Bell's Theorem cannot close the loophole of spatial locality

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Ramzi Suleiman

Dept. of Psychology, University of Haifa

Department of Philosophy, Al Quds University

Please address all correspondence to Prof. Ramzi Suleiman, University of Haifa, Haifa 31509, Israel. Email: suleiman@psy.haifa.ac.il, Mobile: 972-(0)50-5474- 215.

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Abstract

Bell's Theorem prescribes that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. However, Bell's proof presupposes that particles which are distanced from each other in space become *spatially disconnected*. However, the theoretical possibility for the existence of *spatial locality* between separated particles had never been refuted empirically.

Here I show that Doppler-like local-realistic relativity theories, which predict that the relativistic length of a body distancing from an observer's rest-frame will stretch rather than contract, could maintain spatial locality between particles, even when the particles are distanced enough to ensure that information about the outcomes of one particle is passed to the other particle faster than light. This implies that local and realistic theories which belong to the aforementioned Doppler-like theories could not be disqualified *a priori* by Bell's Theorem.

Keywords: Bell's Theorem, Entanglement, Nonlocality, Quantum Theory, EPR.

In a recently published *Nature* article, Hensen *et al*.[1] reported a "loophole-free" test of Bell's Theorem, [2,3] in which two electrons' spins were entangled at distance. The authors reported that they have successfully closed the "detection" and the "locality" loopholes; two significant loopholes which have not been hermitically closed in previous experiments. The reported experiment employed an event-ready scheme[4], which enabled the generation of high-fidelity entanglement between the distant electrons spins. An efficient spin readout closed the "detection loophole" by avoiding the fair sampling assumption[5], whereas a fast random basis selection and readout, combined with a spatial separation of the two electrons by 1.3 km, ensured that the obtained entanglement could not have possibly been the result of local variables even if such variables were capable of transmitting the entangled systems outcomes by velocity equaling the velocity of light. Based on their results, Hensen *et al*. expressed optimism that further improvements in the implemented event-ready scheme, with higher entangling rates, could settle the 80 year debate between the stance of quantum theory, which posits that quantum entanglement is nonlocal and thus could not be accounted for by any local-realist theory, and the stance of Albert Einstein, regarding the incompleteness of quantum theory[6] and his strong objection to nonlocality being "spooky action at a distance"[7].

It is argued here that although Hensen *et al*. may have closed the "time-like" or *temporal locality*, a significant loophole concerning *spatial locality* has remained wide-open. Bell's Theorem, like all current theories, presupposes that *two particles that are distanced in space are spatially disconnected*. This presupposition, although in agreement with our intuitions on how nature behaves, has never been empirically tested, although such testing is unavoidable given the fact that intuitions gained and reinforced through accumulated observation and experience with large and slow objects, cannot not be extrapolated automatically to the behavior of small particles moving and spinning with high velocities.

A logical deduction from the above is that the spatial-locality loophole could not be closed by any theory *unless it is proven that no local-realistic theory can predict that spatial-locality may exist between spatially separated bodies*.

Here I prove that the opposite holds. Specifically, it is shown that spatial non-locality between distanced bodies could be violated by a large class of local-realistic Doppler-like relativity theories which prescribe that the observed length of a departing body is stretched along its travel path, and not contracted as prescribed by Special Relativity[8]. For this purpose, consider for example a local-realistic relativity theory of inertial linear motion in which the transformations of time and distance observations from one reference-frame F' to another frame F are given by:

$$\Delta t = \frac{1}{1-\frac{v}{c}}\ \Delta t', \qquad \text{….. (1)}$$

And,

$$\Delta x = \frac{1+\frac{v}{c}}{1-\frac{v}{c}}\ \Delta x' \qquad \text{….. (2)}$$

Where $(\Delta t', \Delta x')$, and $(\Delta t, \Delta x)$ are time interval and distance, as measured in F' and F, respectively, v is the relative velocity between the two frames, and c is the velocity of light as measured in F.

According to Eq. 1, a time dilation will be observed in *F* only when the two reference-frames are distancing from each other, while a time contraction will be observed in F when the two reference-frames are approaching each other. More importantly here is the prediction of Eq. 2, which prescribes that the observer in *F* will measure a distance contraction only when the two reference-frames approach each other, but he or she will measure distance expansion when the reference-frames distance. This means that a particle that is distanced from another particle, as in the EPR experiment, is expected to suffer a relativistic "stretch" along its travel axis. Given a sufficiently high velocity, the two particles, although distanced from each other, could remain spatially connected.

It is noteworthy that the factor $1/(1-\frac{v}{c})$ which determines the time transformation, mimics the widely investigated and utilized Doppler Formula,[9] according to which waves emitted from an approaching body get redshifted (wavelength contraction), whereas waves emitted from a departing body get blue-shifted (wavelength expansion).

It is easy to show that for a body with uniform matter density ρ' along the travel path, the relativistic density in *F* is given by:

$$\rho = \frac{1}{\frac{\Delta x}{\Delta x'}}\ \rho' = \frac{1-\beta}{1+\beta}\ \rho' \qquad \ldots\ldots (3)$$

The relativistic stretch and density are depicted in Figure 1. As shown in the figure, as the velocity *v* increases, the relative stretch increases with increasing rates, approaching infinity when *v* approaches the speed of light. Concurrently, the matter density across the travel path decreases, with rates equal to the rates of increase in stretch, reaching zero at the speed of light.
Although the above example is sufficient to disprove the proposition that no local-realist theory can predict spatial-locality between spatially separated bodies, the number of possible local-realist theories which can disprove the above proposition is infinitely large. In principle, any relativity theory which predicts a sufficiently large relativistic stretch for distancing bodies could falsify the above proposition. It follows that such theories could not be dismissed *a priori* using Bell's Theorem.
It is worth noting that the transformations discussed above are not farfetched. In fact, they could be easily derived from a modification of Special Relativity (SR) in which its axiom

concerning the non-relativism of the speed of light is violated (see SI). Similar violations have been discussed in the literature as possible variants of SR[10-12].

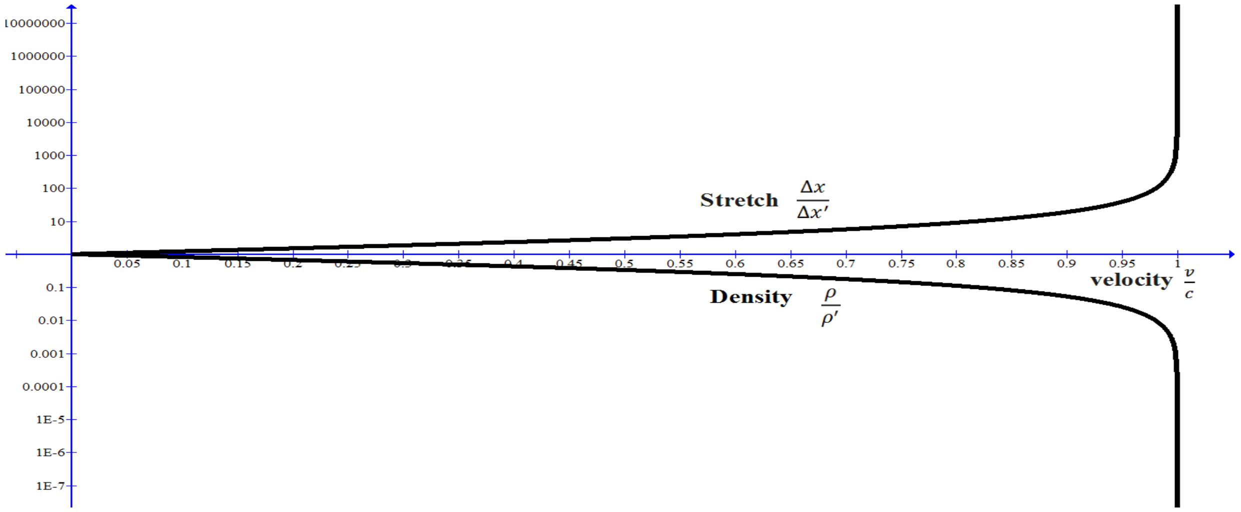

Figure 1: Relativistic stretch and matter density as functions of $\frac{v}{c}$

Interestingly, a theoretical analysis of the rotating disk problem[12] shows that both the speed of light invariance and the Lorentz contraction cannot be supported for rotating frames. In fact, violation of the speed of light invariance is the bases of the Sagnac Effect, which has crucial applications in navigation[13] and in fiber-optic gyroscopes (FOGs),[14] and which has been demonstrated experimentally for both radial and linear motion.[15]

In conclusion, I have shown that the fence erected by Bell's Theorem in front of local-realist theories has a big hole, through which Doppler-like relativity theories of the type discussed here can pass through. Closing this loophole requires variants of Bell's original recipe, in which the possibility of spatial locality can be either tested or eliminated by proper design. Until this is achieved, it remains fair to say that the news of the death of local realism is greatly exaggerated.

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Supplimentary Information

A. Derivation of the time transformation

We consider a simple preparation in which the time duration of an event, as measured by an observer A who is stationary with respect to the point of occurrence of the event in space, is transmitted by an information carrier which has a constant and known velocity v_c, to an observer B who is moving with constant velocity v with respect to observer A. We make no assumptions about nature of the information carrier, which can be either a wave of some form or a small or big body of mass. Aside of the preparation describes above and the measurements taken by each observer, throughout the entire analysis to follow, no further assumptions are made. This also means that we do not undertake any logical steps or mathematical calculations unless measurements of the variables involved in such steps or calculations are experimentally measurable.

We ask: what is the event duration time to be concluded by each observer, based on his or her own measurements of time? And what could be said about the relationship between the two concluded durations?

In a more formal presentation, we consider two observers in two reference frames F and F'. For the sake of simplicity, but without loss of generality, assume that the observers in F and F' synchronizes their clocks, just when they start departing from each other with constant velocity v, such that $t_1 = t_1{}' =0$, and that at time zero in the two frames, origin points of were F and F' were coincided (i.e., $x_1=x_1{}' = 0$).

Suppose that at time zero in the two frames, an event started occurring in F'at the point of origin, lasting for exactly $\Delta t'$ seconds according to the clock stationed in F', and that promptly with the termination of the event, a signal is sent by the observer in F' to the observer in F.

After $\Delta t'$ seconds, the point at which the event took place stays stationary with respect F' (i.e., $x_2{}' =x_1{}'= 0$), while relative to frame F this point would have departed by x_2 equaling:

$$x_2 = v\,\Delta t' \qquad \text{....... (1a)}$$

The validity of Eq. 1a could be checked and verified by more than one operational, i.e., experimentally feasible methods: For example, if the two observers meet any time after the event has terminated, then the observer in F will be able to read the time of the event as registered by the clock stationed in F' and learned what the duration of the event in F', for which the event was stationary. Another operational way by which the observer in F can infer about the actual time of travel until the event terminated and the signal was sent is by mimicking the even in F by having an identical event with the same duration (in its inertial frame), start promptly with the even in F'. It is important to note that the above two operational suggestions presume the rule stating that the laws of nature are the same in the two frames. In the first example, the above restriction leaves no possibility for the observer in F to suspect that the reading of the clock stationed F' in e time duration of the event in reading of the clock at F' (in the first example), or to suspect that a time registered by a clock at his/her own frame F will differ by the time that will be registered for an identical event, by an identical clock placed in F'.

If the information carrier sent from the observer in F' to the observer in F travel with constant velocity V_F relative to F, then it will be received by the observer in F after a delay of:

$$t_d = \frac{x_2}{V_F} = \frac{v\,\Delta t'}{V_F} = \frac{v}{V_F}\,\Delta t' \qquad \text{……. (2a)}$$

Since F' is departing from F with velocity v, we can write:

$$V_F = V_0 - v \qquad \text{…… (3a)}$$

Where V_0 denotes the information carrier's velocity with respect to the event's inertial frame F'. Substituting the value of V_F from Eq. 3a in Eq. 2a, we obtain:

$$t_d = \frac{v\,\Delta t'}{V_0 - v} = \frac{1}{\frac{V_0}{v} - 1}\,\Delta t' \qquad \text{…… (4a)}$$

Due to the information time delay, the event's time duration $\boldsymbol{\Delta t}$ that will be registered by the observer in F is given by:

$$\Delta t = \Delta t' + t_d = \Delta t' + \frac{1}{\frac{V_0}{v} - 1}\,\Delta t' = \left(1 + \frac{1}{\frac{V_0}{v} - 1}\right)\Delta t' = \left(\frac{\frac{V_0}{v}}{\frac{V_0}{v} - 1}\right) = \left(\frac{1}{1 - \frac{v}{V_0}}\right)\Delta t' \qquad \text{…(5a)}$$

Or:

$$\frac{\Delta t}{\Delta t'} = \frac{1}{1-\frac{v}{V_0}}$$ … (6a)

For $v << V_0$ Eq. 6 reduces to the classical Newtonian equation $\Delta t = \Delta t',$ while for $v \to V_0$, $\Delta t \to \infty$ for all positive $\Delta t'$,.

For a communication medium to be fit for transmitting information between frames in relative motion, a justifiable condition is to require that the velocity of the carrier be larger than the velocity of the relative motion, i. e., $v < V_0$.

Quite interestingly, Eq. (6a), derived for the time travel of moving bodies with constant velocity is quite similar to the Doppler's Formula derived for the frequency modulation of waves emitted from traveling bodies. Importantly, in both cases **the direction of motion matters**. In the Doppler Effect a wave emitted from a departing body will be red-shifted (longer wavelength), whereas a wave emitted from an approaching body with be blues-shifted (shorter wavelength). In both cases the degree of red or blue shift will be positively correlated with the body's velocity.

The same applies to the time duration of an event occurring at a stationary point of a moving frame. If the frame is departing from the observer, time will be dilated, whereas if the frame is approaching the observer will contract.

It is especially important to note further that the above derived transformation applies to *all* carriers of information, including the commonly employed *acoustic* and *optical* communication media. For the case in which information is carried by light or by electromagnetic waves with equal velocity, equation (6a) becomes:

$$\frac{\Delta t}{\Delta t'} = \frac{1}{1-\frac{v}{c}}$$ ….. (7a)

Since an objection might be raised for the cases of information translation by means of light or other waves with equal velocity, such objection could be avoided by restricting the theoretical model derived above to wave propagation in mediums that are not a vacuum, which in fact the case in almost all physical situations of interest.

b. Derivation of the distance transformation

To derive the distance transformation, consider the two frames of reference F and F'shown in Figure 1b. Assume the two frames are moving away from each other at a constant velocity *v*. Assume further that at time t_1 in F (and t_1' in F'), a body starts moving in the +*x* direction from point x_1 (x_1' in F') to point x_2 (x_2' in F'), and that its arrival is signaled by a light pulse that emits exactly when the body arrives at its destination. Denote the internal framework of the emitted light by F_0. Without loss of generality, assume $t_1 = t_1' = 0$, $x_1 = x_1' = 0$. Also denote $t_2 = t,\ t_2' = t', x_2 = x,$ and $x_2' = x'$.

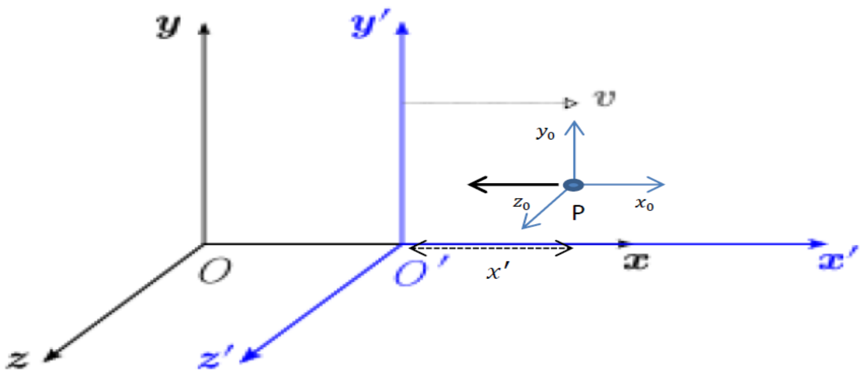

Figure 1b: Two observers in two reference frames, moving with velocity v with respect to each other.

From Eq. (7a), the time duration in F that takes the light signal to reach an observer in F' equals:

$$\Delta t_p = (1 - \left(-\frac{v}{c}\right)\ )\ \Delta t' \qquad \text{..... (1b)}$$

Where $\Delta t'$ is the corresponding time duration in F', and c is the velocity of light in frame F. Because F' is moving away from F with velocity *v*, the time that takes the light signal to reach and observer in F is equal to:

$$\Delta t = \Delta t_p + \frac{v\Delta t}{c} = \Delta t_p + \frac{v}{c}\ \Delta t \qquad \text{...... (2b)}$$

Substituting Δt_p from Eq. (1b) in Eq. (2b) yields:

$$\Delta t = (1 + \frac{v}{c})\, \Delta t' + \frac{v}{c}\, \Delta t, \qquad \text{….. (3b)}$$

or:

$$\frac{\Delta t}{\Delta t'} = \frac{(1+\frac{v}{c})}{(1-\frac{v}{c})}\ . \qquad \text{…… (4b)}$$

But $\Delta\, x = c.\Delta t$ and $\Delta x' = \mathrm{c}.\Delta t'$. Thus, we can write:

$$\frac{\Delta x}{\Delta x'} = \frac{(1+\frac{v}{c})}{(1-\frac{v}{c})} \qquad \text{……. (5b)}$$