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Chapter 1 : This site is temporarily unavailable

Special relativity is mathematically self-consistent, and it is an organic part of all modern physical theories, most notably quantum field theory, string theory, and general relativity (in the limiting case of negligible gravitational fields).

Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives riseâ€”assuming equality of relative motion in the two cases discussedâ€”to electric currents of the same path and intensity as those produced by the electric forces in the former case. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good. The theory to be developed is basedâ€”like all electrodynamicsâ€”on the kinematics of the rigid body, since the assertions of any such theory have to do with the relationships between rigid bodies systems of co-ordinates , clocks, and electromagnetic processes. Insufficient consideration of this circumstance lies at the root of the difficulties which the electrodynamics of moving bodies at present encounters. Definition of Simultaneity Let us take a system of co-ordinates in which the equations of Newtonian mechanics hold good. If we wish to describe the motion of a material point, we give the values of its co-ordinates as functions of the time. We might, of course, content ourselves with time values determined by an observer stationed together with the watch at the origin of the co-ordinates, and co-ordinating the corresponding positions of the hands with light signals, given out by every event to be timed, and reaching him through empty space. But this co-ordination has the disadvantage that it is not independent of the standpoint of the observer with the watch or clock, as we know from experience. We arrive at a much more practical determination along the following line of thought. If at the point A of space there is a clock, an observer at A can determine the time values of events in the immediate proximity of A by finding the positions of the hands which are simultaneous with these events. If there is at the point B of space another clock in all respects resembling the one at A, it is possible for an observer at B to determine the time values of events in the immediate neighbourhood of B. But it is not possible without further assumption to compare, in respect of time, an event at A with an event at B. In accordance with definition the two clocks synchronize if We assume that this definition of synchronism is free from contradictions, and possible for any number of points; and that the following relations are universally valid: If the clock at A synchronizes with the clock at B and also with the clock at C, the clocks at B and C also synchronize with each other. In agreement with experience we further assume the quantity to be a universal constantâ€”the velocity of light in empty space. On the Relativity of Lengths and Times The following reflexions are based on the principle of relativity and on the principle of the constancy of the velocity of light. These two principles we define as follows: Let there be given a stationary rigid rod; and let its length be l as measured by a measuring-rod which is also stationary. We now imagine the axis of the rod lying along the axis of x of the stationary system of co-ordinates, and that a uniform motion of parallel translation with velocity v along the axis of x in the direction of increasing x is then imparted to the rod. We now inquire as to the length of the moving rod, and imagine its length to be ascertained by the following two operations: Current kinematics tacitly assumes that the lengths determined by these two operations are precisely equal, or in other words, that a moving rigid body at the epoch t may in geometrical respects be perfectly represented by the same body at rest in a definite position. Let a ray of light depart from A at the time 4 , let it be reflected at B at the time , and reach A again at the time. Taking into consideration the principle of the constancy of the velocity of light we find that where denotes the length of the moving rodâ€”measured in the stationary system. Observers moving with the moving rod would thus find that the two clocks were not synchronous, while observers in the stationary system would declare the clocks to be synchronous. So we see that we cannot attach any absolute signification to the concept of simultaneity, but that two events which, viewed from a system of co-ordinates, are simultaneous, can no longer be looked upon as simultaneous events when envisaged from a system which is in motion relatively to that system. Let the axes of X of the two systems coincide, and their axes of Y and Z respectively be parallel. Let each system be provided with a rigid measuring-rod and a number of clocks, and let the two measuring-rods, and likewise all the clocks of the two systems, be in all respects alike. Now to the origin of one of the two systems k let a constant velocity v be imparted in the direction of the increasing x of the other stationary system K , and let this velocity be communicated to the axes of the co-ordinates, the relevant measuring-rod, and the clocks. We now imagine space to be measured from the stationary system K by means of the stationary measuring-rod, and also from the moving system k by means of the measuring-rod moving with it; and that we thus obtain the co-ordinates x, y, z, and , , respectively. To any system of values x, y, z, t, which completely defines the place and time of an event in the stationary system, there belongs a system of values , , , , determining that event relatively to the system k, and our task is now to find the system of equations connecting these quantities. In the first place it is clear that the equations must be linear on account of the properties of homogeneity which we attribute to space and time. With the help of this result we easily determine the quantities , , by expressing in equations that light as required by the principle of the constancy of the velocity of light, in combination with the principle of relativity is also propagated with velocity c when measured in the moving system. If no assumption whatever be made as to the initial position of the moving system and as to the zero point of , an additive constant is to be placed on the right side of each of these equations. We now have to prove that any ray of light, measured in the moving system, is propagated with the velocity c, if, as we have assumed, this is the case in the stationary system; for we have not as yet furnished the proof that the principle of the constancy of the velocity of light is compatible with the principle of relativity. At the time , when the origin of the co-ordinates is common to the two systems, let a spherical wave be emitted therefrom, and be propagated with the velocity c in system K. Transforming this equation with the aid of our equations of transformation we obtain after a simple calculation The wave under consideration is therefore no less a spherical wave with velocity of propagation c when viewed in the moving system. This shows that our two fundamental principles are compatible. Thus We now inquire into the signification of. We give our attention to that part of the axis of Y of system k which lies between and. This part of the axis of Y is a rod moving perpendicularly to its axis with velocity v relatively to system K. Its ends possess in K the co-ordinates and The length of the rod measured in K is therefore ; and this gives us the meaning of the function. From reasons of symmetry it is now evident that the length of a given rod moving perpendicularly to its axis, measured in the stationary system, must depend only on the velocity and not on the direction and the sense of the motion. The length of the moving rod measured in the stationary system does not change, therefore, if v and -v are interchanged. Physical Meaning of the Equations Obtained in Respect to Moving Rigid Bodies and Moving Clocks We envisage a rigid sphere 6 of radius R, at rest relatively to the moving system k, and with its centre at the origin of co-ordinates of k. Further, we imagine one of the clocks which are qualified to mark the time t when at rest relatively to the stationary system, and the time when at rest relatively to the moving system, to be located at the origin of the co-ordinates of k, and so adjusted that it marks the time. What is the rate of this clock, when viewed from the stationary system? From this there ensues the following peculiar consequence. If at the points A and B of K there are stationary clocks which, viewed in the stationary system, are synchronous; and if the clock at A is moved with the velocity v along the line AB to B, then on its arrival at B the two clocks no longer synchronize, but the clock moved from A to B lags behind the other which has remained at B by up to magnitudes of fourth and higher order , t being the time occupied in the journey from A to B. It is at once apparent that this result still holds good if the clock moves from A to B in any polygonal line, and also when the points A and B coincide. If we assume that the result proved for a polygonal line is also valid for a continuously curved line, we arrive at this result: If one of two synchronous clocks at A is moved in a closed curve with constant velocity until it returns to A, the journey lasting t seconds, then by the clock which has remained at rest the travelled clock on its arrival at A will be second slow. Thence we conclude that a balance-clock 7 at the equator must go more slowly, by a very small amount, than a precisely similar clock situated at one of the poles under otherwise identical conditions. In the system k moving along the axis of X of the system K with velocity v, let a point move in accordance with the equations where and denote constants. If w also has the direction of the axis of X, we get It follows from this equation that from a composition of two velocities which are less than c, there always results a velocity less than c. For if we set , and being positive and less than c, then It follows, further, that the velocity of light c cannot be altered by composition with a velocity less than that of light. We have now deduced the requisite laws of the theory of kinematics corresponding to our two principles, and we proceed to show their application to electrodynamics.

Chapter 2 : Understanding Einstein: The Special Theory of Relativity | Stanford Online

Albert Einstein, in his theory of special relativity, determined that the laws of physics are the same for all non-accelerating observers, and he showed that the speed of light within a vacuum is.

Rossi and Hoag, Physical Review 57, pg Rossi and Hall, Physical Review 59, pg Rasetti, Physical Review 60, pg Various measurements of the lifetimes of muons. Durbin, Loar and Havens, Physical Review 88, pg Measurements of the lifetimes of pions. An interpretation was given by: Terell, Nuovo Cimento 16 pg More accurate measurement of pion lifetimes. Measurements of pion lifetimes, comparison of positive and negative pions, etc. Measurements of Kaon lifetimes. They compared the frequency of two lasers, one locked to fast-beam neon and one locked to the same transition in thermal neon. A nuclear measurement at 0. Mandelberg and Witten, Journal Opt. Measured the exponent of the quadratic Doppler shift to be 0. If one clock remains in an inertial frame, then the other must be accelerated sometime during its journey, and it displays less elapsed proper time than the inertial clock. Hafele and Keating, Nature , pg proposal. They flew atomic clocks on commercial airliners around the world in both directions, and compared the time elapsed on the airborne clocks with the time elapsed on an earthbound clock USNO. Their eastbound clock lost 59 ns on the USNO clock; their westbound clock gained ns; these agree with GR predictions to well within their experimental resolution and uncertainties which total about 25 ns. By using four cesium-beam atomic clocks they greatly reduced their systematic errors due to clock drift. Engineers Ireland Monograph No. Also commented on in Schlegel, AJP 42, pg Here is a brief description of a repetition in the UK They flew a hydrogen maser in a Scout rocket up into space and back not recovered. Gravitational effects are important, as are the velocity effects of SR. Pierre Meystre and Marlan O. They flew atomic clocks in airplanes that remained localized over Chesapeake Bay, and also which flew to Greenland and back. They stored muons in a storage ring and measured their lifetime. Muon lifetime at rest: Also a test of the clock hypotheses below. The Clock Hypothesis The clock hypothesis states that the tick rate of a clock when measured in an inertial frame depends only upon its velocity relative to that frame, and is independent of its acceleration or higher derivatives. The experiment of Bailey et al. The observed agreement between the lifetime of the stored muons with that of muons with the same energy moving inertially confirms the clock hypothesis for accelerations of that magnitude. Tests of Relativistic Kinematics Kinematics is basically the study of how energy and momentum conservation laws constrain and affect physical interactions. This latter property implies that the newtonian equations for conservation of energy and momentum will be violated by enormous factors for objects with velocities approaching c, and that the corresponding formulas of SR must be used. This has become so obvious in particle experiments that few experiments test the SR equations, and virtually all particle experiments rely upon SR in their analysis. The exceptions are primarily early experiments measuring energy as a function of velocity for electrons and protons. Note that the nomenclature has changed over the past century, and current literature focusses more on rest mass than relativistic mass because rest mass is an invariant property of an object. In this article, use of the word "mass" means rest mass. See also this FAQ page. Elastic Scattering Champion, Proc. A , pg Electron-electron elastic scattering Foley et al. The dispersion relation basically expresses conservation of probability, and its validity at different energies is related to relativistic kinematics. In newtonian mechanics, when two equal-mass objects scatter elastically, in the rest frame of one initial particle the two outgoing particles always travel at right angles to each other. Experiments that Show the Limiting Velocity c Alspector et al. A comparison of neutrino and muon velocities, at Fermilab. A comparison of muon, neutrino, and antineutrino velocities over a range of energies, at Fermilab. Relative velocity measurements of 15 GeV electrons and gammas. See also Brown et al. An analysis combining the results of several experiments gives the result that the Lorentz limiting velocity must be equal to the speed of light to within 12 parts per million. A comparison of neutrino and photon speeds from supernova SNA puts a limit of about 1 part in on their speed difference. Electron Relativistic Mass Variations In the early 20th century there was an alternative theory by Abraham that is now little known, because these experiments rejected it in favor of SR. A critical review of the experimental evidence concerning the Lorentz model compared to the Abraham model was given in: Farago and Jannossy, Il Nuovo Cim. Vol5, No 6, pg Goettingen 2, pg W. Goettingen 3, pg ; W. Goettingen 4, pg 90 W. Physik 19 , and Nachtrag 20, â€” ; W. Physik 19 , ; W. Lavanchy, Comptes rendus , pg Physica Acta 36 , pg Measurements of speed vs. Geller and Kollarits, Am. Carezani, Physical Review A29 , pg Tests of Length Contraction At this time there are no direct tests of length contraction, as measuring the length of a moving object to the precision required has not been feasible. There is, however, a demonstration that it occurs: A current-carrying wire is observed to be electrically neutral in its rest frame, and a nearby charged particle at rest in that frame is unaffected by the current. A nearby charged particle that is moving parallel to the wire, however, is subject to a magnetic force that is related to its speed relative to the wire. If one considers the situation in the rest frame of a charge moving with the drift velocity of the electrons in the wire, the force is purely electrostatic due to the different length contractions of the positive and negative charges in the wire the former are fixed relative to the wire, while the latter are mobile with drift velocities of a few mm per second. This approach gives the correct quantitative value of the magnetic force in the wire frame. This is discussed in more detail in: Purcel, Electricity and Magnetism. It is rather remarkable that relativistic effects for such a tiny velocity explain the enormous magnetic forces we observe. While one cannot actually do any of that in the real world, one can perform experiments in which particles are replaced by antiparticles C , one looks at situations in which left and right are interchanged P , and the particles travel along similar paths but in opposite directions and have opposite spin polarizations T. Lorentz Invariance is the technical term for the statement that SR is valid. A review of various limits, terrestrial and astrophysical. By combining results from two interferometers made of different materials, located in different hemispheres, rotating on tables, they are able to put limits on more parameters of the SME than otherwise. They have also improved both the statistics and systematic errors of the individual interferometers. D 72, These neutrino oscillations display no significant sidereal variation. Note, however, that the LSND results have been a puzzle for several years, as they appear to be inconsistent with other experiments. This lies in the range expected for effects originating from the Planck scale in an underlying unified theory. Search for sidereal variation in the frequency difference between co-located Xe and 3He Zeeman masers sets the most stringent limits to date on leading order Lorentz and CPT violation. D, 60, , D, 63, , D, 70, , B, , , D, 59, , The original GZT papers. Other Experiments The Fizeau Experiment Fizeau measured the speed of light in moving mediums, most notably moving water. SR predicts no aether but does predict that the speed of light in a moving medium differs from the speed in the medium at rest, by an amount consistent to within experimental resolutions with these experiments and with the Fresnel drag coefficient. Amsterdam 17, pg ; Proc. Amsterdam 18, pg ; Amst. Lerche, American Journal of Physics Vol. A more accurate, modern repetition. Includes a moving solid, liquid, and gas. A5 pg

Chapter 3 : Special Relativity | AMNH

By Andrew Zimmerman Jones, Daniel Robbins. In , Albert Einstein published the theory of special relativity, which explains how to interpret motion between different inertial frames of reference â€” that is, places that are moving at constant speeds relative to each other.

We concentrate on the implications of the theory. The document is based on a discussion of the the theory for an upper-year liberal arts course in Physics without mathematics; in the context of that course the material here takes about 4 or 5 one-hour classes. Einstein published this theory in The word special here means that we restrict ourselves to observers in uniform relative motion. This is as opposed the his General Theory of Relativity of ; this theory considers observers in any state of uniform motion including relative acceleration. It turns out that the general theory is also a theory of gravitation. Sometimes one hears that the Special Theory of Relativity says that all motion is relative. This is not quite true. Galileo and Newton had a similar conception. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies.. For Newton, the laws of physics, such as the principle of inertia, are true in any frame of reference either at rest relative to absolute space or in uniform motion in a straight line relative to absolute space. Such reference frames are called inertial. Notice there is a bit of a circular argument here: In any case, from the standpoint of any such inertial frame of reference all motion can be described as being relative. Many of the consequences of the Special Theory of Relativity are counter-intuitive and violate common sense. Einstein correctly defined common sense as those prejudices that we acquire at an early age. The idea behind this word is that there is an all-pervading homogenous massless substance everywhere in the universe, and it is this ether that is the medium through which light propagates. A rough analogy is to a sound wave travelling through the air. The air is the medium and oscillations of the molecules of the air are what is "waving. Presumably the ether is stationary with respect to the fixed stars. This section investigates these two presumptions. Galileo attempted to measure the speed of light around He and a colleague each had a lantern with a shutter, and they went up on neighboring mountains. This is absolutely correct experimental procedure in principle. Some knowledge of the fact that light is a wave and can undergo interference is assumed. A discussion of this occurs in the the first two sections of the document http: In is ironic that Michelson himself wrote in , "The more important fundamental laws and facts of physical reality have all been discovered and they are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote Our future discoveries must be looked for in the 6th place of decimals. One of those clouds was his own experiment with Morley that we describe in this sub-section. As we shall see, the experiment played a part in the development of the Special Theory of Relativity, a profound advance. Recently some people, especially John Horgan in his book The End of Science , have been making similar claims about how the enterprise of science is complete. My opinion is that they are no more correct than was Michelson. I certainly hope they are wrong, because if they are correct all the fun goes out of physics. In fact, as we shall see, I think there are already a couple of clouds on the horizon. One cloud is the failure of our theories of cosmology to account for recent observations of the universe. The other is the failure of the quark model to produce any truly useful results. Before we turn to the experiment itself we will consider a "race" between two swimmers. We have two identical swimmers, 1 and 2, who each swim the same distance away from the raft, to the markers, and then swim back to the raft. The "race" ends in a tie. Now the raft and markers are being towed to the left. In this case the race will no longer be a tie. In fact, it is not too hard to show that swimmer 2 wins this race. A small Flash animation illustrating the above race may be found here. These notes are intended to be non-mathematical, with the exception of a brief use of Pythagoras theorem about right triangles. However, some people would like to see a little bit of the math. Thus, a proof that swimmer 2 above wins the race may be found here. Below, a further small amount of math will appear, but will always be labelled as a Technical note. Insisting on complete statements often makes the problems disappear. One common case of sloppy language leading to poorly formed questions involves the concept of speed. Now we consider the Michelson interferometer, shown schematically to the right. The light source is the red star to the left of the figure. The light from it is incident on a half-silvered mirror, which is drawn as a blue line; this is a "crummy" mirror that only reflects one-half of the light incident on it, transmitting the other half. The two light beams then go to good mirrors, drawn as green rectangles, which reflect the light. The reflected light actually follows the same path as the incident beam, although I have drawn them slightly offset. The two combined beams go from the half-silvered mirror to the detector, which is the yellow object at the bottom of the figure. If the distance from the half-silvered mirror to mirror 1 is equal to the distance to mirror 2, then when the two rays are re-combined they will have travelled identical distances. Thus, they will be "in phase" and will constructively interfere and we will get a strong signal at the detector. If we slowly move mirror 1 to the right, that ray will be travelling a longer total distance than ray 2; at some point the two rays will be "out of phase" and destructively interfere. Moving mirror 1 a bit further to the right, at some point the two rays will be "in phase" again, giving constructive interference. Say we have the interferometer adjusted so we are getting constructive interference at the detector. Then the "race" between the two beams of light is essentially a tie. This may remind you of the race of the swimmers above. So the situation is more like the second race above when the raft is being towed through the water. The interferometer is being "towed" through the ether. The arms of the interferometer were about 1. The apparatus was mounted on a block of marble floating in a pool of mercury to reduce vibrations. They adjusted the interferometer for constructive interference, and then gently rotated the interferometer by 90 degrees. Except that when they did the experiment, they got no result. The interference pattern did not change! It was suggested that maybe the speed of the earth due to its rotation on its axis was cancelling its speed due to its orbit around the sun. So they waited 12 hours and repeated the experiment. Again they got no result. So they waited six months and tried the experiment again. And again they got no result. It was suggested that maybe the mass of the earth "dragged" the ether along with it. So they hauled the apparatus up on top of a mountain, hoping that the mountain would be sticking up into the ether that was not being dragged by the earth. Thus, this attempt to measure the motion of the earth relative to the ether failed. Lorentz was among many who were very puzzled by this result. He proposed that when an object was moving relative to the ether, its length along its direction of motion would be contracted by just the right amount needed to explain the experimental result. If the length of the object when it is at rest with respect to the ether is L0, then if is is moving at speed v through the ether its length becomes L given by: If you chose to look at the brief mathematical supplement above, the structure of this equation may look familiar to you. Einstein "Explains" the Michelson-Morley Experiment When Einstein was 16, in , he asked himself an interesting question: However, there seems to be no such thing, whether on the basis of experience or according to [the theory of electricity and magnetism]. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how, otherwise, should the first observer know, i. He continued to work on this question for 10 years with the mixture of concentration and determination that characterised much of his work. He published his answer in As we shall see, this one statement is equivalent to all of the Special Theory of Relativity, and everything else is just a consequence. Notice that the statement also explains the null result of the Michelson-Morley experiment. However, although the evidence is not certain it seems quite likely that in Einstein was unaware of the experiment cf. But first we should take a few moments to carefully explore just what we mean when we say some event occurred at some particular place at some particular time We imagine a lattice of meter sticks, such as shown to the right, and at each intersection we place a clock. This lattice represents an inertial frame of reference, and we imagine that we are at rest relative to the lattice. We synchronise the clocks to the "Reference Clock. Thus we have to account for the small but finite time it takes light to travel from the Reference Clock to us standing beside another clock. A bit tedious, but fairly straightforward. We imagine some event occurs. We define its position by where it happened relative to the lattice of meter sticks and we define the time when it happened as the time read by the nearest clock. Of course, in practice nobody ever does this sort of thing. We have also put an observer, whom we shall name Lou, at rest in his coordinate system.

Chapter 4 : Einsteinâ€™s theory of relativity â€“ My Albert Einstein Posts

Einstein publishes the special theory of relativity Like Max Planck, Albert Einstein first studied mathematics because he was told that everything interesting in physics had already been.

Albert Einstein published the theory of special relativity in , building on many theoretical results and empirical findings obtained by Albert A. Max Planck , Hermann Minkowski and others did subsequent work. Einstein developed general relativity between and , with contributions by many others after The final form of general relativity was published in Relativtheorie used in by Planck, who emphasized how the theory uses the principle of relativity. In the discussion section of the same paper, Alfred Bucherer used for the first time the expression "theory of relativity" German: By comparison, general relativity did not appear to be as useful, beyond making minor corrections to predictions of Newtonian gravitation theory. Its mathematics seemed difficult and fully understandable only by a small number of people. Around , general relativity became central to physics and astronomy. New mathematical techniques to apply to general relativity streamlined calculations and made its concepts more easily visualized. As astronomical phenomena were discovered, such as quasars , the 3-kelvin microwave background radiation , pulsars , and the first black hole candidates , [3] the theory explained their attributes, and measurement of them further confirmed the theory. Special relativity Main article: Special relativity Special relativity is a theory of the structure of spacetime. Special relativity is based on two postulates which are contradictory in classical mechanics: The laws of physics are the same for all observers in uniform motion relative to one another principle of relativity. The speed of light in a vacuum is the same for all observers, regardless of their relative motion or of the motion of the light source. The resultant theory copes with experiment better than classical mechanics. For instance, postulate 2 explains the results of the Michelsonâ€"Morley experiment. Moreover, the theory has many surprising and counterintuitive consequences. Some of these are: Two events, simultaneous for one observer, may not be simultaneous for another observer if the observers are in relative motion. Objects are measured to be shortened in the direction that they are moving with respect to the observer. Maximum speed is finite: No physical object, message or field line can travel faster than the speed of light in a vacuum. The effect of Gravity can only travel through space at the speed of light, not faster or instantaneously. Relativistic mass , idea used by some researchers. General relativity Main articles: General relativity and Introduction to general relativity General relativity is a theory of gravitation developed by Einstein in the years â€" The development of general relativity began with the equivalence principle , under which the states of accelerated motion and being at rest in a gravitational field for example, when standing on the surface of the Earth are physically identical. The upshot of this is that free fall is inertial motion: This is incompatible with classical mechanics and special relativity because in those theories inertially moving objects cannot accelerate with respect to each other, but objects in free fall do so. To resolve this difficulty Einstein first proposed that spacetime is curved. In , he devised the Einstein field equations which relate the curvature of spacetime with the mass, energy, and any momentum within it. Some of the consequences of general relativity are: Clocks run slower in deeper gravitational wells. This has been observed in the orbit of Mercury and in binary pulsars. Rays of light bend in the presence of a gravitational field. Rotating masses "drag along" the spacetime around them; a phenomenon termed " frame-dragging ". The universe is expanding , and the far parts of it are moving away from us faster than the speed of light. Technically, general relativity is a theory of gravitation whose defining feature is its use of the Einstein field equations. The solutions of the field equations are metric tensors which define the topology of the spacetime and how objects move inertially. Experimental evidence Einstein stated that the theory of relativity belongs to a class of "principle-theories". As such, it employs an analytic method, which means that the elements of this theory are not based on hypothesis but on empirical discovery. By observing natural processes, we understand their general characteristics, devise mathematical models to describe what we observed, and by analytical means we deduce the necessary conditions that have to be satisfied. It makes predictions that can be tested by experiment. In the case of special relativity, these include the principle of relativity, the constancy of the speed of light, and time dilation. Einstein derived the Lorentz transformations from first principles in , but these three experiments allow the transformations to be induced from experimental evidence. The modern view is that light needs no medium of transmission, but Maxwell and his contemporaries were convinced that light waves were propagated in a medium, analogous to sound propagating in air, and ripples propagating on the surface of a pond. This hypothetical medium was called the luminiferous aether , at rest relative to the "fixed stars" and through which the Earth moves. Michelson designed an instrument called the Michelson interferometer to accomplish this. The apparatus was more than accurate enough to detect the expected effects, but he obtained a null result when the first experiment was conducted in , [14] and again in The interpretation of the null result of the Michelsonâ€"Morley experiment is that the round-trip travel time for light is isotropic independent of direction , but the result alone is not enough to discount the theory of the aether or validate the predictions of special relativity. While the Michelsonâ€"Morley experiment showed that the velocity of light is isotropic, it said nothing about how the magnitude of the velocity changed if at all in different inertial frames. The Kennedyâ€"Thorndike experiment was designed to do that, and was first performed in by Roy Kennedy and Edward Thorndike. Stilwell first in [21] and with better accuracy in The strategy was to compare observed Doppler shifts with what was predicted by classical theory, and look for a Lorentz factor correction. Such a correction was observed, from which was concluded that the frequency of a moving atomic clock is altered according to special relativity. Other experiments include, for instance, relativistic energy and momentum increase at high velocities, experimental testing of time dilation , and modern searches for Lorentz violations. Tests of general relativity Main article: Other tests confirmed the equivalence principle and frame dragging. Modern applications Far from being simply of theoretical interest, relativitistic effects are important practical engineering concerns. Satellite-based measurement needs to take into account relativistic effects, as each satellite is in motion relative to an Earth-bound user and is thus in a different frame of reference under the theory of relativity.

Chapter 5 : The Feynman Lectures on Physics Vol. I Ch. The Special Theory of Relativity

The theory of special relativity was developed by Albert Einstein in , and it forms part of the basis of modern physics. After finishing his work in special relativity, Einstein spent a decade.

Both the error and its correction were discovered by Einstein in From the formula itself it is easy to see that this mass increase is very small in ordinary circumstances. Actually, the correctness of the formula has been amply confirmed by the observation of many kinds of particles, moving at speeds ranging up to practically the speed of light. However, because the effect is ordinarily so small, it seems remarkable that it was discovered theoretically before it was discovered experimentally. Empirically, at a sufficiently high velocity, the effect is very large, but it was not discovered that way. Therefore it is interesting to see how a law that involved so delicate a modification at the time when it was first discovered was brought to light by a combination of experiments and physical reasoning. There are really two Einstein theories of relativity. This chapter is concerned with the Special Theory of Relativity, which dates from In Einstein published an additional theory, called the General Theory of Relativity. This latter theory deals with the extension of the Special Theory to the case of the law of gravitation; we shall not discuss the General Theory here. The principle of relativity was first stated by Newton, in one of his corollaries to the laws of motion: That is the meaning of the principle of relativity. This is a simple enough idea, and the only question is whether it is true that in all experiments performed inside a moving system the laws of physics will appear the same as they would if the system were standing still. The relationship of the coordinates in the two systems is clear from the diagram. The principle of relativity has been used in mechanics for a long time. In the 19th century interest in it was heightened as the result of investigations into the phenomena of electricity, magnetism, and light. However, the Maxwell equations did not seem to obey the principle of relativity. Thus one could use these optical phenomena to determine the speed of the ship; in particular, one could determine the absolute speed of the ship by making suitable optical or electrical measurements. This is analogous to the case of sound, the speed of sound waves being likewise independent of the motion of the source. This independence of the motion of the source, in the case of light, brings up an interesting problem: In any case, by measuring the speed of the light going past the car if the Galilean transformation is correct for light , one could determine the speed of the car. A number of experiments based on this general idea were performed to determine the velocity of the earth, but they all failedâ€”they gave no velocity at all. We shall discuss one of these experiments in detail, to show exactly what was done and what was the matter; something was the matter, of course, something was wrong with the equations of physics. What could it be? It seemed almost obvious that these equations must be wrong, so the thing to do was to change them in such a way that under the Galilean transformation the principle of relativity would be satisfied. When this was tried, the new terms that had to be put into the equations led to predictions of new electrical phenomena that did not exist at all when tested experimentally, so this attempt had to be abandoned. In the meantime, H. Lorentz noticed a remarkable and curious thing when he made the following substitutions in the Maxwell equations: In other words, we should change, not the laws of electrodynamics, but the laws of mechanics. It is interesting to discuss what it means that we replace the old transformation between the coordinates and time with a new one, because the old one Galilean seems to be self-evident, and the new one Lorentz looks peculiar. We wish to know whether it is logically and experimentally possible that the new, and not the old, transformation can be correct. To find that out, it is not enough to study the laws of mechanics but, as Einstein did, we too must analyze our ideas of space and time in order to understand this transformation. We shall have to discuss these ideas and their implications for mechanics at some length, so we say in advance that the effort will be justified, since the results agree with experiment. The most famous of these experiments is one performed by Michelson and Morley in It was 18 years later before the negative results of the experiment were finally explained, by Einstein. Schematic diagram of the Michelson-Morley experiment. The Michelson-Morley experiment was performed with an apparatus like that shown schematically in Fig. Let us see why. The denominators represent the modifications in the times caused by the motion of the apparatus. In fact, we surely cannot make them exactly equal. Any small difference in length then becomes unimportant, and what we look for is a shift in the interference fringes when we rotate the apparatus. The apparatus was amply sensitive to observe such an effect, but no time difference was foundâ€”the velocity of the earth through the ether could not be detected. The result of the experiment was null. The result of the Michelson-Morley experiment was very puzzling and most disturbing. The first fruitful idea for finding a way out of the impasse came from Lorentz. So if the apparatus shrinks in the manner just described, we have a way of understanding why the Michelson-Morley experiment gives no effect at all. Although the contraction hypothesis successfully accounted for the negative result of the experiment, it was open to the objection that it was invented for the express purpose of explaining away the difficulty, and was too artificial. In other words, when the outsider sees the man in the space ship lighting a cigar, all the actions appear to be slower than normal, while to the man inside, everything moves at a normal rate. This slowing of the clocks in a moving system is a very peculiar phenomenon, and is worth an explanation. In order to understand this, we have to watch the machinery of the clock and see what happens when it is moving. Since that is rather difficult, we shall take a very simple kind of clock. The one we choose is rather a silly kind of clock, but it will work in principle: We give one of these clocks to the man to take along in his space ship, and he mounts the rod perpendicular to the direction of motion of the ship; then the length of the rod will not change. How do we know that perpendicular lengths do not change? Before the man took it aboard, he agreed that it was a nice, standard clock, and when he goes along in the space ship he will not see anything peculiar. If he did, he would know he was movingâ€”if anything at all changed because of the motion, he could tell he was moving. But the principle of relativity says this is impossible in a uniformly moving system, so nothing has changed. We have already analyzed such a zigzag motion in connection with the Michelson-Morley experiment. That is, it takes a longer time for light to go from end to end in the moving clock than in the stationary clock. Therefore the apparent time between clicks is longer for the moving clock, in the same proportion as shown in the hypotenuse of the triangle that is the source of the square root expressions in our equations. Not only does this particular kind of clock run more slowly, but if the theory of relativity is correct, any other clock, operating on any principle whatsoever, would also appear to run slower, and in the same proportionâ€”we can say this without further analysis. Why is this so? To answer the above question, suppose we had two other clocks made exactly alike with wheels and gears, or perhaps based on radioactive decay, or something else. Then we adjust these clocks so they both run in precise synchronism with our first clocks. When light goes up and back in the first clocks and announces its arrival with a click, the new models also complete some sort of cycle, which they simultaneously announce by some doubly coincident flash, or bong, or other signal. One of these clocks is taken into the space ship, along with the first kind. Perhaps this clock will not run slower, but will continue to keep the same time as its stationary counterpart, and thus disagree with the other moving clock. Ah no, if that should happen, the man in the ship could use this mismatch between his two clocks to determine the speed of his ship, which we have been supposing is impossible. We need not know anything about the machinery of the new clock that might cause the effectâ€”we simply know that whatever the reason, it will appear to run slow, just like the first one. Now if all moving clocks run slower, if no way of measuring time gives anything but a slower rate, we shall just have to say, in a certain sense, that time itself appears to be slower in a space ship. The biologists and medical men sometimes say it is not quite certain that the time it takes for a cancer to develop will be longer in a space ship, but from the viewpoint of a modern physicist it is nearly certain; otherwise one could use the rate of cancer development to determine the speed of the ship! They come to the earth in cosmic rays, and can also be produced artificially in the laboratory. Some of them disintegrate in midair, but the remainder disintegrate only after they encounter a piece of material and stop. How can that be? The answer is that different muons move at various speeds, some of which are very close to the speed of light. The average life has been measured quite accurately for muons of different velocities, and the values agree closely with the formula. We do not know why the muon disintegrates or what its machinery is, but we do know its behavior satisfies the principle of relativity. That is the utility of the principle of relativityâ€”it permits us to make predictions, even about things that otherwise we do not know much about. What does this contraction mean, in terms of measurements made by Joe and Moe? Now what does that mean? How can the clocks be synchronized? There are many ways. One way, involving very little calculation, would be first to locate exactly the midpoint between the clocks. Then from this station we send out a light signal which will go both ways at the same speed and will arrive at both clocks, clearly, at the same time. This simultaneous arrival of the signals can be used to synchronize the clocks. Thus, the analogy to a rotation is complete, and is of such a kind that vectors, i. Thus we contemplate an extension of the idea of vectors, which we have so far considered to have only space components, to include a time component. That is, we expect that there will be vectors with four components, three of which are like the components of an ordinary vector, and with these will be associated a fourth component, which is the analog of the time part. This concept will be analyzed further in the next chapters, where we shall find that if the ideas of the preceding paragraph are applied to momentum, the transformation gives three space parts that are like ordinary momentum components, and a fourth component, the time part, which is the energy. We shall do this in the next chapter. When this change is made in the formula for momentum, conservation of momentum still works. Now let us see how momentum varies with speed. What happens if a constant force acts on a body for a long time? In Newtonian mechanics the body keeps picking up speed until it goes faster than light. But this is impossible in relativistic mechanics. In relativity, the body keeps picking up, not speed, but momentum, which can continually increase because the mass is increasing. After a while there is practically no acceleration in the sense of a change of velocity, but the momentum continues to increase. Of course, whenever a force produces very little change in the velocity of a body, we say that the body has a great deal of inertia, and that is exactly what our formula for relativistic mass says see Eq. The light, of course, because light always travels faster.

Chapter 6 : Special relativity - Wikipedia

My new book Einstein's Pathway to the Special Theory of Relativity (2nd Edition) is coming out in August My new book is a comprehensive monograph on Albert Einstein's Odyssey to Special and General Relativity.

Basics of special relativity[change change source] Suppose that you are moving toward something that is moving toward you. If you measure its speed, it will seem to be moving faster than if you were not moving. Now suppose you are moving away from something that is moving toward you. If you measure its speed again, it will seem to be moving more slowly. This is the idea of "relative speed"â€”the speed of the object relative to you. Before Albert Einstein, scientists were trying to measure the "relative speed" of light. They were doing this by measuring the speed of star light reaching the Earth. They expected that if the Earth was moving toward a star, the light from that star should seem faster than if the Earth was moving away from that star. However, they noticed that no matter who performed the experiments, where the experiments were performed, or what star light was used, the measured speed of light in a vacuum was always the same. He thought that as Earth moves through space, all measurable durations change very slightly. Any clock used to measure a duration will be wrong by exactly the right amount so that the speed of light remains the same. Imagining a " light clock " allows us to better understand this remarkable fact for the case of a single light wave. Also, Einstein said that as Earth moves through space, all measurable lengths change ever so slightly. Any device measuring length will give a length off by exactly the right amount so that the speed of light remains the same. The most difficult thing to understand is that events that appear to be simultaneous in one frame may not be simultaneous in another. This has many effects that are not easy to perceive or understand. Since the length of an object is the distance from head to tail at one simultaneous moment, it follows that if two observers disagree about what events are simultaneous then this will affect sometimes dramatically their measurements of the length of objects. Furthermore, if a line of clocks appear synchronized to a stationary observer and appear to be out of sync to that same observer after accelerating to a certain velocity then it follows that during the acceleration the clocks ran at different speeds. Some may even run backwards. This line of reasoning leads to general relativity. Other scientists before Einstein had written about light seeming to go the same speed no matter how it was observed. This has the remarkable implications that speed-related measurements, length and duration, change in order to accommodate this. The Lorentz transformations[change change source] The mathematical bases of special relativity are the Lorentz transformations, which mathematically describe the views of space and time for two observers who are moving relative to each other but are not experiencing acceleration. To define the transformations we use a Cartesian coordinate system to mathematically describe the time and space of "events". Each observer can describe an event as the position of something in space at a certain time, using coordinates x,y,z,t. The location of the event is defined in the first three coordinates x,y,z in relation to an arbitrary center 0,0,0 so that 3,3,3 is a diagonal going 3 units of distance like meters or miles out in each direction. The time of the event is described with the fourth coordinate t in relation to an arbitrary 0 point in time in some unit of time like seconds or hours or years. Let there be an observer K who describes when events occur with a time coordinate t, and who describes where events occur with spatial coordinates x, y, and z. This is mathematically defining the first observer whose "point of view" will be our first reference. Let us specify that the time of an event is given: This can be calculated as the distance from the observer to the event d observed say the event is on a star which is 1 light year away, so it takes the light 1 year to reach the observer divided by c, the speed of light several million miles per hour , which we define as being the same for all observers. This is correct because distance, divided by speed gives the time it takes to go that distance at that speed e.

Chapter 7 : History of Special Relativity and Einstein's Work of

In , Albert Einstein, a year-old patent clerk, wrote a paper that revolutionized calendrierdelascience.com his Special Theory of Relativity, Einstein explained that the speed of light was constant but that both space and time were relative to the position of the observer.

Gradually I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more desperately I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results How, then, could such a universal principle be found? Autobiographical Notes [p 5] Einstein discerned two fundamental propositions that seemed to be the most assured, regardless of the exact validity of the then known laws of either mechanics or electrodynamics. These propositions were the constancy of the speed of light and the independence of physical laws especially the constancy of the speed of light from the choice of inertial system. In his initial presentation of special relativity in he expressed these postulates as: There is conflicting evidence on the extent to which Einstein was influenced by the null result of the Michelsonâ€"Morley experiment. The derivation of special relativity depends not only on these two explicit postulates, but also on several tacit assumptions made in almost all theories of physics , including the isotropy and homogeneity of space and the independence of measuring rods and clocks from their past history. A more mathematical statement of the Principle of Relativity made later by Einstein, which introduces the concept of simplicity not mentioned above is: Special principle of relativity: Einstein later derived these transformations from his axioms. Principle of relativity Reference frames and relative motion[edit] Figure The primed system is in motion relative to the unprimed system with constant velocity v only along the x-axis, from the perspective of an observer stationary in the unprimed system. The changing of the speed of propagation of interaction from infinite in non-relativistic mechanics to a finite value will require a modification of the transformation equations mapping events in one frame to another. Reference frames play a crucial role in relativity theory. The term reference frame as used here is an observational perspective in space which is not undergoing any change in motion acceleration , from which a position can be measured along 3 spatial axes. An event is an occurrence that can be assigned a single unique time and location in space relative to a reference frame: Since the speed of light is constant in relativity in each and every reference frame, pulses of light can be used to unambiguously measure distances and refer back the times that events occurred to the clock, even though light takes time to reach the clock after the event has transpired. For example, the explosion of a firecracker may be considered to be an "event". We can completely specify an event by its four spacetime coordinates: The time of occurrence and its 3-dimensional spatial location define a reference point. In relativity theory, we often want to calculate the coordinates of an event from differing reference frames. The equations that relate measurements made in different frames are called transformation equations. To gain insight in how spacetime coordinates measured by observers in different reference frames compare with each other, it is useful to work with a simplified setup with frames in a standard configuration. Instead, any two frames that move at the same speed in the same direction are said to be comoving. Lack of an absolute reference frame[edit] The principle of relativity , which states that physical laws have the same form in each inertial reference frame , dates back to Galileo , and was incorporated into Newtonian physics. However, in the late 19th century, the existence of electromagnetic waves led physicists to suggest that the universe was filled with a substance that they called " aether ", which would act as the medium through which these waves, or vibrations travelled. The aether was thought to constitute an absolute reference frame against which speeds could be measured, and could be considered fixed and motionless. Aether supposedly possessed some wonderful properties: The results of various experiments, including the Michelsonâ€"Morley experiment , led to the theory of special relativity, by showing that there was no aether. In relativity, any reference frame moving with uniform motion will observe the same laws of physics. In particular, the speed of light in vacuum is always measured to be c, even when measured by multiple systems that are moving at different but constant velocities. Relativity without the second postulate[edit] From the principle of relativity alone without assuming the constancy of the speed of light i. In the Lorentzian case, one can then obtain relativistic interval conservation and a certain finite limiting speed. Experiments suggest that this speed is the speed of light in vacuum.

Chapter 8 : On the Electrodynamics of Moving Bodies

Special relativity is a theory of the structure of calendrierdelascience.com was introduced in Einstein's paper "On the Electrodynamics of Moving Bodies" (for the contributions of many other physicists see History of special relativity).

In relativity, time is certainly an integral part of the very fabric of the universe and cannot exist apart from the universe, but, if the speed of light is invariable and absolute, Einstein realized, both space and time must be flexible and relative to accommodate this. Minkowski introduced the relativity concept of proper time, the actual elapsed time between two events as measured by a clock that passes through both events. An event is both a place and a time, and can be represented by a particular point in space-time, i. Space-time as a whole can therefore be thought of as a collection of an infinite number of events. So, just as we are accustomed to thinking of all parts of space as existing even if we are not there to experience them, all of time past, present and future are also constantly in existence even if we are not able to witness them. This view of time is consistent with the philosophical view of eternalism or the block universe theory of time see the section on Modern Philosophy. However, if time is a dimension, it does not appear to be the same kind of dimension as the three dimensions of space. For example, we can choose to move through space or not, but our movement through time is inevitable, and happens whether we like it or not. In fact, we do not really move though time at all, at least not in the same way as we move through space. Also, space does not have any fundamental directionality i. With the General Theory of Relativity, the concept of space-time was further refined, when Einstein realized that perhaps gravity is not a field or force on top of space-time, but a feature of space-time itself. Thus, the space-time continuum is actually warped and curved by mass and energy, a warping that we think of as gravity, resulting in a dynamically curved space-time. In regions of very large masses, such as stars and black holes, space-time is bent or warped substantially by the extreme gravity of the masses, an idea often illustrated by the image of a rubber sheet distorted by the weight of a bowling ball. Thus, two synchronized clocks will not necessarily stay synchronized if they move relative to each other. There is a related effect in the spatial dimensions, known as length contraction, whereby moving bodies are actually foreshortened in the direction of their travel. Time dilation as well as the associated length contraction is negligible and all but imperceptible at everyday speeds in the world around us, although it can be, and has been, measured with very sensitive instruments. In the largest particle accelerators currently in use we can make time slow down by , times. At the speed of light itself, were it actually possible to achieve that, time would stop completely. It should be noted that, although a spaceship travelling at close to the speed of light would take , years to reach a distant star , light years away as judged by clocks on Earth, the astronaut in the spaceship might hardly age at all as he travels across the galaxy. This characteristic of relativistic time has therefore spawned much discussion of the possibility of time travel see the separate section on Time Travel. According to Einstein, then, time is relative to the observer, and more specifically to the motion of that observer. Some commentators, like the Christian philosopher William Lane Craig, have suggested that there may be a need to distinguish between the reality of time and our measurement of time: One casualty of the Theory of Relativity is the notion of simultaneity, the property of two events happening at the same time in a particular frame of reference. According to relativistic physics, simultaneity is NOT an absolute property between events, as had always been taken for granted up to that point. Thus, what is simultaneous in one frame of reference will not necessarily be simultaneous in another. For objects moving at normal everyday speeds, the effect is small and can generally be ignored so that simultaneity CAN normally be treated as an absolute property ; but when objects approach relativistic speeds close to the speed of light with respect to one another, such intuitive relationships can no longer be assumed. It is almost as if gravity is somehow pulling or dragging on time, slowing its passage. The closer an object is to another object, the stronger the pull of gravity between them according to an inverse-square law first identified by Sir Isaac Newton , and thus the more the time drag. Again, these effects are negligible at the kinds of gravitational differences experienced in everyday life: There is, however, one aspect of modern everyday life where we do experience the effects of gravitational time dilation: But, just as with a spaceship travelling at near the speed of light, in the extreme gravity at the edges of a black hole, for example, substantial time differences can become apparent. A black hole spins at close to the speed of light, dragging anything in the vicinity around with it, and the huge gravitational pull of a black hole can bend and warp space-time to a substantial degree. At the gravitational singularity at the centre of a black hole, gravity and density is infinite, and all the normal rules of physics just break down. Time effectively stops, just as there is no time beyond the singularity of the Big Bang see the section on Time and the Big Bang. Because of the time dilation effect, a clock in the spaceship literally registers a shorter duration for the journey than the clock in mission control on Earth. In that scenario, Einstein argued, one would expect the astronaut to age much more than the inhabitants of the Earth. Hence, it is the spaceship and its astronaut that experiences the relativistic time dilation, not the Earth.

Chapter 9 : Experimental Basis of Special Relativity

Einstein's theory of relativity is a famous theory, but it's little understood. 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.