A Non-Scientist's Understanding of Relativity

By Mike Balmages, a non-scientist[1]

Pre-Summary

The key to Special Relativity is to understand that to all observers the speed of light ("*c*") will always be the same speed, approximately 186,000 miles per second. Once you accept this, all of the other "consequences" of that fact such as time and distance being different for different observers flow naturally and can be calculated by the algebraic equations developed by Lorentz.

General Relativity is a theory of gravity that says that gravity is not an attractive force acting at a distance but, instead, is an actual curvature of spacetime. The natural state of motion is the shortest possible route in this curved spacetime. The complex equations of General Relativity predict such things as time slowing down in heavy gravity, the bending of light by gravity and black holes.

Introduction

As an amateur astronomer, over the past several years I have read various books and articles on "Relativity." All of these have been oriented toward the non-scientist and general reader and were designed to make Relativity accessible to everyone. The books have included, amongst others, Stephen Hawking's *Brief History of Time,* Lincoln Barrett's *The Universe and Dr. Einstein*, Timothy Ferris's *The Whole Shebang* and Brian Greene's *The Elegant Universe.* They are all wonderful books and I thoroughly enjoyed them and recommend them. The problem is that I did not understand Relativity after reading them. In each book, I would follow the discussions and explanations as they went along but would end up confused.

I just completed a twelve hour course on tape entitled, "Einstein's Relativity and the Quantum Revolution: *Modern Physics for Non-Scientists*," given by Professor Richard Wolfson of Middlebury College in Vermont. The course is from The Teaching Company. The course was excellent and, for the first time, I think I "understand" Relativity. Here is what I understand based on that course and my prior reading[2],[3]:

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1 A lawyer who has not taken a math or science class, other than a few elementary astronomy classes, since he graduated from high school in 1964!

2 This paper is like a book report on that course and all of the other books and articles I have read on the subject. All analyses, opinions and

Special Relativity
Background
Mechanics

During the approximate time period of 1600-1750 the science of physics, the study how the physical world works, was mostly concerned with mechanics, i.e., motion. In his most famous work, *Principia*, published in 1687, Sir Isaac Newton set down the rules of mechanics that basically remain unchanged until now. Newton's work was based on the work of Galileo and many others. (Newton's most famous quote is that he stands on "the shoulders of giants.")

Newton's laws of mechanics include his rules that force equals mass times acceleration (f=ma); that objects at rest tend to stay at rest and objects in motion tend to stay in motion[4]; and for every action there is an equal and opposite reaction. Newton also developed the mathematical formulas that made these rules useful for describing and predicting motion and inventing things.

The Newtonian rules of mechanics are extremely successful and accurate. They describe and predict "normal" motion to an extremely high degree of accuracy. They are still valid, and the Special Theory of Relativity incorporates them and expands on them.[5]

The Principle of Relativity

One aspect of the Newtonian rules of Mechanics is the Principle of Relativity, also known as "The Principle of Galilean Relativity." This principle says (i) that the laws

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facts stated herein are from my intepretation and memory of what I read and listened to. I am the sole creator and owner of and completely responsible for all mistakes that may be in this paper.

3 Since writing the first several drafts of this article, I read *The Ultimate Einstein* by Robert P. Libbon, et al. This is an excellent discussion of relativity mixed with Einstein's personal life and the history of the time.

4 i.e., the natural state of motion is uniform motion in a straight line.

5 Newton also developed his theory of universal gravitation. He stated that gravity is an attractive force that acts at a distance and that all bodies (masses) posses it. Newton said that the force of gravity is proportional to a body's mass and inversely proportional to the square of the distance from the body. These rules very accurately describe and predict the orbits of the planets (with the exception of Mercury, the orbit of which is very slightly different than that predicted by Newton's laws - this slight discrepancy was dealt with by General Relativity).

of mechanics, the rules about motion, are the same for all frames of reference (observers, points of view, or places where you are conducting your experiments) in uniform motion (moving in a straight line at a constant speed), (ii) that there is no such thing as "absolute" motion, but that all motion is only meaningful when it is considered relative to something else, and (iii) that all frames of reference are equally valid.[6],[7],[8]

Electricity and Magnetism

From about 1750 to 1900, Physics turned its major attention to electricity and magnetism. The most basic realization in that was that electricity and magnetism are two aspects of the same thing.

By about 1850 the laws of "electromagnetism" were well known. Instead of being thought of as forces acting at a distance like Newton thought about gravity, the physicists of the time envisioned electrical "fields" and magnetic "fields" respectively surrounding electric charges and magnets. It is these fields that give rise to the actions and forces of electricity and magnetism.

Around 1860, a Scotsman, James Clerk Maxwell, described the laws of electromagnetism in four equations. The first equation said that opposite electrical charges attract and that like electrical charges repel. The second equation said the same thing about magnetic poles. The third equation said that a changing electrical field produces a magnetic field and the fourth equation said that a changing magnetic field produces an electrical field.

Maxwell realized that a changing magnetic field must produce a changing electrical field which in turn must produce a changing magnetic field which must produce a changing electrical field, and so on. He viewed this process as electromagnetic waves. He set out to describe these waves mathematically and calculate the speed at which they would travel. He did this and came up with the speed of

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6 For example, it is just as valid to say that the building is moving towards you and you are stationary as it is to say that you are moving towards the building and it is stationary.

7 "Rest" is just a special case of uniform motion.

8 Non-uniform motion involves a change in speed (acceleration or deceleration) and/or a change in direction. An object in a circular or elliptical orbit is not in uniform motion because it is constantly changing its direction as it travels in its orbit. One way of thinking about non-uniform motion is that it is the kind of motion that you can feel, like when a car goes around a corner. Uniform motion is the kind you can't feel, like being in an airplane in calm air and going at a constant speed.

186,000 miles a second, and the rule that electromagnetic waves always travelled at this speed.

By 1860 the speed of light was already well known and Maxwell realized that light must be an electromagnetic wave.[9]

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[9] Visible light is a small part of the electromagnetic spectrum. We can only "see" the visible light part of the spectrum because our eyes evolved in a solar system of a star that produces most of its electromagnetic waves in that part of the spectrum.

The electromagnetic spectrum is a continuous spectrum that ranges from radio waves on one end to gamma rays on the other. Radio waves have the longest wave lengths and lowest frequencies and gamma waves have the shortest wave lengths and highest frequencies.

The wave length is the distance between two successive wave peaks and the frequency is the number of times per second (or minute or whatever time unit you are using) that the wave moves up and down. The longer the wave length, the lower the frequency and the shorter the wave length, the higher the frequency. The higher the frequency, the higher the energy of the light (electromagnetic) wave (or particle). There are equations which express all of this mathematically.

The wave length of radio waves is measured in meters, while the wave lengths of gamma waves is microscopically small. The spectrum, from longest to shortest wave length, is: Radio waves; microwaves; infrared; visible light; ultraviolet; x-rays; and gamma rays. This grouping is done by wave lengths, but the waves are basically all identical except for their lengths, frequencies and energies. These differences allow the waves to do different things (like penetrate right through your body like x-rays, or be seen by your eyes like visible light). It is a continuous spectrum, meaning that there is an infinite number of possible wave lengths, all right next to each other.

The visible light spectrum ranges from red, which is just shorter in wave length than infrared (hence the name), through violet, which is just longer in wave length than ultraviolet (hence the name). In easy to remember order, it is: ROY G. BIV, or Red, Orange, Yellow, Green, Blue, Indigo, Violet.

All “hot,” “glowing” bodies emit electromagnetic radiation. In this case, “hot” and “glowing” mean anything above absolute zero (about -270 degrees celsius). In other words, all bodies emit electromagnetic radiation. The

The Æther

Physicists of the time, knowing the Principle of Galilean Relativity, which says that there is no such thing as absolute motion and motion can only be described as relative to something else, began to ask, "What do electromagnetic waves (including light) move relative to at speed of *c*?" To answer this, they came up with the concept of the "luminiferous ether" (also "æther").

The reason they did this is that they thought of electromagnetic waves like they thought of sound waves or water waves, as a disturbance of some kind of medium. Sound waves (which are not electromagnetic waves) are a disturbance of air molecules that moves in wave-like fashion. Water waves (which are also not electromagnetic waves) are a disturbance of water which moves in a wave-like fashion.

The ether was thought to pervade all of space, from the farthest star to the sub-microscopic spaces of atoms and molecules. It was invisible and, thus far, undetectable. Light waves (and all electromagnetic waves) were believed to be a disturbance of the ether.

Numerous experiments were done to detect the luminiferous ether and determine whether light waves moving against the "ether wind" went slower than *c* and whether light waves moving with the "ether wind" went faster than *c*. Everyone was sure the answers would be "yes," once the effect of the ether could be measured. If the answers were "yes" it meant that light moved at *c* only with respect to the ether and not with respect to all frames of reference and that, therefore, there was no principle of relativity with regard to electromagnetic waves (because the ether was a "preferred" frame of reference).

The most famous of the experiments to detect the ether wind were the Michelson-Morley experiments (around 1887). They determined unequivocally that the speed of light was the same regardless of whether the light was travelling against the ether wind or with the ether wind. This created a dilemma which was solved by Albert Einstein and the Special Theory of Relativity.

Except for the "ether," the rules of Newtonian and Galilean mechanics (the laws of motion) and the rules of electromagnetism that were developed prior to 1900 essentially are all still valid and accurately predict motion and electric and

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exact types and amounts of radiation a body emits (the spectrum of the body) depend on the body's temperature (how "hot" it is) and to a lesser extent what it is made of.

magnetic phenomena, except when dealing with very high speeds near the speed of light, very large gravitational fields or masses or with sub-atomic, elementary particles.

The Situation as of 1900

So, as of 1900, the situation was this: Physics, the science of the how the physical world works had two main branches, mechanics and electromagnetism[10]. Mechanics was the study of motion and was based the rules developed by Galileo, Newton and others. Those rules (or laws) very accurately described the motion of everyday objects from colliding billiard balls to the paths of the planets.

It was recognized that the laws of mechanics obeyed a relativity principle, which stated that the laws of mechanics are the same for all frames of reference in uniform motion (“Galilean Relativity”). Scientists liked this idea because it was elegant and simple and showed that there is really no preferred frame of reference but that all frames of reference are equally valid.

The other main branch of physics, electromagnetism, was not quite so elegant. It was governed by the rules developed by Maxwell, and others. One of those rules was that there must be electromagnetic waves which always travel at speed *c*. The problem arose when the question was asked, “what was light traveling at *c* relative to.” The answer was the “ether.” There were two main problems with this. One was that this made the ether a preferred frame of reference, eliminating a relativity principle for electromagnetism. The other was that the ether had never been detected and its predicted effect on the speed of light, that the speed of these electromagnetic waves would be affected by the ether “wind,” had not been measured in very sensitive experiments designed to show it existed.

Einstein

Einstein apparently pondered this problem for quite a while and it wasn’t until a few weeks before he published his paper in 1905 that he hit upon the solution. His paper was titled “On The Electrodynamics of Moving Bodies,” and solved the problem of the “ether,” with the Special Theory of Relativity.[11]

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10 "Optics" was another branch.

11 1905 was a big year for the 26 year old Einstein. He was working as a clerk in the Swiss patent office, checking inventions and their patents. He devoted his spare time to physics. In 1905 he published four papers, three of which were monumental. One was on “Brownian Motion,” which is the seemingly random motion of small particles suspended in a liquid. Einstein proved that this motion was caused by molecules and this was proof of the

What Einstein said was that the ether did not exist. Instead he said that, just like mechanics, electromagnetism also obeyed a relativity principle and, therefore, he took the Principle of Galilean Relativity (that the laws of mechanics are the same for all frames of reference in uniform motion) and restated it as, “the laws of physics (mechanics and electromagnetism[12]) are the same for all frames of reference in uniform motion.” One of these laws of physics was the electromagnetic law that light waves must travel at speed *c*. In answer to the question, “relative to what is light (or any other electromagnetic wave) traveling at speed *c*,” Einstein stated that it was traveling at *c* relative to whomever was doing the measuring.

What Einstein had realized a few weeks before he published this paper was that in order to reach this conclusion about *c* he had to give up his everyday and common sense notions of time and space. He realized that time and space were not absolute as everyone (including Newton and Einstein) had always assumed. Instead, time and space were just measurements that were unique to each frame of reference. Depending on the observer’s motion[13], his or her time will move slower or faster than that of someone in another frame of reference. Also, again depending on the observer’s relative motion, his or her measures of space (distances) will be shorter or longer than that of someone in another frame of reference. In other words, everyone moving relative to you will experience time and distance differently than you do.

Keep in mind that these differences in time and space are not just differences caused by some mechanical function of clocks or rulers but rather are actual differences in the passage of time and distances travelled. Time and space are different for everyone and every frame of reference. The reason why it is so hard to "intuitively" understand this is because it is not noticeable in our everyday lives. Although clocks really do run at different speeds for everyone, the differences

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existence of atoms. The second paper was on the photoelectric effect and turned out to be one of the cornerstones of quantum mechanics. Einstein eventually won the Nobel Prize for this paper. The third paper was, “On The Electrodynamics of Moving Bodies.” The fourth paper was a follow-up to the Special Theory of Relativity and explained the equivalence of mass and energy with the formula $E=Mc^2$.

12 and optics

13 relative to some other frame of reference, since it is meaningless to speak about “absolute” motion, without speaking about what you are moving relative to.

here on earth are so small as to be completely unnoticeable. It is only when things travel (relative to other things) at speeds near the speed of light that the differences in time and distance become noticeable.

Today, there are measuring devices that can detect minute differences in time, and they have shown that clocks aboard airplanes flying at supersonic speeds actually do run slower than those left behind on the ground. Again, this is not because the clock mechanism is somehow affected by the travelling. It is because time is actually running more slowly. The differences become noticeable and easily measurable at speeds above about ten percent of *c*.[14]

Here is the key thing, in every instance of relative motion (the only kind of motion that there is), time and distance change by the exact amounts necessary to make *c* always be measured at 186,000 miles per second.[15]

Summary of Special Relativity

(i) Special Relativity arose because Einstein realized that, just like the rules governing motion, the rules governing electromagnetism must be the same for all frames of reference in uniform motion. One of those rules of electromagnetism is that the speed of light, "*c*," is always 186,000 miles per second. In order for *c* to be the same in all frames of reference, Einstein realized that time and space must be unique (different) for each frame of reference. This required him to give up his common sense view of time and space as being fixed and absolutely the same for everyone.

(ii) The Special Theory of Relativity says that the laws of physics are the same for all frames of reference in uniform motion. Einstein realized that not only are the laws of motion (mechanics) the same for all frames of reference but that the laws

[14] One way this does affect us in our everyday lives is that time runs at a different rate on communication satellites whizzing around the earth than it does on earth. The difference is large enough that it has to be taken into account when designing systems that operate pagers, tv's, cell phones, etc. If it wasn't taken into account, none of those things would work as the timing of signals transmitted between the ground based objects and the satellites would be all screwed up.

[15] The mathematics of this is actually fairly simple and Einstein based it on prior equations developed by Lorentz and Fitzgerald. They are called the Lorentz Transformations and were independently developed by both Lorentz and Fitzgerald to explain the failure of the Michelson-Morley experiment to measure the effect of the ether wind.

of electromagnetism and optics also are the same for all frames of reference in uniform motion.

(iii) It is a "special" theory because it deals with the "special" case of uniform motion. It doesn't deal with the more "general" case of any kind of motion (like accelerated motion). That was dealt with in the General Theory of Relativity.

(iv) One of Einstein's conclusions from the Special Theory of Relativity was that, if it is true, it must mean that time and space are not absolute concepts like everybody assumed but, instead, they are personal or different for each person and/or frame of reference.

(v) Under the Special Theory of Relativity, just like under the Principle of Relativity, the concept of absolute motion is meaningless. To say that something is moving, doesn't mean a thing unless you say what it is moving relative to.

(vi) There is no preferred frame of reference and all frames of reference are equally valid.

(vii) We really live in a four dimensional universe, al least on the macroscopic level. Instead of just the three spacial dimensions of length, width and depth, there is the fourth dimension of time. The four dimensions are all part of "spacetime" and the "size" of the dimensions is different for each frame of reference. Each of the dimensions expands or contracts as necessary to make sure that light is always traveling at *c*.

(viii) Later in 1905, Einstein published a follow-up paper to the Special theory of Relativity in which he discussed another conclusion from the theory, i.e. that an objects mass increases as the objects speed increases. This effect is the result of the essential equivalence of mass and energy.[16]

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16 $E=Mc^2$ is the most famous formula in physics and, perhaps, the most famous of all formulas. It is always associated with Einstein and with the atomic bomb. It is, however, not the essential formula or ingredient of Einstein's Special Theory of Relativity. It is also not the essential formula or ingredient of Einstein's General Theory of Relativity. It was not essential to the development of the atomic bomb.

$E=Mc^2$ expresses Einstein's realization of the underlying equivalence of matter and energy. Matter can be changed into energy. And, when it is, the amount of energy that is created is very large compared to the amount of matter that no longer exists, at least from our human, earthly perspective.

(ix) The speed of light is the fastest speed of the universe.[17]

When you burn wood in a fireplace, if you weigh the wood before you burn it and, after you burn it, you weigh the remaining ashes and soot and all of the gases that are given off (gases are still matter, after all, even if we can't see them), the stuff (matter) that is left over will weigh a very tiny bit less than the wood you started with. It is that slight amount of stuff that is missing that caused all of the heat of the fire that warmed you. The amount of energy (heat) that is given off by the fire can be determined by multiplying the amount of the matter that is missing after the wood is burned by the speed of light squared, or to put it another way, $E=Mc^2$.

$E=Mc^2$ is generally associated with nuclear reactions and it does apply to them exactly as it does to wood burning in a fireplace. In a nuclear power plant if you were to weigh all of the uranium or other fuel before it is split (fissioned) into other elements and then weigh all of the elements that are left over, again a small amount of mass would be missing. That small amount is the source of all of the power (energy) produced by the power plant. The only difference between this situation and the fireplace is that the nuclear reaction of the power plant is way more efficient in converting matter into energy, i.e. more matter gets converted into energy.

As $E=Mc^2$ implies, energy can also be converted into matter. The very high energy collisions of particle accelerators both create and destroy matter and their behavior is predicted by Einstein's famous formula.

17 That the speed of light is the fastest speed the universe allows becomes clear from the predictions of the Special Theory of Relativity. These predictions include the facts that (i) as objects get faster they shrink in the direction of travel (distance changes), (ii) as objects get faster time slows down for them, and (iii) as objects get faster their masses increases. All of these effects, which have now been proven to be facts of life, are not at all noticeable at our everyday speeds. They only become noticeable at speeds which are a significant percentage of the speed of light. These effects all increase dramatically at speeds very close to the speed of light. For example although an object's mass may only be doubled at 99% of the speed of light, at 99.99% its mass may be 7 times as much and at 99.999% the speed of light, its mass may be 50 times as much. (These numbers are not necessarily accurate but are just illustrative of the process that occurs.) This type of exponential increase continues until, at the speed of light, the objects mass would be infinite, which would require an infinite amount of energy to get it to go any faster. Since there this no infinite amount of energy, the object can't go any faster.

There are many cool and amazing examples of time and space being different at high speeds, of people going on journeys that last 50 years as measured on earth and only aging a day or so. All of which solely depends on the relative motion between the two bodies.[18] There are also many examples showing that

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The same process works for distance and time. At the speed of light, an object would get infinitely small in the direction of travel and time would go infinitely slowly, either of which effect also prevents the object from exceeding the speed of light.

18 Professor Wolfson uses an example of how time and distance are affected by relative motion: Suppose there is a star that is 10 light years (ly's) from Earth. In essence, the Earth and the star are not moving relative to each other and are therefore in the same frame of reference. If a rocket leaves Earth and travels to the star at 80% of the speed of light (.8*c*), from the perspective of the Earth-star frame of reference, the rocket will take 12.5 years to reach the star (10 ÷ .8 = 12.5) and another 12.5 years to return to Earth. The simple math of the Lorentz transformations shows that to the people on the rocket the trip will take 7.5 years to reach the star and another 7.5 to return to Earth. So, while 25 years will have passed for the people on Earth, only 15 years will have passed for the people who were on the rocket. And, the people on the Earth would observe and measure the length of the round trip to be 20 ly's. The people on the rocket can then look at their odometer and measure how far they went. Their odometer (or yardstick or ruler or any other measuring device) will show that for them the length of the round trip was 12 ly's. This makes sense since, in their frame of reference, they travelled for 15 years at .8*c* (15 years x .8 *c* per year= 12 light years).

(The formula for the time transformation is $t' = t\sqrt{1 - v^2/c^2}$, where t' is the time that passes on the spaceship, t is the time that passes on the Earth, v equals the relative speed of the two frames of reference, and *c* equals the speed of light. In this example, 7.5 (the time that passes for the people on the space ship) = 12.5 (the time that passes for the people on Earth) x the square root of 1 - .64 (the square of .8) over 1, or 7.5 = 12.5 x the square root of .36, or 7.5 = 12.5 x .6.

From this formula you can see why we do not notice time differences in our everyday experiences. Take, for example, the speed of an airplane relative to the ground as 600 miles per hour [equal to 0.166 miles per second]. The time that passes on the airplane for a two hour trip [as measured from the ground frame of reference] would be $2 \times \sqrt{1 - 0.166^2/186{,}000^2}$, which is simultaneity is also relative and events that are simultaneous in one frame of reference are not simultaneous in another frame of reference.[19]

Like Newton, Einstein also stood on the "shoulders of giants," including Michelson, Morley, Lorentz and others. He used all of their work and came up with a very simple explanation of time and space that was a revolutionary way to describe them. Special Relativity is an extremely successful theory. Its predictions have been testable and, so far, have proven to be right on.

Over the next 10 years Einstein worked on gravity and non-uniform motion and figured those out in the General Theory of Relativity.

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equal to 2 x √1-.025/34,596,000,000), which is equal to 2 x √1-0.000000000007226269, which is equal to 2 x √0.999999999992773731, which is equal to 2 x 0.999999999994, which is equal to 1.99999999988 hours. So the special relativity time difference at 600 miles per hour is less than one billionth of an hour. This math my not be exactly correct but you get the picture.

It is only when v [velocity or speed] gets to be a substantial portion of the speed of light that time differences become noticeable. If we do the same calculation for a plane flying at the very fast (and impossible) speed of 185,000 miles per second, the 2 hour trip will take 2 x √1 - $185{,}000^2/186{,}000^2$, which is equal to 2 x √1-34,225,000,000/34,596,000,000, which is equal to 2 x √1-.9892762169, which is equal to 2 x √0.017237831, which is equal to 2 x 0.10355570047, which is equal to .20711140094. So, in the case of an airplane flying at 185,000 miles per second the 2 hour trip will take .20711140094 hours or about 12 minutes for the people on the plane. Again, even if the math is not exact, you see what is going on.

19 This is true of all events that can not possibly have any affect on one another. For instance, if something happens on the sun right now (like a flare of solar material) and something else happens on earth right now (like an explosion), because of the travel time of light, which is the fastest speed at which any information or effect can be transmitted, it is impossible for the flare on the sun to effect the explosion on earth and vice versa. Because of that, it is possible for observers in different frames of reference to view them (i) as happening at the same time, or (ii) the flare happening first and the explosion second, or (iii) the explosion happening first and the flare second. All such observations would be equally valid and correct. For events that can or do have an effect on each other (a cause and effect situation) all observers will see them happening in the same order, although, maybe at different times.

Statement of Special Relativity

The laws of physics are the same for all frames of reference in uniform motion, including the law that all observers will always measure the speed of light to be *c*.

General Relativity
Problems with Special Relativity

Einstein recognized two significant problems with special relativity:

(i) How do you know if you are in a uniformly moving frame of reference? If you "feel" or otherwise observe non-uniform motion it could be that you are in uniform motion but you (or the experiment you are conducting) are being affected by an unseen extraneous force. Einstein determined that if such a force were magnetism or electricity, he would be able to determine what it was, but that if it was gravity, he would not be able to determine that. Therefore, if you saw changing motion you could not tell if you were in a non-uniform frame of reference or if you were in a uniform frame of reference but that gravity was causing the change in motion. As a result, since you could not say for sure whether you were in a uniformly moving frame of reference, you could not say for sure whether the Special Theory of Relativity applied. Einstein felt he needed a more "general" theory which would also account for situations of non-uniform motion. This inability to distinguish between non-uniform motion and the effects of gravity led Einstein to develop the General Theory of Relativity.

(ii) There was no room for gravity in Special Relativity. Newton said that gravity was a force acting at distance. But whose frame of reference determined the distance? As we know, distance is different in each frame of reference.

The Principle of Equivalence

Since Galileo's time (the early 1600's) we have known about the equivalence of gravity's pull on an object and the object's resistance to a change in its motion (its "inertia"). Scientists later called this the "Principle of Equivalence." It says that the "gravitational mass" of a body (the amount of the force by which the body is being attracted by another body) is exactly the same as the "inertial mass" of that body (the amount of the body's resistance to a change in its motion).

The Principle of Equivalence explains why all bodies (heavy or light) fall at the same speed in a gravitational field, a law which was first discovered by Galileo when he supposedly simultaneously dropped two objects of different weights off the Leaning Tower of Pisa and they both hit the ground at the same time.

In the Earth's gravitational field, all falling objects accelerate at the rate of 32 feet per second per second. This means that the speed of a falling object increases an additional 32 feet per second for each second it falls.[20]

Here is how the Principle of Equivalence works. If you drop a tennis ball and a 16 pound shot put at the same time they will hit the ground at the same time. Being so light (little mass), the tennis ball has little inertia (resistance to change in its motion), so it is easy to get it going. However, being so light (little mass), the gravitational pull on it is little. On the other hand, the shot put has great inertia and it takes a lot to get it moving. However, because of its greater mass, it has a much greater gravitational pull on it. In both cases, the inertia (resistance to change in motion) and the gravity are exactly equivalent and produce the same effect, namely falling at the accelerating rate of 32 feet per second per second.[21]

Gravity and Accelerated Motion are the Same

Einstein used the Principle of Equivalence as his basis for the General Theory of Relativity, which is really a theory of gravity. Einstein considered the Principle of Equivalence in the following types of situations:

In the first situation, you are in an elevator that is at rest on Earth (or is in a state of uniform motion, since that is exactly the same as being at rest). You conduct the experiment where you drop the tennis ball and the shot put and they both fall to the elevator floor at exactly the same speed, just as you would expect. Next, you are in the same elevator, only it is in interstellar space far from the immediate gravitational effects of any planet or star. However, the elevator is being accelerated "upward" by a rocket engine that is pushing it at the speed of 32 feet per second per second. You again conduct the experiment by dropping the tennis ball and the shot put and, again, you get the exact same results. (Only, this time it is not the ball and shot put that are falling. Rather, it is the floor of the elevator that is rushing towards them at the speed of 32 feet per second per

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20 At the end of one second an object is falling with the speed of 32 feet per second. At the end of two seconds, it is falling with the speed of 64 feet per second. At the end of three seconds, it is falling with the speed of 96 feet per second, and, so on.

21 The 32 feet per second per second rate is unique to the surface of the earth. Each planet and star will have its own rate of gravitational attraction, depending on its mass and density.

second). From this Einstein concluded that gravity and accelerated motion are indistinguishable.

Free fall in a Gravitational Field and Uniform Motion without Gravity are Indistinguishable

In the second situation you are again in the elevator but some one has cut the cable holding the elevator and you are in "free fall" towards the earth below. You conduct the experiment with the tennis ball and the shot put and neither one falls. They both remain motionless in the middle of the elevator (due to the fact that they have the exact same motion as the elevator). Here the situation of free fall effectively removes the influence of gravity from the experiment. Next the elevator is in interstellar space but, this time, it is at rest (or in uniform-non accelerating-motion). You do the experiment and the lack of gravity keeps both the tennis ball and the shot put motionless in the middle of the elevator. It appears that free fall in a gravitational field and uniform motion without gravity are also indistinguishable.

Einstein felt that if you could so easily remove the effect of gravity then gravity must not be the type of force that we thought it was. Also, he realized that a free fall situation, where a body is accelerating in a gravitational field, is actually a perfect place for the applicability of the Special Theory of Relativity, even though it is in a frame of reference that is not in uniform motion (after all, it is accelerating as it falls).

Light is Curved by Gravity

Einstein envisioned one more situation in a closed elevator type of scenario. Again the elevator is in interstellar space, far from any powerful gravitational effects, and it is being pushed by an accelerating rocket. There is a small hole in the side of the elevator and from the outside someone shines a light beam through the hole. The light beam will hit the wall on the other side of the elevator at a spot somewhat lower than the spot where the hole is. The reason for this is obvious. The elevator is being pulled up as the light beam crosses it and therefore the light beam will have to hit a lower spot. To someone inside the elevator the light beam will follow a curved path downward. Since Einstein believed that the situation in this elevator was equivalent to being at rest in a gravitational filed, he concluded that light would be curved by gravity.

The Tidal Effect

After thinking about all of this, Einstein was not as impressed with the concept of gravity as we had come to think of it, especially since its effects could so easily be eliminated. There was one effect of gravity, however, that he thought was its real essence, and that was the "tidal effect." The tidal effect could not be done away with and it meant that all of these elevators and similar devices of Einstein's thought experiments had to be small. The tidal effect is caused by differences in the "pull" of gravity resulting from parts of an object being (significantly) different distances from the source of the gravity. If there is a 10,000 mile high giant standing on the earth, the force of gravity on his feet is stronger than the force of gravity on his face and, in essence, stretches him out. This would be the case even if he were in free fall in an elevator (a big elevator!) and all the other effects of gravity had been removed by the free fall. Einstein felt that this was the real essence of gravity.

The General Theory of Relativity

Einstein put all of this together in the General Theory of Relativity which is a theory of gravity and says that the laws of physics are the same for all frames of reference because of the following:

Mass Curves Spacetime, etc.

Gravity is not a force acting at a distance like Newton had said. Rather, it is a inherent property of four-dimensional spacetime. It is a curvature of spacetime. All bodies (mass) curve the very fabric of space time. More massive bodies curve it more and the closer you are to the body, the more the curvature. This explains the tidal effect very well (as the giant's feet would be in an area with a greater curvature than the area where his face is located).

The natural state of motion is the shortest path in curved spacetime.

Einstein worked all of this out mathematically in his "field equations," which allow accurate descriptions and predictions of all motion in the universe except for those occurring at the singularities of the big bang and black holes. Amongst the predictions of these equations is that time slows down in very heavy gravitational areas (very curved spacetime). This time dilation of heavy gravity is not the same as the time dilation of Special Theory of Relativity which is the result of differences in relative motion.

Another prediction of the equations is that there are ripples in the fabric of spacetime, in effect gravitational waves, caused by significant gravitational events (like one black hole collapsing into another).

Black holes are also predicted by the equations of General Theory of Relativity. A black hole occurs when mass is so dense that it curves spacetime in its immediate vicinity so much that spacetime curves back on itself. Anything trying to leave the black hole (including light) will follow the shortest possible path from the black hole along this highly curved spacetime and will end up heading right back to the black hole.

Confirmations of General Relativity

The differences in the predictions of the General Theory of Relativity and classical Newtonian mechanics are extremely small and only become significant in very strong gravity. The first confirmation of the General Theory of Relativity, which showed it to be more accurate than Newtonian mechanics was in its prediction of the orbit of Mercury, which had always been slightly different than that predicted by classical Newtonian mechanics. The General Theory of Relativity took into account the heavy curvature of spacetime in the vicinity of the sun and predicted the orbit of Mercury to be exactly in accord with observation.

The most spectacular early confirmation of the theory came on May 29, 1919, during a full eclipse of the sun, when it was determined that starlight passing near the sun was bent around the sun by the exact amount predicted by the General Theory of Relativity. (This showed the starlight to be following the shortest path in curved spacetime.)

In about 1960, physicists at Harvard, measured time differences in clocks at the top and bottom of a building on their campus and confirmed the time dilation prediction of the General Theory of Relativity. Since that time there have been many observational and experimental confirmations of the predictions of General Relativity. These include much circumstantial evidence of the existence of black holes and the discovery of "gravitational lensing" where multiple images of astronomical objects are caused by the light from those objects bending in multiple ways around intervening objects.

Summary of The General Theory of Relativity: General Relativity is a theory of gravity which says that gravity is not an attractive "force" operating at a distance like Newton said but, rather, is a curvature of spacetime. Matter curves the spacetime in its vicinity and the greater the mass of the matter the more the curvature. The equations which Einstein developed to show this predict physical phenomena perfectly in almost all cases and are more accurate than Newtonian physics. Amongst the many predictions which have been verified, are that time slows down in heavy gravitational fields (time dilation), light is bent by gravity (which means that light, like all things, follows the shortest possible path in curved spacetime), and black holes.