History of the Lorentz Transformation and Its Failure To Obey the Law of Causality

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Abstract

The experiments which indicated that the speed of light in free space is the same for all observers regardless of their relative state of motion led Voigt to suggest that the classical (Galilean) velocity transformation (GVT) needed to be amended. His solution introduced the concept of space-time mixing, which ultimately became a fundamental characteristic of the Lorentz transformation (LT). Einstein showed that the LT leads directly to the prediction of both FitzGerald-Lorentz length contraction (FLC) and time dilation (TD). Whether these two findings are consistent with the equality of light speed measurements for observers in different rest frames is investigated. In addition, the relevance of the Law of Causality to the assumptions underlying the derivation of the LT is considered in detail.

Keywords: *Law of Causality, Lorentz transformation (LT), Relativistic velocity transformation (RVT), Galilean velocity transformation (GVT), space-time mixing, Uniform Scaling method*

I. Introduction

Belief in the classical/Galilean velocity transformation (GVT) was quite strong until it became clear in the early 19th century that it was unable to explain the results of certain experiments such as the light-speed damping observed in moving liquids [1]. There was a tendency among physicists to find a rest frame (aether) for light which is analogous to that which is well known for sound waves. Voigt [2] deviated from this general trend by suggesting that the GVT should be amended to adapt in such a way as to guarantee that two observers in relative motion to one another must agree on the speed of light in free space. He proposed inserting a parameter in the GVT equations to accomplish this objective. His publication coincided with the report [3] of the null result obtained on the basis of the newly developed interferometer by Michelson and Morley. They showed that the effect is completely independent of the season of the year in which the experiment was carried out.

Although Voigt was successful in achieving the goal of equal light-speed for different observers, he was not able to satisfy Galileo's Relativity Principle with his new set of space-time equations (VT). This problem was corrected by Larmor [4] and Lorentz [5] independently by multiplying each of the right-hand sides of the four VT equations by a factor of $\gamma(v) = (1-v^2/c^2)^{-0.5}$. The result has come to be known as the Lorentz transformation (LT). Einstein [6] employed the LT as the centerpiece of his Special Theory of Relativity (SR). There is another fundamental requirement that must be satisfied, however, in order to construct a physically viable space-time transformation, namely its equations must be internally consistent. This point will be discussed in detail in the following section.

II. FitzGerald-Lorentz Length Contraction and Time Dilation

The GVT is derived from the Galilean space-time transformation (GT) given below:

$$\Delta t' = \Delta t \qquad (1a)$$

$$\Delta x' = \Delta x - v\,\Delta t \qquad (1b)$$

$$\Delta y' = \Delta y \qquad (1c)$$

$$\Delta z' = \Delta z. \qquad (1d)$$

Two observers are separating from each other by speed v along the common x-x' coordinate axis. They obtain different values for the distances between each of them in three perpendicular directions ($\Delta x'$, Δx; $\Delta y'$, Δy; and $\Delta z'$, Δz), A critical assumption in the GT is that the elapsed time for the two events is the same for both observers, i.e. $\Delta t' = \Delta t$. The corresponding velocity transformation (GVT) is obtained by simply dividing each of the three spatial differences by the corresponding time difference to obtain the components u_x', u_y', u_z':

$u_x' = (u_x - v)$ (2a)

$u_y' = u_y$ (2b)

$u_z' = u_z.$ (2c)

Voigt's suggestion [2] was to modify eq. (1a) by adding a term which is dependent on Δx in eq. (3a). He also showed that the right-hand sides of eqs. (1c) and (1d) must each be multiplied with γ^{-1} in order to satisfy the light-speed equality condition.

$$\Delta t' = \Delta t - vc^{-2}\Delta x \quad (3a)$$

$$\Delta x' = \Delta x - v\,\Delta t \quad (3b)$$

$$\Delta y' = \gamma^{-1}\,\Delta y \quad (3c)$$

$$\Delta z' = \gamma^{-1}\,\Delta z. \quad (3d)$$

It is evident that the VT is not consistent with the RP, however. Accordingly, the inverse set of equations must be obtained by exchanging the primed and unprimed variables and changing the sign of v. This procedure is known as *Galilean inversion* and simulates what occurs when the two observers exchange their positions in space. This leads to the relation $\Delta y = \gamma^{-1}\,\Delta y'$, which is clearly not the same as when the inverse set of equations is obtained by application of the normal rules of elementary algebra to eq. (3c), i.e. $\Delta y = \gamma\,\Delta y'$.

The LT is formed from the VT by multiplying each of its right-hand sides with a factor of γ: ($\eta^{-} = [(1 - vc^{-2})\,\Delta x/\Delta t]^{-1}$).

$$\Delta t' = \gamma(\Delta t - vc^{-2}\Delta x) = \gamma\,\eta^{-1}\,\Delta t \quad (4a)$$

$$\Delta x' = \gamma\,(\Delta x - v\Delta t) \quad (4b)$$

$$\Delta y' = \Delta y \quad (4c)$$

$$\Delta z' = \Delta z. \quad (4d)$$

The formula for FitzGerald-Lorentz length contraction (FLC) along the x axis is readily obtained by considering the case when $\Delta t = 0$ in eq. (4b):

$$\Delta x' = \gamma\, \Delta x \qquad (5)$$

Note that there is no length contraction in the perpendicular direction, as shown directly in eqs. (4c) and (4b). The amount of the length contraction in other directions is obtained by combining these equations. This was pointed out by both FitzGerald and Lorentz in the 1890s. It was also derived by Einstein in 1905 [6].

The well-known formula for time dilation (TD) was first obtained by Einstein [6] in the following way. He imagined the case of a clock located at rest in the (moving) system S';
He pointed out that the other observer in S would see the clock moving away from him at speed v, so that $\Delta x = v\Delta t$. Substitution in eq. (4a) then leads to the following relation:

$$\Delta t' = \gamma(\Delta t - v^2c^{-2}\Delta t) = \gamma^{-1}\Delta t, \qquad (6)$$

since $1 - v^2c^{-2} = \gamma^{-2}$.

The notation describing the two observers is a matter of great interest. They are referred to as being either stationary (unprimed) or moving (primed). It needs to be kept in mind that each person considers himself to be at rest while objects which are in a different rest frame are considered to be moving. The two observers referred to in eqs. (5) and (6) can nonetheless distinguish their positions by noting the direction in which the other is moving. The only speed-dependent parameter in these two equations depends on v^2, however, so there is no mechanism to distinguish which observer is moving and which is at rest in this case. There is thus a symmetry principle [7] inherent in these LT predictions, whereby it is assumed that each observer thinks that it is the other's clock that is running slower, or whose measure of distance is larger. Accordingly, it is assumed that when the two observers exchange light signals from an identical source, a red shift will be measured in both cases. This assertion of SR has been the subject of great controversy over the past century since Einstein introduced it for the simple reason that
one knows with certainty that two clocks in the same rest frame cannot both be running slower than each other.

III. Lack of Internal Consistency in the Lorentz Transformation

There is a far more consequential argument that raises questions about the validity of the FLC and TD predictions of the LT, however. Taken together with the light-speed equality condition on which the LT is based, the TD and FLC amount to *three separate relationships* that all need to be satisfied in any given application. It therefore needs to be noted that distance, time and speed are not independent of one another, however, since the speed of an object is the ratio of the distance it has moved in a given amount of elapsed time. As a consequence, it is necessary to check whether the above three conditions are consistent with one another.

To this end, consider the case in which the speed of a light pulse is measured while moving along the x,x' axis in rest frame S'. It is found that the light pulse moves a distance of $\Delta x'$ in the elapsed time of $\Delta t'$; in accord with the light-speed postulate, it is found that the ratio $\Delta x'/\Delta t' = c$. To check for internal consistency, the ratio of $\Delta x/\Delta t$ measured by the stationary observer in rest frame S needs to be evaluated using eqs. (5) and (6). The result is:

$$\Delta x/\Delta t = \gamma^{-1}\Delta x/\ \gamma\ \Delta t = \ \gamma^{-2}\Delta x/\gamma\Delta t. \qquad (7)$$

According to the light-speed equality condition, however, $\Delta x/\Delta t = c$, in clear disagreement with eq. (7). In other words, the above example shows unequivocally that the LT is not internally consistent and therefore invalid [8].

There are also other reasons for rejecting the LT. For example, Einstein's light-speed postulate (LSP), which asserts that the speed of light in free space is the same for all observers independent of their state of motion or that of the relevant light source, has also been shown to be untenable [9,10]. It needs to be emphasized that the evidence presented above is not the result of some new experimental information. Rather, it is based on the nature of the LT itself. The same conclusion could have been made at least at the time that Einstein deduced eq. (6) in 1905 [6].

This state of affairs obviously raises the question of why belief in the LT has been so strong among physicists. The most plausible explanation is that there has been a misunderstanding regarding the relationship between the LT and the RVT of eqs. (8a-c) given below:

$$u_x' = (1-vc^{-2}u_x)^{-1}\ (u_x-v) = \eta\ (u_x-v) \qquad (8a)$$

$$u_y' = \gamma^{-1}(1-vc^{-2}u_x)^{-1}\ u_y = \eta\ \gamma^{-1}\ u_y \qquad (8b)$$

$$u_z' = \gamma^{-1}(1-vc^{-2}u_x)^{-1}\ u_z = \eta\ \gamma^{-1}\ u_z. \qquad (8c)$$

The RVT has proven to be quite effective in explaining a broad variety of experimental results obtained in the study of the collisions of high-energy particles. It was also used successfully by von Laue in 1907 to explain the Fizeau-Fresnel light-damping experiment. It is therefore an indispensable component of relativity theory that needs to be preserved in all circumstances. The point that is apparently easily missed in this connection is that the RVT is in no way dependent on the LT for its derivation. For example, it can also be deduced on the basis of the

VT of eqs. (3a-d). As pointed out above, one simply needs to divide the three spatial quantities by the corresponding time difference to achieve this result. Einstein [6] was the first to notice that the RVT can be derived in this manner, but the role of the LT is this respect is not unique.

IV. Law of Causality and the Clock-rate Corollary to Newton's First Law of Motion

In order to find a viable alternative to the LT, it is important to note that the space-time transformations in general assume that the relationships contained therein deal exclusively with objects and observers which are freely moving through space, i.e. which are all *inertial systems.* In this connection, it is important to note that the clocks employed by the two observers are not subject to the application of any unbalanced force. According to the Law of Causality, they are therefore expected to maintain constant rates indefinitely. Newton's First Law of Motion (Law of Inertia) states that freely moving objects will continue with the same speed and direction as long as they are not subject to an unbalanced force. The conclusion that inertial clocks will not change their rates spontaneously can therefore be viewed a corollary to Newton's First Law [13-14]. As a consequence, it must be assumed that *the ratio Q of the rates* of any two such inertial clocks will itself be a constant. In practice, this means that when the two clocks employed in space-time transformations measure the elapsed time for a given event, their respective values Δt and $\Delta t'$ will always occur in the same ratio:

$$\Delta t' = \Delta t/Q. \quad [9]$$

The proportionality relationship of eq. (9) stands in direct contrast to the space-time mixing character of eq. (4a) of the LT, thereby proving that the LT is incompatible with the Law of Causality. This is yet another reason for eliminating the LT as a possible space-time transformation.

It was recognized by Poincaré [15] that the LT implies that events which are simultaneous for one observer may not be so for another located in a different rest frame. For example, if $\Delta t=0$ in eq. (4a), the corresponding time difference $\Delta t'$ will not be equal to zero if both v and Δx are not equal to zero. This possibility is generally referred to as remote non-simultaneity (RNS). It is clear from eq. (9), however, that RNS cannot occur when this equation is used in its place; either both time differences are equal to zero or both are not in this case. Einstein [16] used the example of two lightning strikes on a passing train to illustrate this possibility.

In order to apply eq. (9) in actual practice, it is clearly necessary to know the value of the parameter Q for the relevant two inertial frames. This can be obtained by experiment by comparing the measured values for the elapsed time of a given event. A survey of all relevant experimental data [17] indicates that the elapsed time registered on a given clock is inversely proportional to γ (v), where v is the speed of the clock relative to a specific rest frame referred to as the Objective Rest Frame (ORS):

$$\Delta t' \gamma (v') = \Delta t \, \gamma (v). \quad [10]$$

This relationship is thus deserving of the designation Universal Time-dilation Law (UTDL). For example, in the Ives-Stilwell experiment [18], it was found that the period of radiation emitted by an accelerated light source decreases with the latter's speed relative to the laboratory, in agreement with the UTDL prediction within the relevant error limits; in this case the ORS to be used as reference for the speed of the light source is the laboratory rest frame. The same relationship holds true for the period of gamma rays emitted from a Mössbauer source which were observed in the ultracentrifuge experiment of Hay et al. [18]. In the study of the rates of atomic clocks carried on board circumnavigating airplanes carried out by Hafele and Keating [19,20] in 1971, however, it was found that the ORS is the earth's polar axis or simply the rest frame of the earth's center of mass (ECM).

The value of Q can therefore be obtained by combining the UTDL with eq. (9).

$$Q = \gamma (v') / \gamma (v). \quad [11]$$

In this equation it is critical to distinguish between the observer, who is located in rest frame S, and the object of the measurement, which is located in rest frame S'. A useful way to look upon Q is as a conversion factor between the unit of time in S' and that in S. In other words, the time difference $\Delta t'$ is converted to the corresponding value Δt in the unit employed in S by multiplying it with Q, i.e. $\Delta t = Q \, \Delta t'$, consistent with eq. (9). In the following, eq. (9) will be referred to as *Newtonian Simultaneity*, in recognition of the longstanding view of Newton and colleagues that events in one rest frame occur simultaneously in any other. The conversion factor Q' to be employed by an observer at rest in S' is the reciprocal of that employed by the stationary observer located in S. This reciprocal relationship between conversion factors is the same as used in everyday life. For example, the conversion factor in going from m to cm is 100, whereas the corresponding factor in going from cm to m is 1/100 = 0.01.

V. The Newton-Voigt Transformation

In order to construct a viable relativistic space-time transformation, it is first and foremost necessary to eliminate the internal consistencies of the LT. More positively, it is important to ensure that the Law of Causality is faithfully obeyed in the equations. In addition, the transformation must be consistent with Galileo's RP. It also must provide a straightforward description of the various experiments such as Fresnel-Fizeau light damping which indicate that the speed of light in free space is the same for all observers. Each of these objectives can be attained by combining the RVT with the Newton Simultaneity relation of eq, (9).

In order to demonstrate that the transformation is consistent with the RP, it is necessary to show that the application of Galilean Inversion leads directly to the corresponding inverse transformation. This is guaranteed in the case of the RVT because of the identity relationship [22]:

$$\eta \eta' = \gamma^2 \quad (12)$$

(the definition of η is given before the LT eqs. (4a-d) and η' is related to η by application of Galilean Inversion). As already discussed, the parameter Q' in the inverse transformation of eq. (9) must be equal to 1/Q. Consistency with the experiments indicating that the speed of light is the same for both observers is guaranteed by the inclusion of the RVT of eqs. (8a-c):

The resulting transformation is referred to as the Newton-Voigt transformation (NVT):

$$\Delta t' = \Delta t/Q \qquad (13a, 8))$$

$$\Delta x' = (\eta/Q)(\Delta x - v\Delta t) \qquad (13b)$$

$$\Delta y' = (\eta/\gamma Q)\Delta y \qquad (13c)$$

$$\Delta z' = (\eta/\gamma Q)\Delta z \qquad (13d)$$

Newtoinian Simultaneity is included explicitly in eq. (13a). The three spatial equations are obtained by "melding" the respective RVT eqs. (8a-c) with eq. (9); for example, eq, (8a) is multiplied with Δt' on the left-hand side and by Δt/Q on the right-hand side to obtain eq, (13b) of the NVT, i.e. $\Delta x' = u_x'\Delta t' = \eta (u_x - v)\Delta t/Q = (\eta/Q)(\Delta x - v\Delta t)$.

If the following linear combination of the squares of the primed quantities in the NVT is formed, the result is:

$$\Delta x'^2 + \Delta y'^2 + z'^2 - c^2 \Delta t'^2 = (\eta/\gamma Q)^2(\Delta x^2 + \Delta y^2 + z^2 - c^2 \Delta t^2) \quad (14)$$

If the speed of the object/ light pulseis equal to c on the left-hand side of eq. (14), it must also be equal to c on the right-hand side, consistent with the equal light-speed condition imposed by the NVT. If eq. (9) is applied for the two elapsed time values, it follows that the spatial values must conform to the analogous proportionality relations ships, i.e.

$$\Delta x' = \Delta x/Q \quad (15a)$$

$$\Delta y' = \Delta y/Q \quad (15b)$$

$$\Delta z' = \Delta z/Q, \quad (15c)$$

in order for the equality to be maintained for any direction of the light pulse. Another way of expressing this condition on the spatial variables is to say that the unit of distance in all three directions varies in the same proportion as for time. In other words, time dilation is accompanied by distance expansion, and by the same fraction in all three directions, not the asymmetric contraction implied by the FLC of the LT.

An analogous relation holds for the LT, with the constant on the left-hand side being replaced by a value of unity. The same situation holds for the VT eqs. (3a-d), in which case the aforementioned constant has a value of γ^{-2}. Thus, the condition of equal scaling of the spatial and time coordinates is seen to be the consequence of the light-speed condition. The fact that the FLC and TD relations of eqs.(5,6) can be derived from the LT is thus just another example of the inconsistency inherent in the LT equations, The deficiency is removed for the NVT by the imposition of Newtonian Simultaneity, i.e. eq. (9), in its definition.

As mentioned above, Einstein's version of the light-speed postulate [LSP] is not viable [9,10]. In order to provide a satisfactory explanation of the various experimental results which indicate that the speed of light is the same for all observers {1, 10, 11], it is sufficient to assume instead that the speed of light in free space relative to its source is always equal to c. At the same time, it is clear that this can only be the case if the unit of velocity/speed is the same in all rest frames. It would be inconsistent with the RP if two observers measured different values for the relative speed of two objects and could thereby distinguish between their respective states of motion on this basis. This condition also leads to the conclusion that the unit of distance must vary in the same manner as elapsed time, i.e. in accord with eqs. (15a-c), since only in this way is it possible for the unit of speed to be the same in both rest frames.

Experiment [24] has shown that inertial mass scales in the same manner as time. As a result, the conversion factor is Q for all three fundamental quantities, distance, time and inertial mass. The corresponding values for all other physical properties are therefore integral multiples of Q. The value of the corresponding exponent can be obtained on the basis of its composition in terms of these three quantities. This is the basis for the Uniform Scaling method, details of which are given in Ref. [25]/

It is important to see that there are other experiments which are not consistent with the RVT. The same argument which proves that the LSP is invalid [9,10] also shows that two observers in relative motion to one another must disagree on the value of the light speed emitted from a given source [23]. In this case the GVT, which is equivalent to vector addition of velocities, needs to be applied in order to successfully predict the relationship between the different values of the light speed measured by the two observers. Each of the examples considered above in which the RVT successfully predicts that the speed of light is the same in two different rest frames *involves only a single observer* whose measurements are carried out *under different circumstances*. For example, in the example of the Fresnel-Fizeau light damping experiment [1,12], the measurement is carried out in one case while the liquid is flowing through the apparatus at speed v relative to the laboratory , whereas the other value is obtained while the liquid is stationary. The ranges of application for the RVT and GVT are thus seen to be mutually exclusive [23].

VI. Conclusion

The history of the Lorentz transformation begins with the suggestion by Voigt in 1887 that the results of experiments such as Fresnel-Fizeau light damping and the Michelson-Morley null interference study might be explained by amending the classical Galilean transformation to include a term which mixes the spatial and time coordinates. The space-time transformation (VT) he derived is not consistent with Galileo's Relativity Principle, however. Larmor and Lorentz independently eliminated this problem while still satisfying the equal-velocity condition by multiplying each of the latter equations on the right-hand side with a factor of γ (v). The resulting set of space-time equations has come to be known as the Lorentz transformation (LT).

At this point, both FitzGerald and Lorentz noted that the LT is consistent with the asymmetric length contraction relationship (FLC) shown in eq. (5).

Einstein came to the same conclusion in his 1905 paper, but he also showed that the LT indicates that there is also a time dilation effect (TD), whereby a moving clock always runs slower than its stationary counterpart. In spite of the positive effects this conclusion has had on future scientific investigations, it nonetheless serves as proof that the LT is not a viable transformation. It claims that an observer will measure a shorter distance traveled by a light pulse in another rest frame, while at the same time obtaining a greater elapsed time for the same event. This prediction stands in clear contradiction to the underlying hypothesis of the LT, however, namely that both observers must measure the same speed for the light pulse, i.e. the same ratio of distance to time. The LT is therefore not internally consistent and must be eliminated from consideration as a physically valid space-time transformation.

Both the VT and LT derivations ignore a basic point about the clocks employed to measure elapsed times in the two rest frames. Both clocks are assume to be freely moving/inertial and therefore are characterized by rates that remain constant indefinitely. This relationship amounts to a corollary to Newton's First Law of Motion and is necessary in order to be consistent with the Law of Causality. Consequently, the elapsed times for a given event measured using the two clocks must always occur in the same ratio, i.e. $\Delta t' = \Delta t/Q$, where Q is the value of the clock-rate ratio. The latter equation is referred to as Newtonian Simultaneity in recognition of the fact that it requires that all events must occur simultaneously for all observers, i.e, $\Delta t=0$ implies that $\Delta t'=0$ as well. Newtonian Simultaneity is clearly at odds with the space-time mixing claimed on the basis of the LT.

The true relativistic transformation must be consistent with the Law of Causality as well as satisfying the RP. The Newton-Voigt transformation (NVT) of eqs. (13a-d) satisfies both requirements and is also consistent with the RVT, since the latter is obtained from it by the usual procedure of equating the velocities measured for a given object to the ratios of the respective values for distances and times, i.e. $u_x = \Delta x/\Delta t$ etc. in eqs. (2a-c). The parameter Q can best be seen as the conversion factor between the elapsed times for a given event obtained by the two observers. The Uniform Scaling method assumes that the same conversion factor applies for the respective measurements of distance and inertial mass. The conversion factors for all other physical quantities such as energy and linear momentum can be obtained as integral multiples of

Q on the basis of their compositions in terms of the latter three fundamental quantities. Consistent with this interpretation is the fact that the corresponding factor for the reverse conversion is always the reciprocal of that in the forward direction, e.g. Q'=1/Q. This relationship is consistent with what is known for other conversion factors commonly employed in everyday life, such as between m and cm and dollars and cents. Finally, it is found that the application of these conversion factors always maintains the various laws of physics implied in the RP definition.

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