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Einstein's theory of relativity is a famous theory, but it's little understood. Basically, the theory of relativity refers to two different elements of the same theory: general relativity and special relativity. The theory of special relativity was introduced first, and was later considered to be a special case of the more comprehensive theory of general relativity.

Theory of Relativity Concepts

Einstein's theory of special relativity - localized behavior of objects in inertial frames of reference, generally only relevant at speeds very near the speed of light

Lorentz transformations - the transformation equations used to calculate the coordinate changes under special relativity

Einstein's theory of general relativity - the more comprehensive theory, which treats gravity as a geometric phenomenon of a curved spacetime coordinate system, which also includes noninertial (i.e. accelerating) frames of reference
Fundamental principles of relativity

What is Relativity?

Classical relativity (defined initially by Galileo Galilei and refined by Sir Isaac Newton) involves a simple transformation between a moving object and an observer in another inertial frame of reference. If you are walking in a moving train, and someone stationary on the ground is watching, your speed relative to the observer will be the sum of your speed relative to the train and the train's speed relative to the observer. You're in one inertial frame of reference, the train itself (and anyone sitting still on it) are in another, and the observer is in still another.
The problem with this is that light was believed, in the majority of the 1800s, to propagate as a wave through a universal substance known as the ether, which would have counted as a separate frame of reference (similar to the train in the above example). The famed Michelson-Morley experiment, however, had failed to detect Earth's motion relative to the ether and no one could explain why. Something was wrong with the classical interpretation of relativity as it applied to light ... and so the field was ripe for a new interpretation when Einstein came along.

Introduction of Special Relativity

In 1905, Albert Einstein published (among other things) a paper called "On the Electrodynamics of Moving Bodies" in the journal Annalen der Physik. The paper presented the theory of special relativity, based upon two postulates:
Einstein's Postulates

Principle of Relativity (**First Postulate**): The laws of physics are the same for all inertial reference frames.

Principle of Constancy of the Speed of Light (**Second Postulate**): Light always propagates through a vacuum (i.e. empty space or "free space") at a definite velocity, c, which is independent of the state of motion of the emitting body.

Actually, the paper presents a more formal, mathematical formulation of the postulates. The phrasing of the postulates are slightly different from textbook to textbook because of translation issues, from mathematical German to comprehensible English.
The second postulate is often mistakenly written to include that the speed of light in a vacuum is c in all frames of reference. This is actually a derived result of the two postulates, rather than part of the second postulate itself.

The first postulate is pretty much common sense. The second postulate, however, was the revolution. Einstein had already introduced the photon theory of light in his paper on the photoelectric effect (which rendered the ether unnecessary). The second postulate, therefore, was a consequence of massless photons moving at the velocity c in a vacuum. The ether no longer had a special role as an "absolute" inertial frame of reference, so it was not only unnecessary but qualitatively useless under special relativity.

As for the paper itself, the goal was to reconcile Maxwell's equations for electricity and magnetism with the motion of electrons near the speed of light. The result of Einstein's paper was to introduce new coordinate transformations, called Lorentz transformations, between inertial frames of reference. At slow speeds, these transformations were essentially identical to the classical model, but at high speeds, near the speed of light, they produced radically different results.

Effects of Special Relativity

Special relativity yields several consequences from applying Lorentz transformations at high velocities (near the speed of light). Among them are:
Time dilation (including the popular "twin paradox")
Length contraction
Velocity transformation
Relativistic velocity addition
Relativistic doppler effect

Simultaneity & clock synchronization
Relativistic momentum
Relativistic kinetic energy
Relativistic mass
Relativistic total energy
In addition, simple algebraic manipulations of the above concepts yield two significant results that deserve individual mention.

Mass-Energy Relationship

Einstein was able to show that mass and energy were related, through the famous formula E=mc2. This relationship was proven most dramatically to the world when nuclear bombs released the energy of mass in Hiroshima and Nagasaki at the end of World War II.

Speed of Light

No object with mass can accelerate to precisely the speed of light. A massless object, like a photon, can move at the speed of light. (A photon doesn't actually accelerate, though, since it always moves exactly at the speed of light.)
But for a physical object, the speed of light is a limit. The kinetic energy at the speed of light goes to infinity, so it can never be reached by acceleration.

Some have pointed out that an object could in theory move at greater than the speed of light, so long as it did not accelerate to reach that speed. So far no physical entities have ever displayed that property, however.

Adopting Special Relativity

In 1908, Max Planck applied the term "theory of relativity" to describe these concepts, because of the key role relativity played in them. At the time, of course, the term applied only to special relativity, because there was not yet any general relativity.
Einstein's relativity was not immediately embraced by physicists as a whole, because it seemed so theoretical and counterintuitive. When he received his 1921 Nobel Prize, it was specifically for his solution to the photoelectric effect and for his "contributions to Theoretical Physics." Relativity was still too controversial to be specifically referenced.

Over time, however, the predictions of special relativity have been shown to be true. For example, clocks flown around the world have been shown to slow down by the duration predicted by the theory.

Albert Einstein didn't create the coordinate transformations needed for special relativity. He didn't have to, because the Lorentz transformations that he needed already existed. Einstein was a master at taking previous work and adapting it to new situations, and he did so with the Lorentz transformations just as he had used Planck's 1900 solution to the ultraviolet catastrophe in black body radiation to craft his solution to the photoelectric effect, and thus develop the photon theory of light.

Origins of Lorentz Transformations

The transformations were actually first published by Joseph Larmor in 1897. A slightly different version had been published a decade earlier by Woldemar Voigt, but his version had a square in the time dilation equation. Still, both versions of the equation were shown to be invariant under Maxwell's equation.
The mathematician and physicist Hendrik Antoon Lorentz proposed the idea of a "local time" to explain relative simultaneity in 1895, though, and began working independently on similar transformations to explain the null result in the Michelson-Morley experiment. He published his coordinate transformations in 1899, apparently still unaware of Larmor's publication, and added time dilation in 1904.

In 1905, Henri Poincare modified the algebraic formulations and attributed them to Lorentz with the name "Lorentz transformations," thus changing Larmor's chance at immortality in this regard. Poincare's formulation of the transformation was, essentially, identical to that which Einstein would use.

The transformations apply to a four-dimensional coordinate system, with three spatial coordinates (x, y, & z) and one time coordinate (t). The new coordinates are denoted with an apostrophe, pronounced "prime," such that x' is pronounced x-prime. In the example below, the velocity is in the xx' direction, with velocity u:

x' = (x - ut) / sqrt (1 - u2 / c2)
y' = y

z' = z

t' = { t - (u / c2) x } / sqrt (1 - u2 / c2)

The transformations are provided primarily for demonstration purposes. Specific applications of them will be dealt with separately. The term 1/sqrt (1 - u2/c2) so frequently appears in relativity that it is denoted with the Greek symbol gamma in some representations.
It should be noted that in the cases when u << c, the denominator collapses to essentially the sqrt(1), which is just 1. Gamma just becomes 1 in these cases. Similarly, the u/c2 term also becomes very small. Therefore, both dilation of space and time are non-existent to any significant level at speeds much slower than the speed of light in a vacuum.

Consequences of the Transformations

Special relativity yields several consequences from applying Lorentz transformations at high velocities (near the speed of light). Among them are:
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Simultaneity & clock synchronization
Relativistic momentum
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Relativistic total energy
Lorentz & Einstein Controversy

Some people point out that most of the actual work for the special relativity had already been done by the time Einstein presented it. The concepts of dilation and simultaneity for moving bodies were already in place and the mathematics had already been developed by Lorentz & Poincare. Some go so far as to call Einstein a plagiarist.

There is some validity to these charges. Certainly, the "revolution" of Einstein was built on the shoulders of a lot of other work, and Einstein got far more credit for his role than those who did the grunt work.

At the same time, it must be considered that Einstein took these basic concepts and mounted them on a theoretical framework which made them not merely mathematical tricks to save a dying theory (i.e. the ether), but rather fundamental aspects of nature in their own right. It is unclear that Larmor, Lorentz, or Poincare intended so bold a move, and history has rewarded Einstein for this insight & boldness.

In Albert Einstein's 1905 theory (special relativity), he showed that among inertial frames of reference there was no "preferred" frame. The development of general relativity came about, in part, as an attempt to show that this was true among non-inertial (i.e. accelerating) frames of reference as well.

Evolution of General Relativity

In 1907, Einstein published his first article on gravitational effects on light under special relativity. In this paper, Einstein outlined his "equivalence principle," which stated that observing an experiment on the Earth (with gravitational acceleration *g*) would be identical to observing an experiment in a rocket ship that moved at a speed of *g*. The equivalence principle can be formulated as:

we [...] assume the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system.

as Einstein said or, alternately, as one *Modern Physics* book presents it:

There is no local experiment that can be done to distinguish between the effects of a uniform gravitational field in a nonaccelerating inertial frame and the effects of a uniformly accelerating (noninertial) reference frame.

A second article on the subject appeared in 1911, and by 1912 Einstein was actively working to conceive of a general theory of relativity that would explain special relativity, but would also explain gravitation as a geometric phenomenon.

In 1915, Einstein published a set of differential equations known as the *Einstein field equations*. Einstein's general relativity depicted the universe as a geometric system of three spatial and one time dimensions. The presence of mass, energy, and momentum (collectively quantified as *mass-energy density* or *stress-energy*) resulted in a bending of this space-time coordinate system. Gravity, therefore, was movement along the "simplest" or least-energetic route along this curved space-time.

The Math of General Relativity

In the simplest possible terms, and stripping away the complex mathematics, Einstein found the following relationship between the curvature of space-time and mass-energy density:

(curvature of space-time) = (mass-energy density) * 8 *pi G* / *c*4

The equation shows a direct, constant proportion. The gravitational constant, *G*, comes from Newton's law of gravity, while the dependence upon the speed of light, *c*, is expected from the theory of special relativity. In a case of zero (or near zero) mass-energy density (i.e. empty space), space-time is flat. Classical gravitation is a special case of gravity's manifestation in a relatively weak gravitational field, where the *c*4 term (a very big denominator) and *G* (a very small numerator) make the curvature correction small.

Again, Einstein didn't pull this out of a hat. He worked heavily with Riemannian geometry (a non-Euclidean geometry developed by mathematician Bernhard Riemann years earlier), though the resulting space was a 4-dimensional Lorentzian manifold rather than a strictly Riemannian geometry. Still, Riemann's work was essential for Einstein's own field equations to be complete.

What Does General Relativity Mean?

For an analogy to general relativity, consider that you stretched out a bedsheet or piece of elastic flat, attaching the corners firmly to some secured posts. Now you begin placing things of various weights on the sheet. Where you place something very light, the sheet will curve downward under the weight of it a little bit. If you put something heavy, however, the curvature would be even greater.

Assume there's a heavy object sitting on the sheet and you place a second, lighter, object on the sheet. The curvature created by the heavier object will cause the lighter object to "slip" along the curve toward it, trying to reach a point of equilibrium where it no longer moves. (In this case, of course, there are other considerations -- a ball will roll further than a cube would slide, due to frictional effects and such.)

This is similar to how general relativity explains gravity. The curvature of a light object doesn't affect the heavy object much, but the curvature created by the heavy object is what keeps us from floating off into space. The curvature created by the Earth keeps the moon in orbit, but at the same time the curvature created by the moon is enough to affect the tides.

Proving General Relativity

All of the findings of special relativity also support general relativity, since the theories are consistent. General relativity also explains all of the phenomena of classical mechanics, as they too are consistent. In addition, several findings support the unique predictions of general relativity:

- Precession of perihelion of Mercury
- Gravitational deflection of starlight
- Universal expansion (in the form of a cosmological constant)
- Delay of radar echoes

Hawking radiation from black holes

Fundamental Principles of Relativity

- **General principle of relativity**: The laws of physics must be identical for all observers, regardless of whether or not they are accelerated.
- **Principle of general covariance**: The laws of physics must take the same form in all coordinate systems.
- **Inertial motion is geodesic motion**: The world lines of particles unaffected by forces (i.e. inertial motion) are timelike or null geodesic of spacetime. (This means the tangent vector is either negative or zero.)
- **Local Lorentz invariance**: The rules of special relativity apply locally for all inertial observers.
- **Spacetime curvature**: As described by Einstein's field equations, the curvature of spacetime in response to mass, energy, and momentum results in gravitational influences being viewed as a form of inertial motion.

The equivalence principle, which Albert Einstein used as a starting point for general relativity, proves to be a consequence of these principles.

General Relativity & the Cosmological Constant

In 1922, scientists discovered that application of Einstein's field equations to cosmology resulted in an expansion of the universe. Einstein, believing in a static universe (and therefore thinking his equations were in error), added a cosmological constant to the field equations, which allowed for static solutions.

Edwin Hubble, in 1929, discovered that there was redshift from distant stars, which implied they were moving with respect to the Earth. The universe, it seemed, was expanding. Einstein removed the cosmological constant from his equations, calling it the biggest blunder of his career.

In the 1990s, interest in the cosmological constant returned in the form of dark energy. Solutions to quantum field theories have resulted in a huge amount of energy in the quantum vacuum of space, resulting in an accelerated expansion of the universe.

General Relativity & Quantum Mechanics

When physicists attempt to apply quantum field theory to the gravitational field, things get very messy. In mathematical terms, the physical quantities involve diverge, or result in infinity. Gravitational fields under general relativity require an infinite number of correction, or "renormalization," constants to adapt them into solvable equations.

Attempts to solve this "renormalization problem" lie at the heart of the theories of quantum gravity. Quantum gravity theories typically work backward, predicting a theory and then testing it rather than actually attempting to determine the infinite constants needed. It's an old trick in physics, but so far none of the theories have been adequately proven.

Assorted Other Controversies

The major problem with general relativity, which has been otherwise highly successful, is its overall incompatibility with quantum mechanics. A large chunk of theoretical physics is devoted toward trying to reconcile the two concepts: one which predicts macroscopic phenomena across space and one which predicts microscopic phenomena, often within spaces smaller than an atom.

In addition, there is some concern with Einstein's very notion of spacetime. What is spacetime? Does it physically exist? Some have predicted a "quantum foam" that spreads throughout the universe. Recent attempts at string theory (and its subsidiaries) use this or other quantum depictions of spacetime. A recent article in New Scientist magazine predicts that spactime may be a quantum superfluid and that the entire universe may rotate on an axis.

Some people have pointed out that if spacetime exists as a physical substance, it would act as a universal frame of reference, just as the ether had. Anti-relativists are thrilled at this prospect, while others see it as an unscientific attempt to discredit Einstein by resurrecting a century-dead concept.

Certain issues with black hole singularities, where the spacetime curvature approaches infinity, have also cast doubts on whether general relativity accurately depicts the universe. It is hard to know for sure, however, since black holes can only be studied from afar at present.

As it stands now, general relativity is so successful that it's hard to imagine it will be harmed much by these inconsistencies & controversies until a phenomena comes up which actually contradicts the very predictions of the theory.

Quotes about Relativity

"Spacetime grips mass, telling it how to move, and mass grips spacetime, telling it how to curve" — John Archibald Wheeler.

"The theory appeared to me then, and still does, the greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition, and mathematical skill. But its connections with experience were slender. It appealed to me like a great work of art, to be enjoyed and admired from a distance." — Max Born