons do not get pulled in.)

Ghez's co-authors include Tuan Do, lead author of the Science paper, a UCLA research scientist and deputy director of the UCLA Galactic Center Group; AurelienHees, a former UCLA postdoctoral scholar, now a researcher at the Paris Observatory; Mark Morris, UCLA professor of physics and astronomy; Eric Becklin, UCLA professor emeritus of physics and astronomy; SmadarNaoz, UCLA assistant professor of physics and astronomy; Jessica Lu, a former UCLA graduate student who is now a UC Berkeley assistant professor of astronomy; UCLA graduate student Devin Chu; Greg Martinez, UCLA project scientist; Shoko Sakai, a UCLA research scientist; Shogo Nishiyama, associate professor with Japan's Miyagi University of Education; and Rainer Schoedel, a researcher with Spain's Instituto de Astrofısica de Andalucıa.

The National Science Foundation has funded Ghez's research for the last 25 years. More recently, her research has also been supported by the W.M. Keck Foundation, the Gordon and Betty Moore Foundation and the Heising-Simons Foundation; as well as Lauren Leichtman and Arthur Levine, and Howard and Astrid Preston.
In 1998, Ghez answered one of astronomy's most important questions, helping to show that a supermassive black hole resides at the center of our Milky Way galaxy. The question had been a subject of much debate among astronomers for more than a quarter of a century.

A powerful technology that Ghez helped to pioneer, called adaptive optics, corrects the distorting effects of the Earth's atmosphere in real time. With adaptive optics at Keck Observatory, Ghez and her colleagues have revealed many

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surprises about the environments surrounding supermassive black holes. For example, they discovered young stars where none was expected to be seen and a lack of old stars where many were anticipated. It's unclear whether S0-2 is young or just masquerading as a young star, Ghez said.

In 2000, she and colleagues reported that for the first time, astronomers had seen stars accelerate around the supermassive black hole. In 2003, Ghez reported that the case for the Milky Way's black hole had been strengthened substantially and that all of the proposed alternatives could be excluded.
In 2005, Ghez and her colleagues took the first clear picture of the center of the Milky Way, including the area surrounding the black hole, at Keck Observatory. And in 2017, Ghez's research team reported that S0-2 does not have a companion star, solving another mystery.

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