Superluminal Motion and Causality from a Laboratory Perspective

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Abstract

Since the dawn of relativity in the first two decades of the twentieth century, it has been maintained that faster-than-light (superluminal) motion could produce time travel into the past with its accompanying causality-violating paradoxes; hence, it was concluded that it is impossible to exceed the speed of light. However, there are two different approaches to superluminal communication around a closed loop, with one leg of the loop purportedly leading into the past. One scheme employs direct signals between a receiver in motion relative to a transmitter. This is called Method I in this paper. In the other, moving observers "hand-off" information between momentarily-adjacent observers in relative motion passing each other, which is designated Method II. It is shown that the correct application of superluminal physics in the former method clearly precludes causality violation, but it is more subtle in the latter approach. An analysis of what would be observed in a physics laboratory, compared to what is inferred from a Minkowski diagram, attests that causality violation does not occur in either method. Thus causality is *not* violated by superluminal communication.

1 Introduction

In 1907 Albert Einstein considered it to be "sufficiently proven" that any velocity greater than that of light is an impossibility[1] by analysis of the Lorentz transformation equations (LTE). Given an inertial frame moving at velocity v with respect to a "stationary" frame, the time differential in the moving frame over a distance Δx in the stationary frame is

$$\Delta t' = \gamma(\Delta t - \frac{v\Delta x}{c^2}) \tag{1}$$

where Δt refers to the time differential in the "stationary" frame, c is the speed of light and $\gamma = 1/\sqrt{1 - v^2/c^2}$. He concluded that for Δt less than $v\Delta x/c^2$, $\Delta t'$ would be negative, implying that any such speedy object would arrive at its destination before it departed from its origination point, according to a moving observer. Similarly, Richard Tolman pointed out in 1917 that velocities greater than the speed of light presented the possibility that effect could precede cause.[2]

The assertion that causality can be violated by superluminal travel is also mainstream thought in this century. David Mermin[3] wrote,

"In the [moving] frame the object is in two different places at the same time! This is such a bizarre situation that one's suspicion is strengthened that the difficulty we have already encountered in producing an object moving faster than light must be a reflection of the impossibility of such motion."

Figure 1 is a Minkowski diagram depicting the conventional view that superluminal communication results in causality violation.[4] The horizontal axis is distance and the vertical axis is

[1] A. Einstein, "Uber das Relativitatsprinzip ...," Jahrb. Radioakt. Elektron. 4, 411 (1907)

[2] R. C. Tolman, The Theory of Relativity of Motion, (Berkeley, California, 1917), p. 54

[3] N. D. Mermin, It's About Time, (2005), pp. 53-54.

[4] *e.g.,* P. A. Tipler and R. A. Llewellyn, Modern Physics, (2008), p. 55.

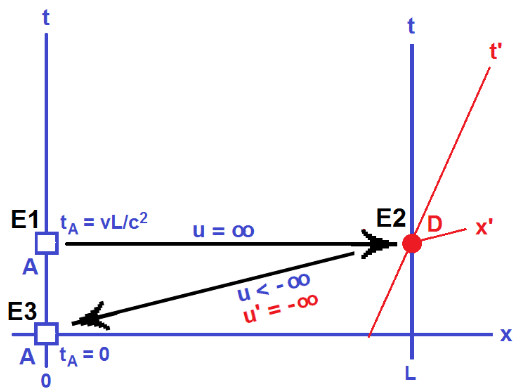

Figure 1: Typical Minkowski diagram showing purported causality violation. A and D are assumed to have some technology that allows superluminal communication.

the time axis in the "stationary" frame (labeled t), and the axes in the moving frame are labeled x' and t'. What is considered "stationary" and what is considered "moving" are, of course, arbitrary; however, the viewpoint in Figure 1 is from the frame in which A is at rest, as indicated by the fact that the t and x axes are perpendicular to each other. A and D are observers that have the hypothetical capability of sending signals to each other faster than the speed of light. The word "observer" means a conscious entity or a device that can indicate position and local time and relay that data to a conscious entity. Observer D is moving at some positive velocity, v, with respect to A, where v is less than c. According to the Lorentz transform, the axes of the moving frame, x′and t′, are tilted with respect to the stationary frame, the t′axis of the moving frame being defined by $t = x/v$ and the x′axis being defined by $t = vx/c^2$, where t and x are coordinates of the stationary frame. D is at x = L when the superluminal signal is received, and its time is $t_D{}' = 0$.

According to this view, A originates a signal at event E1, at time $t = vL/c^2$, and transmits it to D faster than the speed of light. The speed of the signal is represented as being infinitely-fast in Figure 1 by the horizontal black arrow. D receives the signal at time $t_D{}' = 0$, at event E2 and then transmits it instantaneously back to A at time $t_A = 0$, at event E3. The downward-sloping, leftward-going black arrow follows the x' axis, indicating that the speed of the signal is infinitely-fast in the moving frame ($\Delta t' = 0$). Thus A at event E3 receives the signal from his future self at event E1, which apparently allows the earlier A to receive messages from the future. If such is possible, then causality can be violated. The speed of the signals need not be infinitely fast to produce this apparent problem, but they do need to be significantly faster than the speed of light in most cases.

O. M. P. Bilaniuk, V. K. Deshpande and E. C. G. Sudarshan considered superluminal particles in the context of special relativity.[5] G. Feinberg later coined the name "tachyon"[6] for a particle that always travels faster than the speed of light, satisfies the principle of relativity and is Lorentz-invariant. The limiting value is c, but, as Feinberg points out, a limit has two sides.

The possibility of "backward in time" phenomena with tachyons is akin to Wheeler's concept of antimatter particles being normal matter particles moving backward in time.[7] Alternatively, a "reinterpretation principle" has been proposed wherein such tachyons would have "negative energy."[5] Others call this the "switching procedure" wherein the source of the tachyons becomes the receiver and the receiver becomes the source as perceived by certain observers.

The properties of tachyons were addressed in a previous paper,[8] which demonstrated that direct tachyon communication (Method I) as well as one leg of Method II does *not* create causality

[5] O. M. P. Bilaniuk, V. K. Deshpande E. C. G. Sudarshan, "'Meta' Relativity," American Journal of Physics, 30, (10): 718-723 (1962)

[6] G.Feinberg, "Possibility of Faster-Than-Light Particles," Physical Review, 159, (5): 1089-1105 (1967)

[7] R. P. Feynman, "The Theory of Positrons, Physical Review, 76, pp. 749-759 (1949)

[8] G. L. Harnagel, "Causality Between Events with Space-Like Separation," viXra 1908.0306

problems, and would seem to militate against the other "hand-off" leg doing so either. This paper demonstrates that superluminal communication by Method II, which is widely believed to allow communication with the past, does *not* do so, and does *not* present the bizarre absurdities of going backward in time which mainstream thought purports to occur with superluminal motion.

2 Method I (Tachyon Dynamics)

As discussed previously,[8] the Lorentz transform and the Minkowski diagram are kinematic representations of reality, concerned with geometrically possible motion, but does not address dynamics, which considers the effects of momentum and energy. The 4-vector momentum is[9]

$$\mathbf{P} = (\gamma mc, \gamma mv_x, \gamma mv_y, \gamma mv_z) \tag{2}$$

and the inner product of $\mathbf{P}$ with itself is the well-known relativistic energy equation,

$$E^2 - p^2c^2 = m^2c^4 \tag{3}$$

where m is imaginary for tachyons, $p = \gamma mu$ and u is the 3-vector velocity of the tachyon. Rewriting Equation (3) with m replaced with im and $u > c$, leads to

$$E^2 = \frac{m^2u^2c^2}{u^2/c^2 - 1} - m^2c^4 = \frac{m^2c^4}{u^2/c^2 - 1} \tag{4}$$

The m in Equation (4) is the absolute value of the tachyon invariant mass. This shows that E, the energy of a tachyon, approaches zero as the tachyon velocity, u, approaches infinity. As a practical matter, any successful signal transmission requires at least *some* expenditure of energy, hence it is not physically possible to send or receive a tachyon signal at infinite speed. When this paper refers to infinite speed it is to be understood as an idealization with the awareness that it will signify some speed that merely approaches infinity.

[9]D. J. Morin, *Special Relativity: For the Enthusiastic Beginner*, Createspace Independent Publishing Platform, p. 167 (2017)

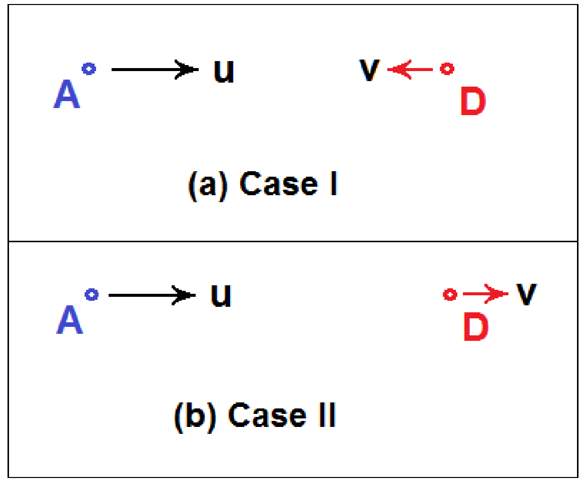

Figure 2: The two cases of direct superluminal communication (Method I).

Figure 2 presents the two situations that can occur with direct tachyon communication. The receiver moves toward the source (Figure 2a), referred to as Case I, or it moves away from the source (Figure 2b), which is called Case II. In Figure 2a, observer D is moving toward stationary observer A at velocity, v, and A sends an (almost) infinitely-fast signal, u, directly to D. The signal's energy relative to A is

$$E = \frac{mc^2}{(u^2/c^2 - 1)^{1/2}} \tag{5}$$

and the signal's momentum relative to A is

$$p = \frac{mu}{(u^2/c^2 - 1)^{1/2}} \tag{6}$$

The matrix to transform from the stationary frame (in which A is at rest) to the moving frame of D is

$$\eta = \begin{bmatrix} \gamma & (-\gamma v/c) & 0 & 0 \\ (-\gamma v/c) & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

So

$$\mathbf{P}' = \eta \mathbf{P} \tag{7}$$

where $\mathbf{P} = (E/c, p, 0, 0)$. Thus

$$E' = \frac{\gamma(mc^2 - mvu)}{\sqrt{u^2/c^2 - 1}} \tag{8}$$

As u approaches infinity, E approaches zero and E' approaches $-\gamma mvc$. Since D is moving in the negative x direction for Case I, its velocity is negative; thus the signal is observed by D as having significantly more energy because energy is frame-dependent, and velocity is also frame-dependent, as presented in Equation (5). When a stationary observer sends a signal to an approaching observer who is moving at velocity v with respect to the stationary observer, the approaching observer measures a velocity u', the velocity of said signal or object with respect to the moving observer, according to the kinematics of the Lorentz transformation, is[10]

$$u' = \lim_{u \to \infty} \frac{u - v}{(1 - \frac{uv}{c^2})} = \frac{c^2}{-v} \tag{9}$$

The value of u' as u increases without limit is also shown for v negative. This equation shows that when the signal velocity relative to the stationary frame, u, is (nearly) infinite, the velocity relative to the moving frame is (nearly) $u' = c^2/v$. Interestingly, this kinematic result is inherent in the Lorentz transformation equation for time as presented in Equation (1) since $\Delta t'$ approaches $\gamma v \Delta x/c^2$ as Δt approaches zero, and that term is primarily responsible for the relativity of simultaneity. Thus the signal travels *slower* relative to D according to Equation (9), and slower speed results in higher energy according to Equation (4), and that energy is $E = mc^2/(\sqrt{u^2/c^2 - 1})$, which is $E = \gamma mvc$ for $u = c^2/v$.

In Figure 2b, observer D moves away from observer A and A attempts to send a superluminal signal toward D. The signal must have *some* energy relative to D, that is, $E' > 0$ in Equation (8), therefore

$$E' = \frac{\gamma(mc^2 - mvu)}{\sqrt{u^2/c^2 - 1}} > 0 \tag{10}$$

Since v is positive, this can only happen if $c^2 > vu$, or $u < c^2/v$.

With this understanding of the dynamics of tachyons, one can immediately see that an infinitely-fast signal cannot be sent from A to D as depicted in Figure 1. Rather, A must send it no faster than $u = c^2/v$, which means it will leave A at E3 and arrive at D no sooner than $t = vL/c^2$, where L is the distance between A and D when the tachyon signal is received by D.

Furthermore, D and A are still moving away from each other during the second leg of the signal path, so D cannot send the signal back to A at a speed faster than A could send it to D; that is, u' must be greater than (*i.e.*, less negative than,) $-c^2/v$. A, however, will observe it moving at $u = -\infty$. Therefore, the *correct* signal path is from E3 to E2 to E1, just the *reverse* of what is depicted in Figure 1, so the signal will arrive back at A no sooner than $t = vL/c^2$, the round-trip time being $\Delta t > vL/c^2$. Thus there is no causality violation because tachyons cannot create a loop involving negative time as presumed in Figure 1, yet the signal travels back and forth *greater* than the speed of light.

But what about other observers, moving at other relative speeds, who may eavesdrop on the signal? If the transmitter were sending the signal infinitely fast, then anyone moving away from the sender couldn't receive the signal. If they were moving toward the sender, they would receive the signal at velocity $u = c^2/v_1$, where v_1 is the velocity of the eavesdropper with respect to the sender. Consequently, he would not be able to send a message back to the sender before it was sent, either.

Direct tachyon communication between observers in relative motion is very simple, straightforward and Δt in Equation (1) is *never* less than $v\Delta x/c^2$, so causality cannot be violated by

[10] J. D. Jackson, *Classical Electrodynamics*, p.361 (1965),

Method I.

3 Method II in a Laboratory Environment and Presentation in a Minkowski Diagram

Direct communication with transmitters and receivers in relative motion (Method I) was shown to preserve causality, but it has been claimed that an additional stationary observer, B, can be located at E2 in Figure 1 who can receive an infinitely-fast tachyon signal from A and then pass it to D by a radio signal (or some sublight method) with infinitesimal delay since B and D are in very close momentary proximity. In addition, a moving observer, C, is supplied adjacent to A at the appropriate time to receive infinitely fast tachyons from D and then pass it back to A. This is Method II, "handing off" the message to a momentarily adjacent observer in relative motion, which is purported to avoid the speed limitations of Method I and thus violate causality; that is, a message can be sent into the past. There are many different "hand-off" arrangements that purport to do this, but the one presented in Figure 3 distills them all down to the basics. This is similar to Figure 1 except that events E1 and E2 represent the tachyon transmission occurring solely between A and B which are at relative rest and, presumably, can be sent (nearly) infinitely-fast.

At event E2, B passes the information received from A to observer D who is momentarily adjacent, then D transmits a tachyon signal (nearly) infinitely-fast to C , which arrives at event E3. C is momentarily adjacent to A and can pass it to A *before* A will initiate it at event E1, thus creating the possibility of a causality violation. The only limit to tachyon speed between transmitters and receivers at relative rest is that, apparently, the tachyons must arrive with *some* energy to allow detection. The speeds of u and u' in Figure 3 are idealized to infinity. It is extremely easy to fall into the block universe concept, which asserts that the past exists and is accessible from the present, when manipulating the Lorentz transform and the Minkowski diagram; however, dealing with events as observed in a laboratory adds important aspects to a critical analysis of the situation.

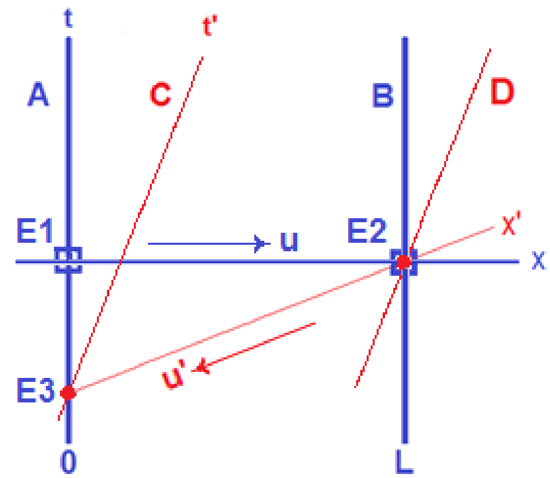

Figure 3: A "hand-off" arrangement that purportedly violates causality.

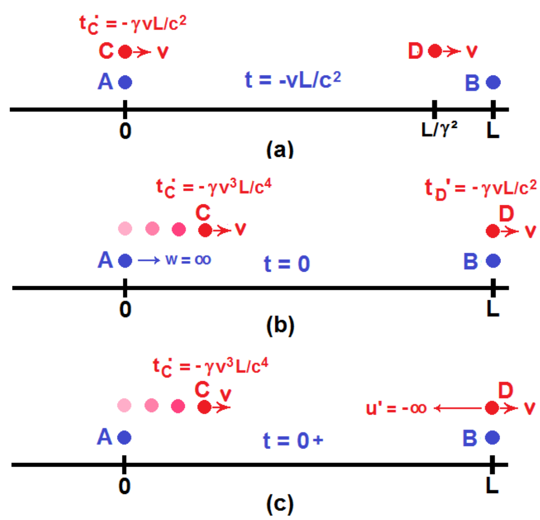

Figure 4: The "hand-off" arrangement from the perspective of an observer in a laboratory.

Figure 4 presents the same scenario as Figure 3, but from the perspective of an observer in a laboratory environment. The vertical axis is the y-axis which shows that the path of C and D is offset a small amount from A and B which lie on the x-axis. The positions of objects in the laboratory are illustrated at three different "snapshots" of time, and is consistent with the concept of the Minkowski diagram as instantaneous layers of constant time:[11]

"We build a spacetime by taking instantaneous snapshots of space at successive instants of time and stacking them up."

Each snapshot is what an observer in a laboratory instantaneously detects with his instruments. Even though the instruments are spatially separated, their times can be synchronized and their results assembled such that each batch of measurements consists of a single instant in time. Therefore, in the lab view, the scenario starts when C is adjacent to A, at laboratory time $t = -vL/c^2$ (Figure 4a). The time according to C's clock is $t'_C = -\gamma vL/c^2$.

As time passes in the laboratory, it also progresses for C and D. This is a principle that is easily glossed over when analyzing a Minkowski diagram, but it is clearly demonstrated, both in Figure 4 and by the LTE for time (see Equation (1): Time in one frame is directly proportional to time in the other frame. Figure 4b depicts laboratory time $t = 0$. C's clock is at $t'_C = -\gamma v^3L/c^4$, but D's clock is at $t'_D = -\gamma vL/c^2$ due to the relativity of simultaneity as prescribed by the LTE. When B (whose clock reads $t = 0$) passes the message to D, D's clock reads $t'_D = -\gamma vL/c^2$.

The laboratory viewpoint isn't so different from the Minkowski diagram. If Figure 4a, b and c were stacked one on top of the other, this would satisfy Norton's portrayal for constructing the Minkowski diagram as foliations of time, and the time axis of the Minkowski diagram comes out of the page in the stacked view. In the Minkowski diagram, the y-axis of the lab view goes into the page. Rotating the Minkowski diagram around the x-axis by 90 degrees hides the time axis and reveals the y-axis.

[11] *pitt.edu/ jdnorton/teaching/HPS*$_0$*410/chapters/ spacetime/*

The position of a moving object such as C in Figures 3 and 4 is simply defined as $x_C = v(t + vL/c^2)$. If D were to transmit a tachyon signal to C infinitely fast, by algebraic manipulation C would (apparently) receive it when C was at x = 0 (at $t'_C = -\gamma vL/c^2$); however, the laboratory observer claims C is at $x = v^2L/c^2$ when D launches the signal (the bright red spot in Figure 4c), not at $x = 0$ (the lightest pink spot). So which C receives the tachyon signal?

Does the physicist ignore the fact that Method I cannot violate causality, yet declare that Method II "proves" that tachyons *would* violate causality and, therefore, superluminal motion is impossible, or does he look for the reason why tachyons are better behaved in the Method I scenario than they are in Method II? Tachyons *appear* to have the ability to go backward in time because of Equation (1), but this causes an infinity to appear in the velocity equation when u' approaches $-c^2/v$:

$$u = \lim_{u\to\ -c^2/v} \frac{u' + v}{(1 + \frac{u'v}{c^2})} = -\infty \qquad (11)$$

So how do we deal with an infinity? Usually, when the dependent variable of an equation becomes infinite, it represents a break-down of that equation, a warning about the limitation of its domain of applicability. If we inspect the LTE, we find that this is the point where the time, t', goes to zero and the signal transmission time becomes instantaneous in the moving frame. Beyond that point, t' becomes negative and transmission time becomes *less than* zero, thus the concern expressed by Mermin that an object would be in two places at once.

The signal is launched from D at $t = 0$ in the laboratory frame, so if the speed of the signal is less than infinite, it will meet C at time $t > 0$ and $x_C > v^2L/c^2$. If its speed is infinite, it will meet C at $t = 0$ when $x_C = v^2L/c^2$, but if they meet when $x_C < v^2L/c^2$, *the signal must travel* ***faster*** *than infinity* in the laboratory frame!

"Faster than infinity" and pressing beyond infinity are absurd and unphysical, therefore we must heed the warning that $u = -\infty$ and $E = 0$ at $u' = -c^2/v$ and concede that this is a limit at and beyond which D can no longer send a successful signal to A. This would seem to present a limit on the domain of applicability of the LTE when dealing with superluminal phenomena, but there is also another way to underscore this. David Morin has a procedure for dealing with relativity,[12] and it becomes fundamental when tachyons are concerned:

"An extremely important strategy in solving relativity problems is to plant yourself in a frame and stay there. The only thoughts running through your head should be what you observe. That is, don't try to use reasoning along the lines of, 'Well, the person I'm looking at in this other frame sees such-and-such.' This will almost certainly cause an error somewhere along the way, because you will inevitably end up writing down an equation that combines quantities that are measured in different frames, which is a no-no."

Besides David Morin, others have expressed similar restrictions when dealing with relativity problems. Erasmo Recami stated,[13]

"one should never mix together the descriptions of one phenomenon yielded by different observers, otherwise -even in ordinary physics- one would immediately meet contradictions"

In other words, an observer should believe what he sees and what his instruments measure, and those instruments are at rest with respect to the observer. Taylor and Wheeler wrote in a similar vein:[14]

"To allow the train observer to make only measurements with respect to the train, forcing her to ignore Earth, let the train be a cylinder without windows"

Although the sentiment is the same, the restriction on windows seems too severe. Certainly, it's fine to observe the earth frame and make measurements of objects at rest therein, but one shouldn't presume one knows what they observe and what they believe their capabilities are. Note also that Tayor and Wheeler require us to take what we see in the train frame as fact. What about the track frame? The Principle of Relativity requires that it must be followed in *any* inertial frame.

So in Figure 4, a physicist in the laboratory sees that C is *not* at x = 0 when D launches the signal: C is obviously at $x_C = v^2L/c^2$, the time on C's clock reads $t_C' = -\gamma v^3L/c^4$ and the time on D's clock reads $t_D' = -\gamma vL/c^2$. This means that the minimum value for $\Delta t' = t_C' - t_D'$ is $vL/\gamma c^2$, so $u' = -c^2/v$.

Ignoring the mindset proposed by Morin, Recami, Taylor and Wheeler leads to the belief that a signal could arrive at its destination before it is sent, which is absurd on the face of it. Figure 5 demonstrates this irrationality as a laboratory sequence of the tachyon signal propagating backward in time.

How can anything happening solely between D and C at rest within a moving frame have any effect on what happens in the laboratory? Can time go backward in the laboratory in *any* case? If time *can* go backward in the lab, can it go backward *only* in the lab? Wouldn't it extend outside the lab also? How far outside? The whole earth? The whole *universe?* Fortunately, these absurd questions need not be addressed since the principle advocated by Morin, Recami, Tayor and Wheeler, plus the restrictions ordained by relativity of simultaneity, entropy and the arrow of time, forbid the possibility of time reversing in the laboratory. *Time cannot go backward!*

[12] D. Morin, Introduction to Classical Mechanics, Cambridge Univ. Press (2008), p.522

[13] E. Recami, "Classical tachyons and possible applications," Revista del nuovo Cimento," 9:6 (1986), p. 66

[14] E. F. Taylor and J. A. Wheeler, Spacetime Physics, 1991, p. 62.

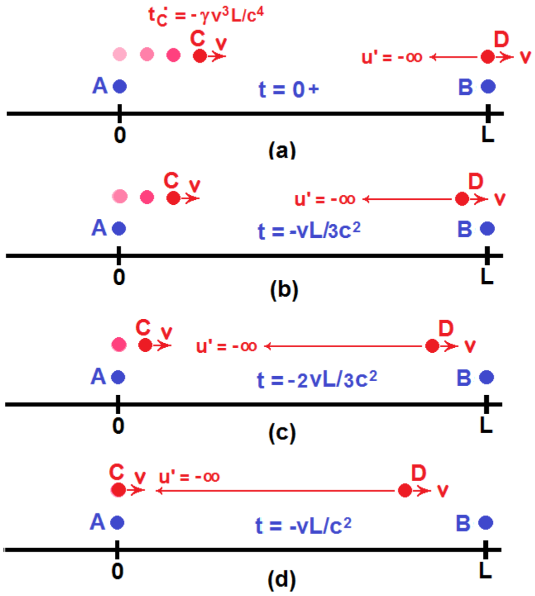

Figure 5: Can time in a laboratory be reversed by a tachyonic signal between moving observers?

Since time cannot go backward, it's obvious that, from the perspective of A and B in the laboratory, C cannot receive the signal before laboratory time $t = 0$ (when C is at $x = v^2L/c^2$). If C receives the signal at *that* lab time, then it travels at $u = -\infty$ in the lab frame and D sends it at velocity $u' = -c^2/v$. This is exactly what happens with Method I, and the reason why C can't receive it sooner is because C doesn't exist at x = 0 when D launches the signal, given the logistics and perspective of Figure 4. Of course, the most recent position of C isn't adjacent to A, so the message cannot be passed to A, and this arrangement fails. This failure can be corrected, perhaps, by the arrangement in Figure 6, wherein C is relocated so it is adjacent to A when D is adjacent to B.

So B passes the message to D at $t = 0$, and C receives it and passes it to A at $t_A = vL/c^2$, *after* A initiates it. B could also have initated the message at t = 0 and it wouldn't arrive back to B before it was initated, either.

By a similar argument, the velocity of the tachyon signal launched by A is limited to c^2/v.

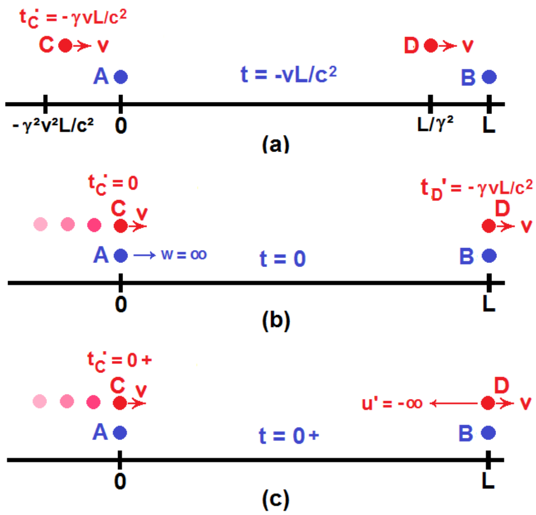

Figure 6: Correcting the "hand-off" failure in Figure 4 in accordance with legitimate tachyon reception

From the perspective of C and D, B is moving to the left, thus the most recent position of B receives the tachyon signal, not any past position. Therefore, the correct laboratory arrangement is depicted in Figure 7. A sends the tachyon signal to B at velocity $w = c^2/v$ due to the logistics of the arrangement at $t = 0$ and D sends the signal to C at $u' = -c^2/v$; however, the signal is observed in the laboratory to travel at $u = -\infty$.

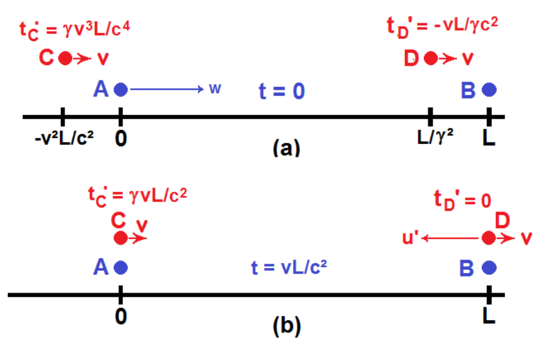

Figure 7: The appropriate "hand-off" arrangement from the perspective of an observer in a laboratory.

Of all the possible "hand-off" arrangements, why is this one correct? First of all, Figure 7 is consistent with direct tachyon communication between moving observers (Method I) in that the round-trip message time is $\Delta t = vL/c^2$. Second, it preserves Relativity of Simultaneity RoS): time in the moving frame obeys the LTE which requires that it be dependent upon position as viewed from the lab frame. Other arrangements have different time delays, one such (Figure 6) even has $\Delta t = 0$; however, this one would have time going backward for C and D, so it fails on that account. It seems strange that introducing extra participants in the communication process could actually reduce the time to send a message around a loop, and it doesn't.

It may seem unsatisfactory that the speed of tachyons can be limited within any given inertial frame, yet in the "hand-off" scenario it's limited to $c < w < c^2/v$. Observer A *could* transmit the signal to B at $u = \infty$ in Figure 7, but B would have to wait until D was adjacent, so sending it at any speed between $w = c^2/v$ and infinity doesn't change the time when D receives it. Interestingly, from the perspective of C and D, D *could* send the tachyon signal infinitely fast (to past C), but past C would have to wait until A was adjacent, so sending it infinitely fast doesn't change the time that A receives it.

Claiming that D *can* send the message to C infinitely fast in Figures 4, 5 and 6 *and* complete a message loop is doing exactly what Morin, Recami, Tayor and Wheeler say *not* to do. D sees C at x = 0, but A and B must not use that reasoning because it doesn't apply to them. Furthermore, it makes no difference whether viewed from the laboratory of A and B or from the equally-valid laboratory of C and D. The Principle of Relativity requires that all inertial frames are equivalent, so what C and D see is valid: A cannot send a message infinitely fast to B, according to them, but presuming that A can do so is a "no-no."

Figure 7 also avoids the problems that arise when an infinity is encountered. When A sends the tachyon signal to B at $w = c^2/v$, $w' = \infty$, and that infinity represents a limit of the domain of applicability of the LTE, as discussed previously. Similarly, when D sends the tachyon signal to C at $u' = -c^2/v$, $u = -\infty$, also a limit of the domain of applicability of the LTE.

Tachyon communication by Method II is made unnecessarily more complex than Method I. It is greatly simplified when RoS and other important factors are strictly obeyed, Thus, as is the case for Method I, Δt in Equation (1) is *never* less than $v\Delta x/c^2$ for Method II, either, so causality is not violated in either method.

4 Conclusion

It has been demonstrated definitively that direct tachyon communication in a loop between transmitters and receivers in relative motion (Method I) always obeys causality. This is an important point because textbooks and other sources have claimed that this method *does* violate causality.[4,15,16]

It has also been shown that adding additional participants (Method II) can't violate causality either, provided that tachyons aren't imbued with fictitious properties. The limitations of rationality and logistics apply particularly to the "hand-off" approach, infringement of which has been responsible for assertions of causality violation. The validity of any one of those limitations is sufficient to refute these assertions:

(1) A tachyonic signal propagating from Observer D to Observer C as depicted in Figure 4 cannot possibly have any effect on Observers A and B, let alone the assertion that it would cause time to go backward for A and B.

(2) A tachyonic particle propagating such that it arrives before it is sent represents that particle being in two places at once, which violates conservation of energy.

[15] http://www1.phys.vt.edu/takeuchi/relativity/notes/section10:html

[16] J. D. Norton, https://www.pitt.edu/jdnorton/teaching/HPS-0410/chapters/spacetime-tachyon/index

(3) Although time symmetry (isotropy) exists at the quantum level, it ***never*** *goes backward at the "classical" level where a large collection of particles (i.e., observers) are involved, thus Figure 4 represents an impossibility.*

(4) Relativity of Simultaneity (RoS) is a fundamental consequence of relativity theory. Method I obeys causality because energy is frame dependent, energy is frame dependent because velocity is frame dependent, and velocity is frame dependent because of RoS. Thus Method I inherently obeys RoS, but claims that Method II violates causality rest on the dubious foundation presuming that RoS can be defeated, which is incorrect.

It would be quite extraordinary for the conclusions of Method II to disagree with those of Method I. If tachyons obey any of the limitations (1) through (4), then Method II *will* agree with Method I. Thus tachyon signals can be sent at near-infinite speed between transmitters and receivers at rest in a laboratory, the speed being governed only by the sensitivity of the receivers, but they can't send a message around a loop and thereby violate causality and RoS. Detection of the laboratory signals by moving observers will obey causality, even though events with space-like separation in the laboratory may appear to have effect before cause for some observers (hypothetically, some observers E and F) not participating in the loop process. The mere observation of the fact that an event appears to happen at C before another event happens at D (which purportedly is the cause of the event at C), doesn't produce a message being sent backward in time because E and F are unable to receive the signal due to energy considerations.

The fact that *one* arrangement of a message loop, employing the "hand-off" method (Figure 7), is fully consistent with causality and with tachyon dynamics in the direct method (Section 2), while all others fail in one way or another, is sufficient to affirm that tachyons never violate causality. Consequently, causality violation as a disproof of faster-than-light speeds is a canard. Although it has been asserted that just *one* valid proof that tachyons travel backward in time is sufficient to refute *all* proofs to the contrary, the problem is that all those other "proofs" require that tachyons be suffused with unphysical properties and that basic tenets of relativity be violated.

Futhermore, it has been argued just the opposite in the context of general relativity:[17]

"If CTC's are allowed, and if the above vision of theoretical physics' accommodation with them turns out to be more or less correct, then what will this imply about the philosophical notion of free will for humans and other intelligent beings? It certainly will imply that intelligent beings cannot change the past. Such change is incompatible with the principle of self-consistency. Consequently, any being who went through a wormhole and tried to change the past would be prevented by physical law from making the change; i.e., the 'free will' of the being would be constrained."

The "hand-off" scenarios of special relativity are analogous to the closed timelike curves (CTC's) of general relativity discussed in the quote. That is, the constraints imposed on CTC's are of a general nature and would certainly apply in the subset of general relativity, which is special relativity. Thus any "hand-off" scenario must obey causality by the laws of physics. As to constraining "free will," the laws of physics do that routinely.

This paper has demonstrated how physical law, specifically, the relativity of simultaneity, may be applied to require this obedience. *If* tachyons exist, they will behave exactly the way they have been described in Sections 2 and 3 of this paper, and tachyons may well exist.

[17] J. Friedman, M. S. Morris, I.D. Novikov, F. Echeverria, G. Klinkhammer, K. S. Thorne and U. Yurtsever, "Cauchy problem in spacetimes with closed timelike curves," Phys. Rev. D, 42:6 (15 Sept. 1990), pp. 1915-1930.

Although there is no solid experimental evidence at present for faster-than-light physical phenomena, it has been hypothesized that the electron antineutrino may be tachyonic.[18,19] This line of thought is still very much active,[20,21] and several experiments have been performed to actually measure the mass of the electron anitneutrino. The Mainz experiment[22] ran between 1997 and 2001 and obtained a value of $-0.6 \pm 2.2 \pm 2.1\, eV^2$ for the square of the neutrino mass. The Troitsk experiment ran between 1994 and 2004 and obtained a value of $-0.67 \pm 2.53\, eV^2$,[23] thus the most likely value for the neutrino mass from these experiments is *imaginary*! The initial results from the KATRIN experiment,[24] put the value at $-1.0 + 0.9 - 1.1\, eV^2$, but the experiment expects to reduce the uncertainty to $\pm 0.2\, eV^2$ eventually. Although the error bars are only about two sigma, we have an interesting sequence of experimental results: as the experimental error is reduced, the expected value shifts more negative! This is contrary to what would be expected as more accurate experiments are performed. The final results from KATRIN will be most interesting.

Even if neutrino mass is found to be imaginary, it may be difficult to experimentally confirm that they would be superluminal. Because the absolute value of the neutrino mass is on the order of one electron volt, neutrino energy would also need to be in the same range to travel significantly faster than light. Presently, neutrino detectors aren't sensitive to such low energies; however, this is irrelevant to the main thesis of this paper because other tachyonic candidates than neutrinos may be discovered; and tachyon energy considerations in the context of special relativity prove theoretically that Method I always obeys causality, and multiple arguments militate against assertions that Method II violates causality. So if and when the existence of tachyons is confirmed, we need not worry that our past histories can be altered or erased.

5 Acknowledgments

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[22] C. Kraus *et al*, "Final results from phase II of the Mainz neutrino mass search in tritium β decay, arXiv:hep-ex/0412056v2 (2005)

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[24] M. Aker et al., "An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN," Phys. Rev. Lett. 81, 1562 (2019), arXiv 1909.06048