On the theory of flat spacetime

M. Sultan Parvez

Louisiana State University at Alexandria,
Department of Math and Physical Sciences, Alexandria, LA 71302

Abstract

Special relativity turns out to be more than coordinate transformations in which the constancy of the speed of light plays the central role between two inertial reference frames. Special relativity, in essence, is a theory of four-dimensional flat spacetime. Euclidean space spans three of the spacetime’s dimensions and time spans the fourth. Properties of light may not be needed to describe spacetime, which exists independently of light. The article shows that a theory of spacetime can be constructed from a geometric viewpoint in which the speed of light does not play any role. Moreover postulating four-dimensional geometry significantly simplifies the concept of special relativity.

I. INTRODUCTION

Einstein published his famous paper on the theory of special relativity over one hundred years ago. Although there has been much work on this field of study, discussion and debate remains alive.

Special relativity (SR) was born out of conflicts in the late 19th century between Maxwell’s electrodynamics and Newtonian mechanics. Solutions to Maxwell’s equations in free space are electromagnetic waves with a fixed speed, \( c = 1/\sqrt{\varepsilon_0 \mu_0} \), which obviously contradicted with the requirement of a medium for a wave and Galilean transformations of Newtonian mechanics.

At first, physicists thought that the problem was with Maxwell’s equations. Attempts to modify Maxwell’s equations to make them invariant under the Galilean transformations, however, ended in failure. Such modifications led to the prediction of new electrical phenomena, which could not be found experimentally.

Then in 1903 Lorentz made a remarkable discovery. He found that when he applied the Lorentz transformation of coordinates and time (Equation (21)), to Maxwell’s equations, the equations remained invariant.

Maxwell’s equations were only thought to express electromagnetism in the rest frame of ether, the postulated medium for light. When the Michelson-Morley experiment produced a null result for the change of the velocity of light due to the Earth’s hypothesized motion through the ether, an expla-
nation was provided by Lorentz and others that ether remains undetected because length in the direction of motion is contracted and time is dilated. This apparently solved the conflicts between Maxwell’s electrodynamics and Newtonian mechanics, but the physical meaning of the origin of the Lorentz transformations remained unexplained.

In 1905 Einstein sought an alternate explanation. Einstein’s paper *On The Electrodynamics of Moving Bodies* demonstrated that two simple postulates, viz., (i) the equivalence of inertial frames, and (ii) the invariance of the speed of light, can resolve all the asymmetries that arise when Maxwell’s electrodynamics are applied to moving objects. The paper showed that an introduction of ether is unnecessary for the transformation of the set of coordinates of an event into another inertial frame’s set of coordinates in a consistent theory of the electrodynamics of moving bodies. The absence of ether also conformed with the result that ether cannot be detected experimentally. Although Lorentz transformations, time dilation, and length contraction are derived in detail, the paper did not mention anything about the union of space and time. Einstein used the constant speed light signal as the sole means of communication in all experiments and the sole means of interpretation of all gedanken experiments.

Minkowski, in 1908, greatly enhanced Einstein’s work. The most significant feature of his paper is the existence of the invariance of four-dimensional interval and the invariance of other physical quantities in 4-dimensional form. This new formulation gave rise to the concept of spacetime as we know today. In this new formulation the Lorentz Transformation appears to be merely a rotation in the complex co-ordinate system \((t, x, y, z)\).

At first Einstein was skeptical of Minkowski’s work. Einstein believed that Minkowski was merely rewriting the laws of special relativity in a new mathematical language and that the abstract mathematics obscured the underlying physics. However, Einstein changed his mind and used 4-dimensional spacetime to develop the general theory of relativity.

Although 4D spacetime is the underlying foundation of the general theory of relativity, SR is customarily introduced with Einstein’s postulates as the consequences of the measurements of the constant speed of light without referring to spacetime geometry. For these reasons novices of SR often incorrectly conclude that the finite speed of light creates an illusion in the measurement of distance and time, and that if signals other than light can be used as the means of communication, the Lorentz contraction and time dilation would disappear.
In general relativity the bending of light rays was explained by the curvature of spacetime. On the other hand, the second postulate in SR lacks a logical foundation, unlike the self-explanatory first postulate. Although constancy of speed of light is supported by experiments (e.g., the Michelson-Morley experiment), it was not supported by sound logical arguments. The uncomfortableness with the second postulate is almost as old as the postulate itself.

A student of SR rightfully suspects the result of Michaelson-Morley experiment and its interpretation. Certainly an experiment can alter the result of a previous experiment, and interpretations of experiments can also differ.

We attempt here to reconstruct a version of SR using a geometrical point of view of spacetime without using light. If spacetime exists independent of light, a description of spacetime should not depend exclusively on light.

II. THE NEW POSTULATE

Obviously the first thing to do to remove the role played by the light in SR is to replace the second postulate. This can be done by an alternate postulate as follows: Space and time form a 4-dimensional continuum with time being the fourth dimension extension of 3D Euclidean space, and all nonaccelerating reference frames are equivalent. The association of light is eliminated from the postulates of SR and is replaced with spacetime geometry.

Since the proposed postulate is an extension of 3-D space, it is logically comprehensible and is less intrusive as postulating the original second postulate. The space coordinates and time are also found to have the same status in the wave equations in mechanics and electrodynamics.

III. DEPICTION OF SPACETIME AND SCALING THE TIME AXIS

Historically time and space are measured in two different units. Most importantly we have to use two different types of instruments to measure them. A stationary ruler cannot be used to measure time, nor can a clock be used to measure distance. Our postulate of 4D spacetime demands that the time measurement and the distance measurement must be related. Drawing a coordinate system of the spacetime could resolve this and many other issues. Since we proposed that time is another dimension in spacetime, we have a situation in which time can be represented by an axis perpendicular to all three space axes.
A 2D-slice of the spacetime can be depicted, as is done customarily, by plotting a reference frame with time, \( t \), along the vertical and \( x \) axis only of the space along the horizontal. Similarly a diagram of 3D-slice of the spacetime can also be constructed by adding the \( y \) axis along the horizontal. A diagram of the whole spacetime, however, is impossible.

Again, as is customary, a point in the spacetime diagram represents an event, and a line represents a world line of a particle moving with a speed \( v \), where,

\[
v = \frac{dx}{dt} = \frac{1}{dt/dx} = \text{slope of the line}
\]

In spacetime diagram, time is another dimension. How are time and space scales related in a spacetime diagram? The time unit and distance unit must be proportional to each other, i.e.,

\[
|\Delta \hat{t}| = \frac{1}{c} |\Delta \hat{r}|
\]

where \( \Delta \hat{t} \) is the unit time separation in the 4D spacetime and \( \Delta \hat{r} \) is a unit distance in the 3D Euclidian space. \( c \) is the constant of proportionality between space and time units, and is also known as the spacetime conversion factor. Equation (1) should be valid in all nonaccelerating reference frames; otherwise, the reference frames would not be equivalent. Equation (1) is the universal relation between time and space. \( c \) is a frame independent universal constant.

Equation (1) can be used to define a new unit of time in terms of a conventional unit of distance (or it can also be used to define a new unit of distance in terms of a conventional unit of time):

\[
|\Delta \hat{t}| = \frac{1}{c} \times 1.0 \text{ meter}
\]

It is customary in this type of situation to set the conversion factor or the proportionality constant \( c \) to 1 to make Equation (2) the defining equation for a new unit of time. Since we have chosen \( c \) to be unitless, this new unit of time is meter.

Using the relation, \((\Delta \hat{r})^2 = (\Delta x_{\hat{r}})^2 + (\Delta y_{\hat{r}})^2 + (\Delta z_{\hat{r}})^2\) of Euclidian geometry, we get from Equation (1),

\[
(\Delta \hat{t})^2 = (\Delta x_{\hat{r}})^2 + (\Delta y_{\hat{r}})^2 + (\Delta z_{\hat{r}})^2
\]

assuming space is isotropic. \( \Delta x_{\hat{r}}, \Delta y_{\hat{r}}, \) and \( \Delta z_{\hat{r}} \) are the magnitudes of three components of a unit vector \( \Delta \hat{r} \). There is a set of values for \( \Delta x_{\hat{r}}, \Delta y_{\hat{r}}, \) and \( \Delta z_{\hat{r}} \) to satisfy Equation (3). Similarly in another inertial frame, \( S' \), moving with some speed with respect to frame \( S \),

\[
(\Delta \hat{t})^2 = (\Delta x'_{\hat{r}})^2 + (\Delta y'_{\hat{r}})^2 + (\Delta z'_{\hat{r}})^2
\]

Since it is impossible to draw and work with a 4D diagram, it is instructive to work
with the special case of the 2D slice—the $t$-$x$ plane—of the 4D-spacetime and then generalize the work to the 4D case. In the $t$-$x$ plane Equation (3) reduces to

$$|\Delta  \hat{t}| = |\Delta  \hat{x}|$$

(5)

Similarly in the frame $S'$, we get from Equation (4),

$$|\Delta \hat{t}'| = |\Delta \hat{x}'|$$

(6)

In actual spacetime there is no coordinate system, let alone a preferred coordinate system. There are only events. To calibrate their time scale, observers must rely on special events whose time and space separations are identified as equal. That means there are two things the observer has to consider: 1) The same set of events must be used by all observers for calibration of their time axis or to determine the spacetime conversion factor; and 2) These events must be a special set of events, such that the ratio of the space separation to the time separation of any of these events is same in all frames.

The scaling equations, Equations (5) and (6), tell more than just how to plot the time scale compared to the space scale. An equivalent expression to Equation (5) can be written as

$$\Delta t_0 = \Delta x_0$$

(7)

where $\Delta t_0$ can be written as $|\Delta \hat{t}|s$, $s$ is a real number. Similarly $\Delta x_0$ can be written as $|\Delta \hat{x}|s$. Only a set of events’ time and space coordinates in a reference frame satisfy Equation (7). In the $t$-$x$ plane the locus of those special events is the straight line making 45° with $x$-axis. The special events that satisfy Equation (7) can be used to calibrate a clock or to determine the spacetime conversion factor $c$. Observers must agree on the special events and all observers must use the same events to calibrate their time axis or determine the spacetime conversion factor. This is the only way the time axis can be calibrated. Otherwise, if two observers have their own set of special events that differ and calibrate their time axes differently or determine different values of the spacetime conversion factor, then the transformation of coordinates of an event from one frame to another would be meaningless. If an observer identifies an event as a special event, it must also be a special event in all other frames.

The scaling equation also describes two other types of events: (1) the events for which their time coordinates $\Delta t$ are greater than their space coordinates $\Delta x$, known as timelike events, and (2) the events for which their space coordinates $\Delta x$ are greater than their time coordinates $\Delta t$, known as spacelike events. Although the special events are otherwise known as lightlike events, we will call them special events here and put a subscript “0” to distinguish them from other events.
The implication of Equation (7) is that two events that have equal time and space separations will also have equal time and space separations in all other inertial reference frames. That is,

\[ \Delta t_0 = \Delta x_0 = \Delta t'_0 = \Delta x'_0 \]  

(8)

Measuring from the origin, (Measuring coordinates of a given event means measuring with respect to an event at the origin. Referencing coordinates of a given event always implies dealing with two events—the given event and the event origin.) the set of special events \( \{ \Delta t_0, \Delta x_0 \} \) that satisfies Equation (7) have equal time and space separation and forms a straight line in the \( t-x \) plane with slope 1 (see Figure 1). We will call this line the special line.

![FIG. 1: The \( t-x \) plane of the spacetime diagram showing the special line and a special event.](image)

Also note that the set of special events \( \{ \Delta t_0, \Delta x_0 \} \) is the locus of the coordinates of a moving object with a velocity of one (or \( c \) in conventional unit). Such objects will also move with the same speed in all other reference frames. Therefore a speed of 1 is an invariant speed.

Suppose an observer \( S \) uses the coordinates \( t \) and \( x \) as above and that another observer \( S' \), with coordinates \( t' \) and \( x' \) is moving along the positive \( x \) direction of \( S \) with a velocity \( v \). Suppose again that the two events 1 and 2 are recorded as \( (t'_0, 0) \) and \( (0, x'_0) \), respectively in frame \( S' \). The subscript 0 again means that the time separation and the space separation between the two events are same, i.e.,

\[ |0 - t'_0| = |x'_0 - 0| \]  

(9)

How do these two events look from \( S \)?

The \( t' \) axis is the world line of a particle at rest at \( x' = 0 \) with respect to \( S' \). The world line of the same particle in \( S \) will be a straight line with a slope of \( 1/v \). The \( t' \) axis looks like that shown in Figure 2. Event 1 is somewhere on the \( t' \) axis as in the Figure 2 with coordinates \( (t_{10}, x_{10}) \).

Since events 1 and 2 satisfy Equation (9) in frame \( S' \), in frame \( S \) they will also satisfy,

\[ |t_{20} - t_{10}| = |x_{20} - x_{10}| \]  

(10)

From the point of view of \( S \), \( \Delta t_0 \) represents the measurement of the time interval between events \( (t_{20}, x_{20}) \) and \( (t_{10}, x_{10}) \), and \( \Delta x_0 \) represents the space interval between the same
two events. Event 2 \((t_{20}, x_{20})\) which satisfies Equation (10) is shown in Figure 2. To keep the value of spacetime conversion factor the same and the time and space interval equal in the frame S, the \(x'\)-axis must be a line with a slope of \(v\) in the frame S. It is clear that the simultaneous events \((x'\)-axis\) in frame \(S'\) are not simultaneous in frame S.

\section*{IV. THE SPACETIME METRIC}

Our postulate that space and time form a 4D continuum demands that space-time separations must have an invariant relation under changes of coordinates. Otherwise space and time would be two separate entities. As a matter of fact, the existence of a spacetime metric equation is the necessary and sufficient condition for the spacetime to be a 4D continuum.

We assign three dimensions \((x, y, z)\) to space because the distance \(d^2 = \Delta x^2 + \Delta y^2 + \Delta z^2\) between two points in space is invariant under rotation or translation of coordinates. We know that the 4D Euclidean metric equation, \(\Delta d_1^2 = \Delta t^2 + \Delta x^2 + \Delta y^2 + \Delta z^2\), between two events in spacetime does not remain invariant under changes of coordinates between two inertial reference frames.

Consider two inertial reference frames, S with coordinates \((t, x, y, z)\) and \(S'\) with coordinates \((t', x', y', z')\), with \(S'\) moving at a constant speed \(v\) relative to S along the direction of the positive \(x\) axis. Let \(x\) and \(x'\) axes coincide along the direction of relative motion. Let the coincidence of the origins of S and \(S'\) be event 1. Event 1 can be recorded in both frames as \((t_1 = x_1 = y_1 = z_1 = 0)\) and \((t'_1 = x'_1 = y'_1 = z'_1 = 0)\) according to the standard configuration. Suppose another event 2 is recorded in frame \(S'\) as \((t'_2, 0, 0, 0)\) as shown in the Figure 3. How would the time separation \(\Delta t' = t'_2 - t'_1 = t'_2 - 0\) be recorded in the frame S?

We shall use the properties of the special coordinates of spacetime and of the Pythagorean relation of space coordinates to examine how the separation between two events transforms in another frame of refer-
Consider a special event $Q_0(t'_0, 0, y'_0, 0)$ simultaneous to event 2 in frame $S'$ as shown in the Figure 3. Because $Q_0$ is a special event, its time separation and space separation are equal,

$$\Delta t' = t'_0 = y'_0 = \Delta y'$$

(11)

where $\Delta y' = y'_0 - y'_1$, and, of course $y'_1 = 0$.

Now let us look at the events 1, 2 and $Q_0$ in the spacetime diagram of $S$. Event 1 is on the origin of frame $S$. Event 2 is on the $t'$ axis and will have coordinates $(t_2, x_2 = vt_2, 0, 0)$ as shown in the Figure 4. Event $Q_0$ has the coordinates $(t_0 = t_2, x_0 = vt_2, y_0 = y'_0, 0)$ in frame $S$ as shown in the Figure 4. Because $Q_0$ is a special event, its time separation and space separation are equal,

$$(t_0 - t_1)^2 = (x_0 - x_1)^2 + (y_0 - y_1)^2$$

or,

$$\Delta t^2 = \Delta x^2 + \Delta y^2$$

(12)

where $\Delta t = (t_0 - t_1) = (t_2 - t_1)$, $\Delta x = (x_0 - x_1)$, and $\Delta y = (y_0 - y_1)$. Now $\Delta y$ and $\Delta y'$ are equal. Combining Equations (11) and (12) we get,

$$\Delta t'^2 = \Delta t^2 - \Delta x^2$$

(13)

Similarly in another frame $S''$,

$$\Delta t''^2 = \Delta t'^2 - \Delta x''^2$$

(14)

So, the separation of coordinates of two events measured from two inertial frames moving in the $x$ direction with respect to each other is related by,

$$\Delta t^2 - \Delta x^2 = \Delta t'^2 - \Delta x'^2$$

(15)

Generalizing Equation (13) in 4D spacetime, the space and time separations between two events observed in two inertial frames must obey,

$$(\Delta t')^2 - (\Delta x')^2 + (\Delta y')^2 + (\Delta z')^2 = (\Delta t)^2 - (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2$$

(16)
Equation (16) prompted us to define the invariant interval between any two events that are separated by coordinate increments \((\Delta t, \Delta x, \Delta y, \Delta z)\) as

\[
\Delta s^2 = (\Delta t)^2 - (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2 \quad (17)
\]

Equation (17) can be verified by calculating intervals in two different frames.

V. THE LORENTZ TRANSFORMATIONS

The Lorentz transformations can be deduced from the spacetime metric equation (17).

The Lorentz transformations can actually be derived in a variety of ways.\(^8\) For example, the original derivation\(^1\) of the transformation by Lorentz occurred prior to the theory of special relativity and did not use the postulates of relativity at all. Lorentz used the negative result of the Michelson-Morley experiment and the field equation of Maxwell to derive length contraction.

The derivation of the Lorentz transformation from the invariance of interval can also be found in many books.\(^4\) The derivation has been included here for a review and for the completeness of the topic.

The Lorentz transformation expresses the coordinates of \(S'\), which moves with speed \(v\) on the positive \(x\)-axis relative to \(S\), in terms of the coordinates of \(S\). The lengths perpendicular to the \(x\)-axis are the same when measured by \(S\) or \(S'\). The most general linear transformation, then, is

\[
t' = \gamma t + \beta x \quad (18a)
\]
\[
x' = \alpha t + \sigma x \quad (18b)
\]
\[
y' = y \quad (18c)
\]
\[
z' = z \quad (18d)
\]

\(\gamma, \beta, \alpha, \) and \(\sigma\) are at most a function of \(v\).

From the considerations of the inertial frames alone, one can easily show\(^1\) that

\[
\sigma = \gamma \quad (19)
\]

and

\[
\frac{\alpha}{\sigma} = \frac{\beta}{\gamma} = -v \quad (20)
\]

Therefore the transformation equations (18a) and (18b) become,

\[
t' = \gamma(t - vx) \quad (21)
\]
\[
x' = \gamma(x - vt) \quad (22)
\]

Now comes the most important part of the derivation: using the invariance of the interval. Substituting Equations (21) and (22) in (17) and after some straightforward calculations, one gets,

\[
\gamma = \pm \frac{1}{\sqrt{1 - v^2}} \quad (23)
\]

The + sign is the proper choice in the above equation to avoid an inversion of the coordinates.
Therefore, the complete Lorentz transformations is,

\[
\begin{align*}
 t' & = \frac{t - vx}{\sqrt{1 - v^2}} \\
x' & = \frac{x - vt}{\sqrt{1 - v^2}} \\
y' & = y \\
z' & = z 
\end{align*}
\]

(24a) (24b) (24c) (24d)

VI. DETERMINATION OF THE SPACETIME CONVERSION FACTOR

Determination of \(c\) using any equation and method of special relativity—from the point of view of 4D-spacetime geometry—will give the value of the spacetime conversion factor and not the speed of light. For example if we use a \(K\) meson decay data in laboratory frame and rest frame to determine \(c\) using Equation (17), the value of \(c\) thus obtained would be the value of the spacetime conversion factor and not of the speed of light. For example if we use a \(K\) meson decay data in laboratory frame and rest frame to determine \(c\) using Equation (17), the value of \(c\) thus obtained would be the value of the spacetime conversion factor and not of the speed of light. For example if we use a \(K\) meson decay data in laboratory frame and rest frame to determine \(c\) using Equation (17), the value of \(c\) thus obtained would be the value of the spacetime conversion factor and not of the speed of light.

Another way to determine the value of the spacetime factor would be from the measurements of the speed of a moving object from two different reference frames and by using the velocity addition formula. A third way would be using Equation (7) and identifying the special events. Suppose when several reference frames coincide, a firecracker explodes at the origin. Suppose in one frame at a distance of 1.0 m, another firecracker explodes at the time of 3.34 ns (1/c seconds, \(c\) in m/s).

These two events would be special events, and the special events in one frame means one has special events in all frames. Measuring their space and time coordinates and using Equation (7), all observers can determine the spacetime conversion factor. In practice, a number of firecrackers must explode at different times and the set which gives the same value of the ratio of space to time coordinates would be identified as the special events.

None of the above mentioned methods uses light. Would it not be interesting to compare the results thus obtained with the speed of light? Also, to date, the accuracy of the above methods does not match the accuracy of determining the speed of light.

How do the spacetime conversion factor and the speed of light differ? In spacetime, light signals produce events whose time and space coordinates are equally separated. All observers see them equally separated. Measuring the coordinates of these events and taking the ratio to determine the spacetime conversion factor is essentially the same as measuring the speed of light! Conversely, we realize that the trail of events produced by light are the special events from the measurement that the speed of light is the same in all reference frame. The only connection we can see between the speed of light and the spacetime conversion factor is that if an object’s time and space coordinates sat-
ify Equation (7), then the object is moving with the speed $c$ and that speed will be the same for all reference frames. The fact that the speed of light is a constant speed for all observers—as measured in the Michelson-Morley experiment—confirms that light produces special events. Therefore, the speed of light and the spacetime conversion factor should not have different values.

VII. RESULTS AND DISCUSSION

According to Einstein’s (the traditional view of the special relativity theory) point of view, the constancy of the speed of light has the status of a law of nature, and the Lorentz transformations are required to keep the speed of light constant. Space contraction, time dilation, and time desynchronization follow as a logical necessity from the empirical fact of the constancy of the speed of light. There is no way to reason from the knowledge of space and time itself that space contraction and time dilation and desynchronization can take place.

Spacetime geometry, on the other hand, can explain all the counter intuitive notions of special relativity including the constancy of the speed of light. First of all, there is no prefered reference frame because there are no reference frames in spacetime, but rather only events. We artificially construct reference frames for the convenience of making measurements and keeping records, and equivalent reference frames are the best we can construct! There are three types of events. Events that are time-like are time-like to all equivalent observers. Events that are space-like are space-like to all equivalent observers. Events that are special are special to all equivalent observers.

It is the defective construction of the reference frames that creates the “illusion” of the length contraction, time dilation, time desynchronization, and a finite constant speed of light in our measurements. If a reference frame measures the proper time between two events, that reference frame cannot measure the proper distance between those events. Similarly an observer who can measure the proper distance between two events cannot measure the proper time between those events. Consider the example of atmospheric muons. The half life of a muon is 1.5 $\mu$s in its rest frame. A fraction 1/8 of the muons—created at 60 km above Earth and coming vertically down—survive at sea level. Proper time between the event of creation of the muons and the event of muons reaching sea level can be measured from the muon’s rest frame. This proper time is 4.5 $\mu$s ($1.5 \mu$s $\times 3$). From the muon’s rest frame, the proper distance between these two events cannot be measured. But proper distance between the
events can be measured from Earth and is 60 km. Now we can combine these two reference frames to construct a hypothetical reference frame by plotting the proper time versus the proper distance of the events, similar to constructing a vector from two orthogonal vectors. Let us call this hypothetical frame the proper frame. Now if we define a hypothetical “proper speed” by dividing the proper distance by proper time, this proper speed doesn’t always have to be less than the conventional speed of light. As a matter of fact, the proper speed of the atmospheric muons is $1.3 \times 10^{10}$ m/s, over forty times faster than the conventional speed of light! There is no length contraction or time dilation in the proper reference frame. It is our inability to construct such a proper reference frame that produces all of the counterintuitive measurement results. At low speed the measurement of the coordinate time and distance have values close to the proper time and proper distance, hence at low speed, a reference frame resembles a proper reference frame.

VIII. CONCLUSION

The theory of special relativity can be simplified conceptually by a postulate of four dimensional spacetime. The four dimensional spacetime postulate provides a geometrical view of space-time, a better logical foundation, and a consistent picture with the theory of general relativity. With this geometrical picture, one can make a transition from general relativity to special relativity by simply setting the spacetime curvature equal to zero. All of the counterintuitive notions, including the frame independence of the speed of light, appear as consequences of the postulate.

In this geometrical picture of space-time, the metric equation, not the Lorentz transformation equations, is the most important equation and the most important concept.

* Electronic address: sparvez@lsua.edu

1 A. Einstein, “Zur Elektrodynamik bewegter Körper,” Annalen der Physik 17, 891–921 (1905).

2 See S. E. Whittaker, A History of the Theories of Aether and Electricity, 2 volumes, (Harper Torchbook edition, 1960).

3 See Albert Einstein and others, The Principle of Relativity (Dover Publications, June 1, 1952).

4 Richard C. Tolman, “The Second Postulate of Relativity,” Phys. Rev. (Series I) 31, 26–40 (1910).

5 See W. Pauli, Theory of Relativity (Pergamon Press, 1958), p. 5–9.

6 For a good discussion on time measurement
see Charles W. Misner, Kip S. Thorne and John A. Wheeler, *Gravitation* (W. H. Freeman and Company, 1973), p. 23–28.

7 For a good discussion on the equivalence of time and space see Edwin F. Taylor and John Archibald Wheeler, *Spacetime Physics* (W. H. Freeman and Company, 2nd ed., 1992), p. 1–5.

8 R. Weinstock, “New approach to special relativity,” Am. J. Phys. **33**, 640–645 (1965).

9 A. R. Lee, T. M. Kalotas, “Lorentz transformations from the first postulate,” Am. J. Phys. **43**, 434–437 (1975).

10 J.-M. Lévy-Leblond, “One more derivation of the Lorentz transformation,” Am. J. Phys. **44**, 271–277 (1976).

11 H. M. Schwartz, “A simple new approach to the deduction of the Lorentz transformations,” Am. J. Phys. **53**, 1007–1008 (1985).

12 H. A. Lorentz, “Simplified theory of electrical and optical phenomena in moving systems,” Proc. Acad. Science Amsterdam **I**, 427–443 (1899).

13 H. A. Lorentz, “Electromagnetic phenomena in a system moving with any velocity less than that of light,” Proc. Acad. Science Amsterdam **IV**, 669–78 (1904).

14 See, for example, Bernard F. Schutz, *A First Course in General Relativity* (Cambridge University Press, UK, 2000), p. 24.

15 Nalini Easwar and Douglas A. MacIntire, “Study of the effect of relativistic time dilation on cosmic ray muon flux—An undergraduate modern physics experiment,” Am. J. Phys. **59**, 589–592 (1991).