On the Naturalness and Generality of the Relativity Principle

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Abstract

Special relativity theory postulates that the laws of physics are the same in all inertial frames of reference (the relativity postulate), and that the velocity of light in vacuum has the same value *c* in all inertial frames of reference (constancy of *c* postulate). We show, based on basic principles, that nature is endowed with symmetry with respect to its laws, such that the principle of relativity is a genuine property of nature, which is independent on the constant velocity of light, or on any other constant. We also show that the principle of relativity is associated with spatial *asymmetry*, such that the direction of relative motion matters. For frames of reference departing from each other, an observer in one frame will measure time and distance extension, with respect to the time and distance measured in the other frame, while for reference frames approaching each other, the same observer will measure time and distance contraction with respect to the same occurrence. No less important, we show that the principle of relativity is valid for *all* physical systems, independently of the type of information carrier utilized in the system, and is not specific to systems in which information between reference frames is transmitted by light, or other electromagnetic waves.

Keywords: relativity principle, special relativity, Lorentz invariance, Lorentz factor, symmetry.

Introduction

Special relativity theory (Einstein, 1905) postulates that 1) the laws of physics are the same in all inertial frames of reference (the principle of relativity); and 2) the velocity of light in vacuum has the same value *c* (= 299 792 458 m/s) in all inertial frames of reference (constancy of *c*).

The second axiom guarantees the consistency of the theory with the Lorentz invariance principle (Lorentz, 1904), stating that the laws of physics are invariant under a Lorentz transformation between the coordinates of two frames of reference, moving at constant velocity with respect to each other.

By postulating the constancy of the velocity of light in vacuum, Albert Einstein sought to reconcile the physics of moving bodies with electrodynamics. Mathematically, reliance on Lorentz transformation is represented in special relativity by the famous Lorentz factor, a fundamental element in the theory's departure from classical physics, and in its construction of a new relativistic physics of space and time.

The literature on the constancy of the speed of light, and its place in a general theory of physics, is too large to be reviewed here. Decent discussions of these issues can be found in several articles (see, e.g., Drory, 2015, 2016; Gao, 2017). On the experimental side, tests of the constancy of c are usually interpreted as lending support to the isotropy and constancy of the speed of light (see, e.g., Krisher, et al., 1990; Müller et al., 2003; Antonini, et al., 2005). Notwithstanding, almost everyone agrees that the constancy of c postulate is counterintuitive. When considering the relative motion between two cars traveling on a highway, we subtract or add velocities, depending on whether the two cars are traveling in the same or in opposite directions. Similarly, sound waves emitted from a moving source with respect to a detector are redshifted or blueshifted, according to Doppler's formula, depending on whether the waves' source is traveling away or toward the detector. So why are the photons, be it a particle or wave, an exception? In this respect, David Mermin asked rhetorically: "How can this be? How can there be a speed c with the property that if something moves with speed c then it must have the speed c in any inertial frame of reference? This fact—known as the constancy of the speed of light—is highly counterintuitive. Indeed, 'counterintuitive' is too weak a word. It seems downright impossible" (Mermin, 2005, p. 25). We also contend that there is no logical explanation for why light, whether it is conceived as corpuscle, wave, or both, behaves differently than other things known to us in the universe.

Notably, several attempts have been made to drop the constancy of light postulate of special relativity theory (see, e.g., Ignatowski, 1910; Torretti, 1983; Brown, 2005; Behera, 2003, 2007; Feigenbaum, 2008; for a comprehensive references list, see Gao, 2017). However, it has been recently argued that all the derivations of the Lorentz transformations from special relativity, without including its second postulate, are flowed, and that one must assume in the derivation the constancy of c postulate, just as was done by Einstein himself (Drory, 2015, 2016; Gao, 2017).

Another inconvenience with regard to the constancy of c postulate comes from the incoherency between the narrowness and specificity of this postulate and the overarching generality of the relativity postulate. While the first principle is universal in scope, the second is only a particular property of light, which has obvious electrodynamic origins in Maxwell's theory (Gao, 2017). Similarly, Mermin (1984) remarked that "relativity is not a branch of electromagnetism and the subject can be developed without any reference whatever to light" (Mermin, 1984, p. 119). In fact, Einstein himself admitted to some extent (Einstein, 1935) that juxtaposing the general law of relativity with the specific principle of constancy of c is an incoherent mixture (see Stachel, 1995).

In this short article, we avoid the question of the constancy of c (c.f., Albrecht & Magueijo, 1999; Magueijo & Smolin, 2002; Magueijo, 2003; Barrow, 1999) and focus on the first axiom of special relativity, i.e., the relativity postulate. We shall show that the symmetry in the laws of physics is guaranteed by nature itself. In other words, the relativity principle need not be postulated because it follows quite naturally from basic principles. If our claim holds true, then the first postulate of special relativity becomes redundant, and, consequently, the second axiom, which was introduced by Einstein to reconcile special relativity with the Lorentz invariance principle, becomes useless.

Furthermore, we shall demonstrate that the relativity of simultaneity principle, is also a genuine property of nature. More far reaching is our conclusion hereafter that the symmetry of the laws of nature, being embedded in nature itself, hold true for *all* systems of initially moving bodies, regardless of the velocity of the signal, which carries information from one frame to another, provided that the velocity of the information carrier is constant with respect to its source, and exceeds the relative velocities between the system's reference frames. This implies that the relativity principle is a general inherent property of nature and is independent of c or any other specific constant.

On the Naturalness of Relativity

To show that nature is inherently symmetric, with respect to its laws, consider two reference frames, $F \text{ and } F'$, moving with constant velocity v with respect to each other (see Fig. 1). A "stationary" observer in frame F defines events with

coordinates t, x, y, z. Another observer in F' defines events using the coordinates t', x', y', z'. For simplicity, assume that the coordinate axes in each frame are parallel (x is parallel and x', y to y', and z to z'), and that the two systems are synchronized, such that at $t = t' = 0$, $(x, y, z) = (x', y', z') = (0, 0, 0)$.
According to the Lorentz transformations, if an observer in F records an event t, x, y, z, then the observer in F' records, the same event with coordinates

$$t' = \gamma\,(\mathrm{t} - \frac{v\,x}{c^2}),$$
$$x' = \gamma\,(x - v\,t),$$
$$y' = y,$$
$$z' = z \qquad (1)$$

Where v is the relative velocity between the two frames of reference, c is the velocity of light in vacuum, and γ is the Lorentz factor defined as

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}}, \quad (\beta = \frac{v}{c}). \qquad (2)$$

By algebraically solving the equations in (1) for $(t,\ x,\ y,\ z)$ in terms of (t', x', y', z') or by physically writing the event's equations from the point of view of the observer in F, the resulting inverse Lorentz transformations are

$$t = \gamma\,(t' + \frac{v\,x}{c^2}),$$
$$\mathrm{x} = \gamma\,(x' + v\,t),$$
$$y\ = y',$$
$$z = z'\ . \qquad (3)$$

Because the positive direction of the x axis is arbitrary, the two sets of equations have an identical form.
This type of symmetry is claimed to necessary for achieving the desired symmetry of the laws of physics. In Special relativity theory, the second axiom concerning the constancy of c, is sufficient for producing the same type of symmetry, and Albert Einstein was the first to derive the Lorentz transformation based on his special relativity theory (see Drory, 2015, 2016; Gao, 2017).

However, as we shall show hereby, this type of symmetry is fundamentally different from the symmetry dictated by the basic laws of Nature. Consider the case in which a physical *occurrence* starts at the point of origin in F' at $t_1' = 0$, and lasts for a period of $\Delta t' = t_2' - t_1' = t' - 0 = t'$, as measured by an observer at the occurrence rest frame in F'. We use the term occurrence to denote a physical time-dependent process. By this we seek to differentiate it from the term "event", which in physics came to mean an occurrence that is sharply localized at a single point in space and instant of time. In this terminology, we speak here about a continuum of events on the time dimension.

In non-quantum systems, in which a possible entanglement between F and F' could be ignored, the observer at F has no way of knowing when the event at F' ended, unless information is sent to him from the observer at F' indicating the termination of the event. Such information could be sent by any type of information carrier as long as its velocity, V_c, exceeds the relative velocity v at which F' is departing from F, i.e., V_c should satisfy $V_c > v$. After t seconds for an observer in F, the reference frame F' will be at distance $x = v\ t$. Thus, the information about the termination of the physical occurrence will arrive to the observer at F with a delay of:

$$t_d = \frac{x}{V_c} = \frac{v\ t}{V_c}\ . \tag{4}$$

Thus, the termination time registered by the observer at F will be

$$t = t' + \frac{v\ t}{V_c}\ , \tag{5}$$

which could be written as

$$t = \frac{1}{1 - \frac{v}{V_c}}\ t' = \frac{1}{1-\beta}\ t'\ , \tag{6}$$

where $\beta = \frac{v}{V_c}$.

Derivation of the distance transformation, using the same method, is detailed in the appendix. The resulting transformation is

$$x = \frac{1+\beta}{1-\beta}\, x'. \tag{7}$$

To show that equations (6) and (7) are invariant with the frame of reference, consider the situation from the point of view of an observer in F', who observes an occurrence of duration Δt as measured in the occurrence's rest frame F. Because the relativity principle dictates that no inertial frame of reference is preferred to other inertial frames of reference, it follows directly that the transformations for time and distance, will read as follows:

$$t' = \frac{1}{1+\beta}\, t \tag{8}$$

and

$$x' = \frac{1-\beta}{1+\beta}\, x\ . \tag{9}$$

Which are identical to equations (6) and (7), for time and distance, respectively, except for the sing of β, which does not break the symmetry, since the positive direction of the x axis is arbitrary.

This result implies: (1) that basic laws of physics, are sufficient to preserve the symmetric of the laws of physics. (2) that the transformations of time and distance between two inertial frames, as dictated by the basic laws of nature, are fundamentally different from the Lorentz transformations. (3) that the emerging symmetry applies to all information carriers, and not restricted to light, as long as the information carrier is travels faster than v.

Notably, for $\beta \to 0$ ($v << V_c$), we obtain

$$t = \lim_{\beta \to 0} \frac{1}{1-\beta}\, t' = t', \tag{10}$$

and

$$x = \lim_{\beta \to 0} \frac{1}{1-\beta} \; x' = x', \tag{11}$$

thus restoring the classical Galilean relationships. It is worth noting that when our concern is how time intervals and lengths transform from one inertial frame of reference to another, no synchronization of clocks at the two reference frames is needed.

Relativity of Simultaneity

The relativity of simultaneity, extensively discussed in the literature about Special relativity theory (see e.g., Galison, 2003), is a major constituent of the departure of modern physics from Galileo–Newton's physics. Since light takes a finite time to traverse a distance in space, it is not possible to define simultaneity with respect to a universal clock shared by all observers. As an example, two events, which occur simultaneously at spatially separated points in space at one reference frame, will not be observed as simultaneous in another frame, moving with respect to the first.

In the example of two frames of reference moving with respect to each other, if two events e_1' and e_2' take place simultaneously at distances x_1' and x_2' ($x_2' > x_1'$) from the origin in F', then they cannot be recorded as taking place simultaneously by an observer in F, because the information about the occurrence of e_2' will take more time to reach an observer in F than the information about the occurrence of e_1'. Thus, our discovered symmetry does not violate the impossibility of simultaneity advocated by Poincaré, Einstein, and others (Poincaré, 1898–1913; 1900; Einstein, 1905).

Spatial Asymmetry

Interestingly, the symmetry of the time and distance transformations with respect to the choice of the system's coordinates is associated with an *asymmetry* with regard to the directionality of relative motion between the reference frames. As shown in equation (6), for $\beta > 0$ (i.e., for F and F' departing from each other), we have $t > t'$ (time extension), whereas for $\beta < 0$ (i.e., for F and F' approaching each other), we have $t < t'$ (time contraction). Similarly equation (7) reveals that, for $\beta > 0$ (i.e., for F and F' departing from each other), we have $x > x'$ (length extension), whereas for $\beta < 0$ (i.e., for F and F' approaching each other), we have $x < x'$ (length contraction). Also, it is pretty obvious, without making the necessary calculations, that simultaneity could occur *only* if the two events occur at the same point in F' $(i.e., x_1' = x_2')$.

Conclusions

The main conclusions from the above analysis can be summarized in the following points:

1. Nature is endowed with symmetry with respect to its laws. In other words, the principle of relativity is a genuine property of nature, and does not require any axiomatization.
2. The relativity of simultaneity is secured by nature as well.
3. The principles of relativity and the impossibility of simultaneity, being general inherent properties of nature, are independent of c or any other constant.
4. The symmetry dictated by the basic laws of nature, without putting any restrictions, is fundamentally different from the symmetry of the Lorentz transformations.
5. The principle of relativity is associated with spatial asymmetry, such that the direction of relative motion matters. For frames of reference departing from each other, an observer in one frame will measure time and distance extension, with respect to the time and distance measured in the other frame, while for reference frames approaching each other, the same observer will measure time and distance contraction with respect to the same occurrence.

Note that this asymmetry in direction fits well with the Doppler effect. Waves emitted by an approaching body suffer blueshift, while waves emitted by a receding body suffer redshift. Interestingly, the spatial asymmetry argued on the basis of our analysis echoes nicely with similar arguments raised by well-grounded research in chemistry and microbiology, which emphasizes the crucial role of asymmetry, or "chirality," in the creation and development of all living organisms, from amino acids to the human body (e.g., Wagnie're, 2007; Guijarro & Yus, 2008). This body of research further suggests that the source of all asymmetry in life is to be traced back to the physical asymmetry of the universe (see, e.g., Bock & Marsh, 1991; Borchers, Davis, & Gershwin, 2004). Such a view was succinctly expressed by Louis Pasteur, the celebrated chemist and microbiologist, who wrote that: "The universe is an asymmetrical entity. I am inclined to believe that life as it is manifested to us must be a function of the asymmetry of the universe or of the consequence of this fact" (quoted in Debré, 2000).

6. Finally, the principle of relativity applies to *all* physical systems, independently of the type of the information carrier, and is not specific to systems in which information between reference frames is transmitted by light or other electromagnetic waves. This result holds true provided that the velocity of the information carrier is constant relative to its source and exceeds the relative velocities between the system's reference frames.

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Appendix A

Derivation of the Length Transformation

To derive the distance transformation, consider the two reference frames F and F' in Figure A. Without loss of generality, assume that, when F and F' start distancing from each other, $t_1 = t_1{}' = 0$, and $x_1 = x_1{}' = 0$. Assume further that F' has on board a rod placed along its x' axis between the points $x' = 0$ and $x' = x'_2$ (see Figure A) and that the observer in F' uses his clock to measure the length of the rod (in its rest frame) and communicates his measurement to the observer in F. Assume that the information carrier from frame F' to frame F travels with constant velocity V_c (as measured in the source rest frame). To perform the measurement of the rod's length, at $t_1{}' = t_1 = 0$ a signal is sent from the rare end of the rod, i.e., from $x' = x'_2$ to the observer at the point of origin $x' = 0$.

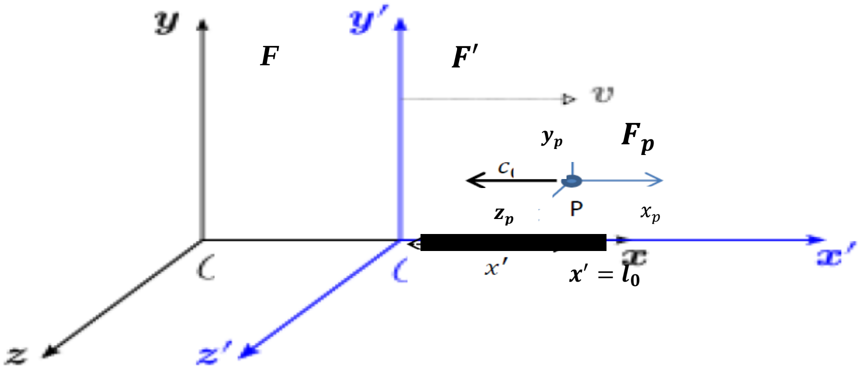

Figure A: Two observers in two reference frames, moving with velocity v with respect to each other.

If the signal arrives to the observer in F' at time $t' = t'_2$, then he or she can calculate the length of the rod as being

$$l_0 = x_2' = v\, t_2'. \tag{1a}$$

Denote by Δt_c is the time duration in the signal's rest frame for its arrival to the observer in F'. Using equation (6), t_2' as a function of Δt_c can be expressed as

$$t_2' = \frac{1}{1 - \frac{-v}{V_c}} \Delta t_p = \frac{1}{1 + \frac{v}{V_c}} \Delta t_c\ , \tag{2a}$$

which could be rewritten as

$$\Delta t_c = (1 + \frac{v}{V_c})\, t_2'. \tag{3a}$$

Because F' is departing F with velocity v, the signal will reach an observer in F at time t_2 equaling

$$t_2 = \Delta t_c + \frac{v t_2}{V_c} = \Delta t_c + \frac{v}{V_c}\ t_2. \tag{4a}$$

Substituting the value of Δt_c from equation (3a) in equation (4a) yields

$$t_2 = (1 + \frac{v}{V_c})\, t_2' + \frac{v}{V_c}\, t_2, \tag{5a}$$

which could be rewritten as

$$t_2 = \frac{(1 + \frac{v}{V_c})}{(1 - \frac{v}{V_c})}\, t_2'. \tag{6a}$$

Substituting the value of t_2' from equation (1a), we get

$$t_2 = \frac{(1+\frac{v}{V_c})}{(1-\frac{v}{V_c})}\frac{l_0}{c} \ . \tag{7a}$$

Thus, the observer in *F* will conclude that the length of the rod is equal to

$$l = c\, t_2 = \frac{(1+\frac{v}{V_c})}{(1-\frac{v}{V_c})}\, l_0 \tag{8a}$$

or

$$\frac{l}{l_0} = \frac{1+\beta}{1-\beta}, \tag{9a}$$

where $\beta = \frac{v}{V_c}$.

Regardless of the value of V_c, the above derived relativistic distance equation predicts *distance contraction only when the two reference frames approach each other* (i.e., for $-1 < \beta \leq 0$). On the other hand, in contradiction of the famous Lorentz contraction, for distancing frames (i.e., $0 < \beta < 1$) equation (9a) predicts *length extension*.