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The Theory of Relativity and Applications: A Simple Introduction

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What if I told you that time can speed up and slow down? What if I told you that everything you think you know about gravity is a lie? When Albert Einstein presented his theory of relativity to the world in the early 20th century, he was proposing just that. And what's more? He's been proven correct.

Einstein's theory has two parts: special relativity, which deals with inertial reference frames and general relativity, which deals with the curvature of space-time. A surface level study of the theory and its consequences followed by a look at some of its applications will provide an introduction to one of the most influential scientific discoveries of the last century.

Special Relativity

Special relativity was published in 1905 and has two overarching ideas:

1. The laws of physics are valid in all inertial reference frames (frames that aren't accelerating) and there is no preferred reference frame.
2. The speed of light is constant for all reference frames ($c = 299,792,458$ m/s).

These ideas come with several bizarre consequences. The first is that time doesn't move at the same rate for two observers that are moving relative to each other. To a person standing still looking at a car speeding past, time would appear to be moving slower for the driver. This effect is referred to as time dilation and can be modeled by: $\Delta t' = \gamma \Delta t$ where γ is called the Lorentz factor. The Lorentz factor is approximately one for speeds much less than the speed of light and increases as the relative speed approaches light speed (Walker, 2012).

Since time can be altered by speed, you're probably wondering about time travel. In a sense, special relativity allows for time travel to the future. Let's say a person leaves Earth on a spaceship that travels at a speed close to the speed of light. Time on the spaceship would be moving slower than time on Earth due to time dilation (Walker, 2012). So the traveler could return to Earth say 100 earth- years after he left, but may have only aged 10 years. The bad news is, to travel back to the past the traveler would need to travel faster than the speed of light. As a person's speed approaches the speed of light, their Lorentz factor becomes infinitely large, therefore the energy ($E = \gamma mc^2$) required to propel them becomes infinitely large. For this reason, traveling to the past is possible only in science fiction movies.



From the 1985 film "Back to the Future"

The strange consequences of special relativity aren't limited to time. In two different inertial reference frames, the length of an object will be different depending on the relative velocity between the frames. For example, a meter stick

traveling directly toward you will appear to be shorter than one meter. This can be modeled as: $L' = L/\gamma$ where γ is the same Lorentz factor as before. This phenomenon is referred to as length contraction (Walker, 2012).

The Doppler effect in light waves is another result of special relativity. In sound waves, the Doppler effect changes the frequency of sound emitted from a source based on that source's motion relative to the detector. That is the reason why police sirens sound high pitched when they are approaching you and low pitched when they are driving away. In light waves, the Doppler effect also alters the frequency, and therefore the wavelength, of sources. Light sources moving away from the detector will have longer wavelengths (called red shifting) and sources moving closer to the detector will have shorter wavelengths (called blue shifting). The greater the relative velocity, the greater the shift in wavelength (Walker, 2012). Scientists have used the detection of red shifted electromagnetic waves to determine how fast the universe is expanding.

At this point you're likely thinking that special relativity is weird and would like some evidence to back up these wild claims. In 1971, Joseph C. Hafele and Richard E. Keating performed an experiment that did just that. They flew two cesium atomic clocks around the world twice and then compared them with clocks that had remained stationary. The clocks disagreed and their difference was exactly predicted by the theory of relativity (Radeska, 2016). In 2017, another experiment was done using strontium clocks, whose accuracy is three times that of cesium clocks, and the theory of relativity was once again upheld (Ananthaswamy, 2017).



Hafele and Keating with their atomic clocks.

General Relativity

General relativity was published in 1915. Instead of inertial reference frames, it deals with acceleration and gravity. General relativity starts with the equivalence principal, which states that the effects of gravity are always equivalent to the effects of an acceleration (Hainline, n.d.). So, if we put a person in a box without windows, they wouldn't be able to tell if they were on Earth feeling Earth's gravity or accelerating in space. From the equivalence principal it follows that we can expect phenomena that occur in reference frames experiencing gravity to match those that occur in accelerating reference frames. One result of this is that light bends around massive objects as a result of gravity.

This observation contradicts Newtonian gravity ($F_g = G \frac{Mm}{r^2}$) because photons (light) are massless and therefore, in a Newtonian physics world, would be unaffected by gravity.

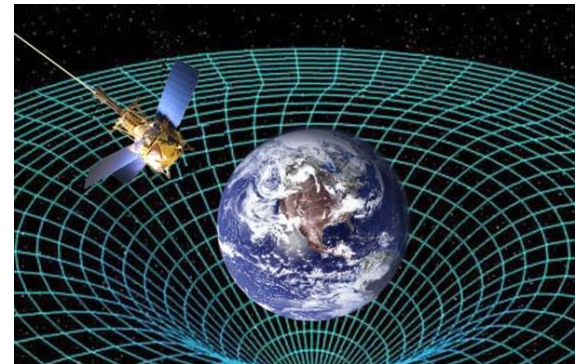
The general theory of relativity redefines gravity as an effect due to the curvature of space-time. Space-time is the entanglement of three-dimensional space and time. It is warped and bent by energy in a way that is described by the Einstein field equations (Pe'er, n.d.). Note here: Einstein's equation: $E = mc^2$ (from special relativity) defines mass as a type of energy, so saying energy warps space-time includes mass energy. There are six independent field equations all of the form:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi GT_{\mu\nu}$$

The left side of the equation deals with the geometry of space-time and the right side deals with the effects of energy (mass). The more massive an object, the more it bends space-time. One way to visualize the warping of space-time around a massive object, like Earth, is to think of a bowling ball on a trampoline. The bowling ball will deform the surface of the trampoline and when you place a marble on the trampoline it will roll toward the bowling ball. In a similar way, the warping of space-time around the Earth results in a pulling of less massive objects (like people) towards the Earth. This is gravity.

One effect of space-time's curvature is gravitational time dilation. Time slows down near massive objects due to the bending of space-time. More massive objects slow time more, because they produce curvier space-time (Hainline, n.d.). There are actually infinite points in space-time within some extremely massive objects, like black holes, where time, from the point of view of an outside observer, slows to a stop ("A black hole is a one-way", 2009).

Einstein's general theory of relativity also predicts the existence of gravitational waves. These are produced by events such as: the explosion of a supernova, the merging of two black holes or when two massive stars orbit each other. Much like ripples in a pond, gravitational waves travel radially outward from the source through space-time losing intensity with distance. These waves move at light speed. They compress and stretch space-time as they travel ("What is a gravitational wave", 2017). In 2015, scientists at the Laser Interferometer Gravitational-Wave Observatory (LIGO) physically sensed the space-time distortion from gravitational waves for the first time. The waves were produced by the collision of two black holes 1.3 billion years ago ("What is a gravitational wave", 2017).



Representation of how Earth bends space-time

Einstein's general theory of relativity has allowed for several advances in science. For instance, scientists couldn't accurately predict the orbit of Mercury until they considered that Mercury goes deeper into curvy space-time when it gets closer to the sun. Also, the bending of light around massive objects, described by general relativity, allows for gravitational lensing. Astronomers use gravitational lensing to view distant stars that are behind other massive celestial bodies (Hainline, n.d.).

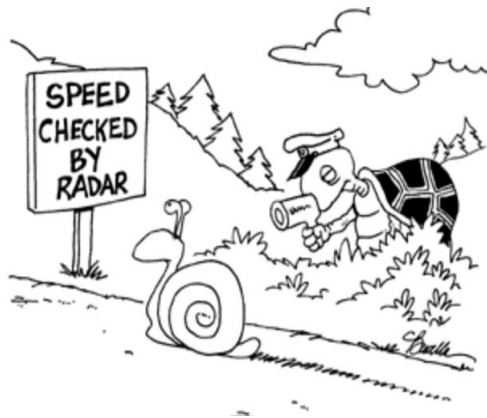
Applications

Einstein's theory of relativity has made many new technologies possible. A world without relativity would be a world without cathode ray televisions, radar guns, the global positioning system and more.

Cathode ray tube (CRT) televisions create pictures by shooting electrons at a phosphorous screen. These electrons are accelerated to high velocities, near 20- 30% of the speed of light. Remember from special relativity that as a particle approaches speeds near light speed, the energy required to propel the particle is increased. Magnets in the television are responsible for placing the electrons in the correct configuration on the screen. They must account for the relativistic effects on these electrons or the picture created will be out of focus (Akpan, 2015). So, we have Einstein to thank for making CRT televisions, the precursor to plasma and LCD televisions, possible.



Cathode Ray Tube television



Another modern technology with a tie to Einstein's theory of relativity is the radar gun. Radar guns are used in the military, professional sports, and, yes, to give out speeding tickets. A radar gun consists of a radio wave emitter and a detector. A police officer points his radar gun at a speeding car. The radar gun emits radio waves. These waves reflect off of the speeding car and travel back to the detector (Akpan, 2015). Based on the amount of wavelength shift, due to the Doppler effect discussed in special relativity, the radar gun is able to calculate the speed of the passing car. So, remember to thank Einstein for making your next speeding ticket possible.

The theory of relativity plays a crucial role in the accuracy of the global positioning system (GPS). The GPS consists of 24 satellites that orbit the Earth. These satellites are about 20,000 km above Earth's surface and are traveling at about 4 km/s (just shy of 9,000 mph). GPS receivers, like the one in your car's navigation system, receive four signals emitted by four satellites. They use these signals to solve four independent linear equations that triangulate your location. These equations can be summarized as: the distance traveled by the light wave (the distance from the satellite to you) is equivalent to the speed of the wave (the speed of light) multiplied by the time it took the wave to get to you.

In order for these equations to work correctly, the GPS satellites must keep very accurate time. They use atomic clocks that are routinely adjusted for the effects of both special and general relativity. The relative speed between the satellites and the Earth will cause a time dilation that slows the GPS clocks. Opposing this effect, a gravitational time dilation is caused because the satellite clocks are further from the Earth and are therefore in less curvy space-time than those on Earth's surface. If these effects weren't accounted for, the errors would be significant; as much as 11 km in only one day (Ashby, 2002).

Einstein's discovery also had a hand in electron beam machining (EBM). EBM is a nontraditional machining process, invented in 1952, that utilizes a beam of high velocity electrons to perform cutting operations. The electrons are produced in the electron beam gun and are accelerated to 50- 80% the speed of light by an anode (Kalpakjian, 2014). With speeds close to the speed of light, the electron's kinetic energy must be calculated using equations that come from special relativity. When these high- energy electrons hit the work piece, their kinetic energies are transferred to thermal energy. This energy melts or vaporizes the work piece material creating the desired cut ("Electron Beam", n.d.). Electron beam machining has allowed for the fast, high precision machining of a variety of parts for the medical, automotive, aerospace and other industries.

Walking through the basics of Einstein's special and general theory of relativity has provided a basic understanding of one of the most important

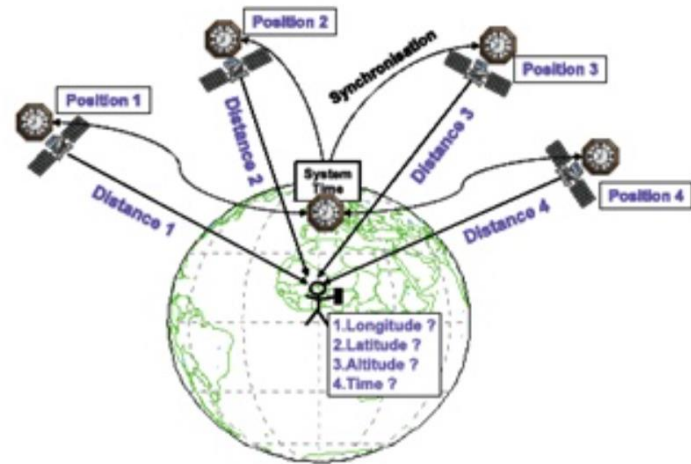
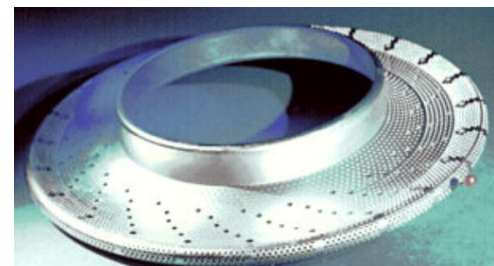


Illustration of four satellites in the GPS triangulating a location



Mixer Disc: 2,340 holes of 0.9 mm diameter drilled by EBM

scientific advances of the last century. The theory of relativity explained previously unexplained scientific observations, led the way for new scientific advances and made many common technologies possible.

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