Preface of 2009 to "The Velocity of Light in Uniformly Moving Frame"

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Abstract: This preface gives a brief historical background to my 1958 Stanford Ph.D. thesis, *The Velocity of Light in Uniformly Moving Frames*. As a graduate student at the University of Chicago in the early 1950's. I thought that by modifying the Lorentz Transformation (L.T.) so as to keep a particle's momentum finite at the speed of light, one could solve the divergence problem of QED, and allow for faster-than-light motion. However, after criticisms by eminent physicists, before and after resuming graduate studies at Stanford, this approach was finally abandoned in favor of a truncated version of the L.T. called the Absolute Lorentz Transformation (A.L.T.) that is consistent with Einstein's principle of general covariance, the metric postulate, and experiment.

At this writing, a little over fifty years have elapsed since I began in the autumn of 1957 the line of investigations into special relativity that are presented here in my Stanford thesis, which was completed and submitted to the University in September 1958. Actually, my studies in special relativity had begun about eight years earlier when I was a graduate student at the University of Chicago. My investigations then were along somewhat different lines, and were directed at obtaining a cut-off to cure the logarithmic divergences that occur in quantum electrodynamics, as well to see whether this would also enable particles to travel faster than light. However these investigations led to very complicated expressions mathematically, and after numerous negative comments from distinguished physicists, I put them aside after I had later gone to Stanford to resume my graduate studies in the fall of 1955, following the offer of a graduate fellowship by the physics department chairman, Leonard Schiff, whose textbook on quantum mechanics is well-known [1]. Although I was unaware of it at the time, Schiff had a deep interest in relativity, particularly in the testing of general relativity. I should mention that I left Chicago in the fall of 1952 and came to San Diego for family reasons, where I eventually worked in the space industry for about two and a half years before resuming my graduate studies in physics at Stanford. In the fall of 1956 Sidney Drell, whose work on quantum electrodynamics is well-known, became my thesis adviser, and although while he welcomed the idea of a cut-off, he didn't

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agree with the ideas of my Chicago approach either, hence, as indicated above, I put them aside. and worked on other ideas, such as the then newly-recognized parity and charge conjugation violations in the weak interactions. The following summer I carried out some calculations about photoproduction of neutral pions [2] at the old Mark III linear electron accelerator that was the ancestor of the present two-mile Stanford linear accelerator, commonly known as SLAC, of which Drell became the Vice-Director, but from which he has since retired.

In the fall of 1957, after the pion photo-production calculations were finished, I decided to tackle the Lorentz transformation again, but this time, instead of trying to modify it, I was interested in improving my understanding of the transformation and special relativity more generally, while at the same time retaining the idea I had developed when I was studying at the University of Chicago about there being an ether. This idea had come about as follows. While there I attended many lectures by Enrico Fermi, and in particular, during the winter and spring quarters of 1949, I attended his course on nuclear physics [3]. In these lectures I learnt for the first time about Dirac's idea of space being filled with a sea of negative energy states [4]. Although before coming to Chicago, I had had a course on quantum mechanics as an undergraduate at Harvard, given by Julian Schwinger, it was a non-relativistic course, and I graduated before I could take the course in relativistic quantum mechanics where the Dirac sea and the so-called hole theory of positrons would be discussed. I might add, parenthetically, that it was in a colloquium given late in 1947 by Schwinger concerning his then recent work on quantum electrodynamics that I learnt of the logarithmic divergence of the first-order correction to the mass of the electron. At any rate, Dirac's idea of a sea of negative energy states struck me as supportive of there being an ether, in the sense that space was not empty i.e., it was not a "void". This latter description of space was the view that had emerged from Einstein's famous 1905 work, and that of course was in conflict with the views of Larmor, Lorentz, Poincaré, and indeed nearly all the physicists of Einstein's time. Also, while at Chicago, I learnt of the experiment of Michelson and Gale, that is an optical analogue of the Foucault pendulum experiment, and also the experiment of Sagnac, both of which seemed more easy to interpret in terms of an ether relative to which the Earth was rotating in the first case, or relative to which the Sagnac interferometer was rotating in the second case. This is briefly discussed in the thesis.

To those who have studied only special relativity, my attempt to retain the ether might seem as though I had taken a step backward;

however, while working in San Diego, but continuing to research relativity in my spare time, I found surprising support from the later work of Einstein on the basis of his general theory of relativity. I should note here that I had commenced the study of general relativity on my own while at Harvard using the text by Peter Bergmann [5], and also that by Arthur Eddington [6], while I also attended lectures on tensor analysis by Léon Brillouin [7]. In 1953, I came across a translation of Einstein's [8] inaugural address in Leiden in 1920 where, following the wishes of Lorentz and Ehrenfest, he had been invited to serve as an annual visiting professor, while retaining his primary position in Berlin. In the address he says,

> "From the point of view of the special theory of relativity, the ether hypothesis has certainly been an empty one at first sight... On the other hand, there is an important argument in favour of the ether. To deny the existence of the ether means, in the last analysis, denying all physical properties of empty space. But such a view is inconsistent with the fundamental facts of mechanics".

It is unfortunate that many texts that are used to teach special relativity never reference this important address by Einstein, although a notable exception is the text by Pauli [9], which however is rarely used, so that many students are left only with the view expressed in Einstein's earlier work of 1905 that contributes to the widespread view that space in the absence of bodies and fields is a void. Interestingly, in 1953, as referenced in the thesis, Dirac wrote in support of an ether. For a fairly recent statement in support of an ether, see the article by the particle physicist, Frank Wilczek [10], entitled, *The Persistence of the Ether.*

However, if one does have the ether in the background of one's thinking about the propagation of light through space as a wave, together with the invariance of its speed in each of two uniformly moving frames, one seems to be entertaining contradictory pictures. (Unless the ether is dragged along completely, but such a view had been shown to be untenable.) To be sure, mathematically, it is easy to understand how this invariance arises from the term that depends on space in the Lorentz transformation for the time, and that gives rise to the relativity of simultaneity. The problem is not one of mathematics, but rather one of intuition.

Thus, upon returning to the Lorentz transformation in 1957, I examined how clocks were to be thought of as synchronized according to the Galilean transformation. It seemed to me, then, that the clocks had been synchronized by instantaneous signals, so that if two events were simultaneous in the ether, they were also simultaneous in the frame moving uniformly with respect to it. In other words, when such hypothetical signals were used, simultaneity assumed an invariant, or as I described it in the thesis, an "absolute" character. Although I was unaware of it at that time, Lorentz himself [11] had argued for an absolute or "true" simultaneity. He said, after he had become aware of Einstein's approach to time and simultaneity, that he still favoured the "true" time and the "true" simultaneity and he went on to say,

> "...together with this goes that we can imagine velocities of any desired magnitude, e.g., a hundred times greater than the velocity of light (quite apart from whether they actually occur), while according to the relativity principle such velocities are ruled out".

He then describes how such signals, in the limit of infinite velocity, would enable us to know what happened, e.g., on the star Sirius simultaneously with what happened on earth.

Thus the thought underlying the transformation I finally constructed was in accord with Lorentz's ideas on simultaneity. Quite interestingly, the transformation also represented the working out of a question put forward by Poincaré in his 1904 address at the St. Louis Exposition, which, regretfully, I had not read when I wrote my thesis, since if I had been able to refer to it, that would have given further support for the path I was following. In that 1904 address, Poincaré asked [12]:

> "What would happen if one could communicate by non-luminous signals whose velocity of propagation differed from that of light? If, after having adjusted the watches by the optical procedure, one wished to verify the adjustments by the aid of these new signals then would appear divergences which would render evident the common translation of the two stations.And are such signals inconceivable, if we admit with Laplace that universal gravitation is transmitted a million times more rapidly than light?"

In the thesis I assumed that there were signals that propagated instantaneously in the ether, and that these signals could be used to synchronize clocks in the moving frame, and thereby reveal the motion of the frame relative to the ether. However, as indicated in the thesis, I made no assumptions about the physical nature of such signals, so that in this sense, it was a mathematical exercise. On the other hand, unlike the possibility mentioned by Poincaré, I did not regard such hypothetical instantaneous signals as having anything to do with gravity, because I was working in the framework of general relativity in which the gravitational interaction is propagated with the speed of light. I might add that I found out later that Lorentz, in a little known paper [13] in 1900 had showed that the gravitational interaction could take place at the speed of light, in contrast with Laplace's model, without incurring the empirically unobserved effects on the motion of the moon that Laplace had found, essentially because the effects of a finite velocity of interaction could be of second order in $\frac{v}{V}$ rather than of first order, where V is the speed of gravity.

The transformation that I eventually came up with, which is given in Eq. (1.12) of the thesis, I called the Absolute Lorentz Transformation (abbreviated subsequently as A.L.T.), since it had some of the basic properties of the Lorentz transformation: such as the Lorentz contraction and the time dilation, while in keeping with Lorentz's viewpoint that I had inferred from his writings, it kept simultaneity invariant, and consequently it did not keep the one-way velocity of light invariant, although, to be sure, the out-and-back velocity, as with the full Lorentz transformation, remained invariant. If the instantaneous signals were to propagate causally (i.e., not propagate backwards in time), there could be only one frame in which light propagated isotropically with speed c when clocks were synchronized with these signals. This is because, as discussed by Einstein [14], a signal that propagated forward in time and faster-than-light in one Lorentz frame can readily be shown to propagate backwards in time in another Lorentz frame. The idea then was that the above privileged frame would be the ether, and all other frames could be ordered according to their speed relative to this frame, and in this sense, one would return to Newton's idea of there being an absolute velocity of a moving body, a view which Lorentz clearly favoured. On the other hand, in keeping with the principle of relativity, it had to be the case that when measurements were made in the standard way, i.e., with clocks that were synchronized according to the procedure described by Einstein in his 1905 paper, or by slowly moving them apart after they had been synchronized when they were together, the A.L.T. would yield experimental results in agreement with the Lorentz transformation, and would therefore make it impossible to determine one's velocity relative to the ether. Thus the failure to detect this velocity in the numerous efforts that had been made with this purpose would not be a consequence of the fact that such a velocity did not exist, but rather because when measurements were made in the standard way, this velocity always cancelled out, thereby engendering the principle of relativity. Physically, one might say the ether does not exert a drag on bodies, nor bodies on the ether, as maintained by Lorentz, who rejected the interpretation of the Fresnel drag coefficient as an actual dragging of the ether.

In the closing chapter of the thesis, I addressed the issue as to what might give rise to the hypothetical instantaneous signals, and discussed the possibility of faster-than-light particles that are now known as "tachyons". I discussed some of their properties, which I had already investigated to some extent seven years earlier when I was at the University of Chicago. Interesting work on this subject in this time period is due to several authors [15–18], and particularly, G. Feinberg [19], to whom we are indebted for the name, "tachyon", as well as a detailed quantum field theoretical analysis. My own contribution to the quantum field formulation, as indicated in the thesis, was to introduce the idea that the tachyons would be created in the faster-than-light region, thereby avoiding the infinite barrier at the speed of light. I also noted that if they were charged, they would exhibit Cherenkov-like radiation, something I had also been able to show in the Chicago period. For additional references to tachyons see the historical review up to 1969 by Fröman [20]. A later further review on the subject by E. Recami [21] appeared in 1986, in which there is a brief reference to my thesis, in fact, the first reference to it in the literature to my knowledge.

After spending a year at the Niels Bohr Institute of Theoretical Physics (in those days it was known as "Universitetets Institut for Teoretisk Fysik", or "University Institute for Theoretical Physics") in Copenhagen in 1958–1959 as a National Science Foundation post-doctoral fellow, where I had interesting discussions with Christian Møller [22], whose work on relativity had led me to Copenhagen, and then subsequently, on an extension of the N.S.F. fellowship, I spent the following year at the Scuola del Perfezionamento in Fisica Téorica e Nucleare in Naples, of which Eduardo Caianiello was the Director. While there, I began to consider a physically-realizable way of re-interpreting the A.L.T., in view of the obvious experimental absence of faster-than-light signals. The idea, which was briefly mentioned in my introduction to general relativity that I wrote when I was in Naples [23], while giving some informal lectures there in the spring of 1960, is that one can think of the clocks in the moving frame as having been synchronized externally with the clocks in the rest frame, with the latter being any arbitrary Lorentz frame, i.e., an inertial frame in which the clocks have been synchronized so that the one-way speed of light is c in all directions. The following is helpful in visualizing how this external synchronization may be made with existing apparatus, and how the transformation may then be interpreted and experimentally verified.

Imagine, as is customary in pedagogical presentations dealing with special relativity, a railroad station that is taken to be an inertial frame, after suitable corrections, and a line of clocks stretching along the station parallel to the tracks. These clocks have all been synchronized in accordance with special relativity, so that the one-way speed of light is c in the forward and rearward directions, the only direction with which we shall be dealing for simplicity. Now let there be a train travelling through the station with velocity v in the positive x-direction, and on the train assume there is a row of clocks along the length of the train similar to those in the station, but which have not been synchronized. Finally, imagine an electro-mechanical system that enables clocks on the station to transfer their time to the clocks on the train. Assume adjustments have been made so that when the clocks on the station all read zero, the connection is made with the clocks on the train, just once, and this is done so rapidly that the time of exchange can be neglected. After the connection has been made and terminated, the clocks on the train run freely at their own rate. If t denotes the time read by the clocks on the station, and t' the time read by the clocks on the train, then when $t=0$, $t'=0$, and hence, under the assumption of a linear relationship, t' is directly proportional to t, i.e., $t' \propto t$, The constant of proportionality follows from special relativity. For example, we know from numerous experiments that have been carried out with relativistic decaying particles, such as the muon, that their lifetimes increase as seen in the lab as they approach the speed of light, and in fact this increase agrees with that predicted by special relativity, so that if T_0 is their lifetime when they are at rest, then when they are travelling with speed v relative to the lab, their lifetime becomes γT_0, where as usual, $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$. This then determines the transformation for the time between the station and the train to be $t' = \gamma^{-1} t$, as given in the thesis. This simple transformation for the time yields the result that if two separated clocks on the station describe an event as simultaneous, $\Delta t = 0$, then clocks on the train will also agree that the events were simultaneous, since $\Delta t' = 0$. This is of course unlike the case for the Lorentz transformation, since $\Delta t_L = \gamma \left(\Delta t - \frac{v}{c^2} \Delta x\right)$, and if $\Delta t = 0$, one has that $\Delta t_L = -\gamma \frac{v}{c^2} \Delta x$, which expresses the relativity of simultaneity. As noted in the thesis, the A.L.T. transformation for the time is needed in addition to the Lorentz contraction of the spatial coordinate to guarantee a null-effect in the unequal arm interferometer experiment of Kennedy and Thorndike.

Now, as shown in the thesis, this transformation for the time has the important property that when the clocks on the train that have been synchronized externally are slowly-moved apart, and the one-way speed of light is measured with them, it turns out to be c. Indeed, one finds that the slowly-moved clocks no longer read t' but $t' - \frac{v}{c^2}x'$, which is just the time read by the clocks whose time is described by the Lorentz transformation. Hence, the slowly-moved clocks yield that the one-way speed of light is c.

In keeping with Niels Bohr's idea to look for examples of complementarity outside of the domain of atomic physics [24], it is helpful to recognize that there is a complementarity between the one-way speed of light and simultaneity, which I did not recognize in the thesis, and hence regretably did not discuss with Bohr when I was in Copenhagen. Thus, one can keep the one-way speed of light invariant in transforming between two uniformly moving frames, but then one must relinquish the invariance of simultaneity and let it become relative, as described by the Lorentz transformation, or, one can keep simultaneity invariant, and let the one-way speed of light become relative, as described by the A.L.T. Furthermore, this is fully in keeping with Einstein's principle of general covariance, which enables one to represent the comparison of the two descriptions in mathematical form.

There are two obvious objections to external synchronization: a) the standard special relativistic approach is based on synchronization *within* a given uniformly moving frame; and b) even if external synchronization is allowed, there is no natural frame in space (i.e. no cosmological railroad station) with respect to which such a synchronization could be made.

The reply to a) is that there is no way to prove *empirically* that there is a relativity of simultaneity between two frames in relative motion, unless one is able to compare the measurements of simultaneity in the two frames. Therefore one frame must make a necessarily external contact with the other frame in order that there can be an exchange of information between the two frames. Such an external contact can obviously be also used to make an external synchronization, and hence can be used to keep simultaneity invariant between the two frames.

With respect to b), the view that there is no natural reference frame in space has to be reconsidered because of the discovery of the Cosmic Microwave Background Radiation (CMBR) by Arno Penzias and Robert Wilson in 1965 [25], who were apparently unaware of the earlier theoretical work of George Gamow, who had predicted the existence of such radiation on the basis of his Big Bang model of cosmology, albeit at a different temperature [26]. For an excellent historical review, together with their own important contributions, see the book by his pupils, Ralph Alpher and Robert Herman [27], *Genesis of the Big Bang.*

In later experiments it was found that the radiation is not uniform in all directions, but is warmer in one direction and colder in the opposite direction, so that it exhibits a dipolar structure [27]. This is to be expected if the CMBR defines a rest frame through which our solar system, and hence the Earth is moving. (Note that in view of the magnitude of this velocity of several hundred kilometers/second, the Earth's velocity around the Sun of $\sim$30 km/sec is, to a first approximation, negligible.) Because of the Doppler effect, the radiation temperature is the highest in the direction in which the Earth is moving, and exhibits a typical cosine dependence. The detection of this velocity through the radiation has led Peebles [28] to describe the result as the "new ether drift". To be sure, the measurement is not that of a true ether drift, because if one places the antennae in an electromagnetically sealed laboratory, so that the CMBR cannot penetrate, obviously one will not be able to measure the frame's velocity relative to the radiation, whereas the idea underlying the determination of a true ether drift is that one can make such a measurement in a closed laboratory. Nevertheless, ignoring very small temperature fluctuations and hence anisotropy in the CMBR of order 10^{-5} [29], and assuming the radiation is at rest with respect to the expanding space of the Friedmann, Robertson, Walker, Lemaître cosmological model, then one can synchronize one's clocks in a moving frame with respect to this CMBR frame, and all clocks so synchronized in these frames in uniform motion relative to the CMBR will keep simultaneity invariant with respect to each other, at the expense of not keeping the one-way speed of light invariant.

Since my work is sometimes compared in the literature with that of Herbert Ives, the following comments are in order. When I was at the University of Chicago, I wrote to Ives describing some of my ideas about modifying the Lorentz transformation that would support the idea of an ether, as I was aware from some of his publications that he also strongly supported the idea of an ether. He wrote me back that he preferred his own approach to mine, and kindly sent me a copy of his paper, *The Fitzgerald Contraction*, referenced in the thesis. However, in this work, he objected to the idea, supported by special relativity, of making measurements of the one-way speed of light with clocks that have been synchronized when they are together, and then moved infinitely slowly apart. He apparently had raised this objection earlier to Percy W. Bridgman [30], who pointed out that one can achieve such a measurement by the method of successive approximation and then passing to the limit. I was unaware of Ives' conversation with Bridgman (since Bridgman's book came out after I had written my thesis as well as my Nuovo Cimento article), nor had I noticed in Ives' Fitzgerald article that he rejected synchronization with slowly-moved clocks. However, after I had formulated my transformation, I became concerned as to whether if one had two clocks that had been synchronized together in the moving frame at point A and one of them was slowly moved to point B, and they were used to measure the one-way speed of light, whether one would obtain c as predicted by special relativity. As the work in Chapter 3 of the thesis shows, this is in fact the case, and in Chapter 4, one can use this result in conjunction with other assumptions to derive the A.L.T. A later derivation was published by me in 1994 [31]. Thus, on this issue of slowly-moved clocks, there is a profound disagreement between the approach in my thesis and the work of Ives. Regretably, Ives died in 1953, and consequently I was never able to get comments from him about the A.L.T., but in view of his objections to Bridgman concerning slowly-moved clocks, it is unlikely he would have changed his position. I might add that I sent a revised copy of my thesis, that I had prepared while in Copenhagen, to Bridgman around June of 1959. But he never replied, and tragically, because of a debilitating case of cancer, he ended his life in 1961, although fortunately he was able to complete his *A Sophisticate's Primer of Relativity*, which was edited posthumously with a prologue and epilogue by Adolf Grünbaum, whose earlier article on synchronization is referenced in the thesis. There is a second edition of Bridgman's book [30], edited by Arthur Miller that contains useful information about the chronology of Bridgman's work on his book. As noted in the thesis, Bridgman's operational methodology played a role in the formulation of the A.L.T. I might add that I took his course on advanced thermodynamics during the fall semester of 1947 when I was at Harvard, although relativity was not discussed.

At this point it is appropriate to turn to the idea of alternative synchronization in a given Lorentz frame that was proposed by Hans Reichenbach [32], and which is referred to in the literature as the "conventionality of synchronization". Although I did not mention Reichenbach in the thesis, I became aware of his ideas through the above-mentioned article by Grünbaum cited in the thesis. Reichenbach showed that it is entirely consistent with the special theory of relativity to synchronize clocks so that the one-way velocity of light is not c, by following a different synchronization procedure than that of Einstein. Let two clocks in a uniformly moving frame be an arbitrary distance apart, one at A the other at B. Then if a light signal leaves the clock at A at time t_1 and strikes a mirror at B at time t_2, and then returns to A at time t_3, according to Einstein's synchronization procedure, $t_2 = t_1 + \frac{1}{2}(t_3 - t_1)$, in accordance with the assumption that the speed of light is the same in both directions. However, Reichenbach argued that no contradiction with the other postulates of special relativity arises if instead of the above synchronization, one sets $t_2 = t_1 + \varepsilon(t_3 - t_1)$, with the following restriction that $0 < \varepsilon < 1$, under the assumption that the one-way speed of light is finite in both directions. Since this synchronization procedure of Reichenbach does not describe a coordinate transformation, I did not attempt to deal with it in the thesis beyond what is briefly stated there. However, in recent years, Anderson et al. [33] have given a coordinate representation for Reichenbach synchronization, by means of a linear local time transformation. Thus, let us suppose that after clocks, whose time will be denoted by t_L, have been synchronized either by Einstein's method, or by slowly-moving them, one introduces another set of clocks in the same frame whose time varies along the x-axis according to the linear relation, $t_R = t_L + \frac{k}{c} x_L$, and whose spatial coordinates are the same as the Lorentz observer, i.e., $x_R = x_L$, $y_R = y_L$, $z_R = z_L$ with $-1 < k < 1$. Transformations of this type were called by Lorentz, "local time transformations". Such a linear transformation for the time that also involves the spatial coordinate seems to have been first used in conjunction with the Doppler effect by Voigt [34]. Now let us think of the Reichenbach synchronization having been made on the train travelling uniformly through the above-mentioned railroad station, and compare it with the time read by the clocks that have undergone external synchronization using the A.L.T. Then, from the thesis, one has $t' = t_L + \frac{v}{c^2} x_L$, $x' = x_L$, $y' = y_L$, $z' = z_L$. In other words, the clocks under the A.L.T. are related to the clocks internally synchronized in the moving frame by a local time transformation. Hence, one can always think of a Reichenbach synchronization (as represented by a linear local time transformation following Anderson et al.) as equivalent to an external synchronization for suitable choice of k. It is readily shown that, for the externally synchronized clocks, one has for a signal sent in the direction of the train's motion, i.e., in the positive x-direction, that $t'_2 = t'_1 + \frac{1}{2}\left(1 + \frac{v}{c}\right)(t'_3 - t'_1)$, and that in the reverse direction, one has $t'_2 = t'_1 + \frac{1}{2}\left(1 - \frac{v}{c}\right)(t'_3 - t'_1)$. Hence in the forward direction $\varepsilon = \frac{1}{2}\left(1 + \frac{v}{c}\right)$, and in the rearward direction, $\varepsilon = \frac{1}{2}\left(1 - \frac{v}{c}\right)$, and since $\frac{v}{c} < 1$, Reichenbach's restriction on ε follows. Thus the thesis anticipates to some extent the interesting analysis of Anderson et al. Although it also important to carefully distinguish between external synchronization involving two Lorentz frames, and alternative synchronization within a given Lorentz frame. The effect of external synchronization is to give rise to clocks that exhibit alternative synchronization to the clocks that obey the time transformation of the Lorentz transformation. For a later discussion of Reichenbach's work see Grünbaum [35]. It should also be remarked that from the standpoint of general relativity, and general covariance, it is entirely obvious that one can introduce a Reichenbach synchronization as represented by a linear local time transformation in a given Lorentz frame. However, as discussed in the thesis, the coefficients of the Minkowski line element, i.e. the $g_{\mu\nu}$, no longer remain the same as for a Lorentz transformation. Nevertheless, since they are still constants, it follows that all the Christoffel symbols vanish, and in the absence of external forces one continues to have $\frac{d^2 x^\mu}{d\tau^2} = 0$, as for the Minkowski metric, corresponding to the fact that Newton's first law holds, so that such a transformation is inertial.

It is of historical interest that the time dilation that is used in the A.L.T. and that follows from special relativity, as I later found out, was actually first introduced by Larmor [36], who found that he needed it in order to keep the d'Alembertian wave equation invariant. Thus, as some historians of science have observed, one might very well speak of the Lorentz-Larmor transformation. On the other hand, it should be emphasized that Larmor, unlike Lorentz, believed that the speed of gravity if finite at all, vastly exceeded that of light, and hence he did not attribute to the transformation the fundamental significance that Einstein did later on, with his emphasis on the speed of light playing the role of a limiting speed. Also, it should be noted that since the appearance of the 1961 article in which the A.L.T. was first published, there have been published many interesting papers, too numerous to reference here, re-deriving, developing, and applying the transformation.

In 2008 I found [37] further support for the invariance of quantum mechanics under local time transformations, as described in Chapter 11 of the thesis. It was shown that when the standard space and momentum commutation relations are enlarged to a spacetime formulation, they remain invariant under arbitrary linear, non-singular spacetime transformations; while also maintaining the vanishing of the commutator of the time with the Hamiltonian operator, so that time can continue to be treated as a c-number in accordance with quantum mechanics.

Finally, while the thesis was being prepared for publication, I was informed by Dr. Gregory B. Malykin [38] that a literature search had found that Albert Eagle, then a lecturer in mathematics at the University of Manchester, UK, had given the A.L.T. including its inverse in a paper published in 1938, hence twenty years before my thesis. Eagle expressed the view that the transformation could be understood as relating the moving frame to the ether frame with clocks that had been synchronized with instantaneous signals [39], which is entirely similar to the viewpoint expressed in the thesis. (Although, as noted above, I now believe the alternate interpretation of the A.L.T. as associated with external synchronization is physically the more reasonable one.) However, Eagle was under the impression that such instantaneous communication could be accomplished by a rotating spindle, i.e, a mechanical device, and hence that one could use such a device to determine the speed of the frame through the ether. The idea that one could send instantaneous signals with a mechanical system is of course entirely false. See Jammer's recent book on simultaneity [40]. This misunderstanding, together with the fact that the quadratic form describing light propagation is not left invariant under the transformation, apparently led Eagle to a mistaken criticism of Minkowski's spacetime formulation of special relativity, and also to a rejection of the general theory of relativity as well, so that he regretably failed to recognize the A.L.T. is in full conformity with Einstein's principle of general covariance, and the metric postulate, and that the A.L.T. actually constitutes an interesting application of general relativity for the simple case of a linear transformation in flat spacetime, which is, in contrast, the approach taken in my thesis.

I am grateful to Dr. Gregory B. Malykin for valuable scholarly correspondence concerning my thesis, as well as many stimulating questions. I am also indebted to his son, Asst.-Prof. Edward G. Malykin, for his further assistance. I am further indebted to Dr. Dmitri Rabounski for encouraging the publication of the thesis in *The Abraham Zelmanov Journal*, and his considerable assistance in helping to accomplishing this.

Submitted on April 04, 2009

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Vol. 2, 2009 **ISSN 1654-9163**

THE ABRAHAM ZELMANOV JOURNAL

The journal for General Relativity, gravitation and cosmology

TIDSKRIFTEN ABRAHAM ZELMANOV

Den tidskrift för allmänna relativitetsteorin, gravitation och kosmologi

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