*Kent A. Peacock*

# Would Superluminal Influences Violate the Principle of Relativity?

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# Would Superluminal Influences Violate the Principle of Relativity?

It continues to be alleged that superluminal influences of any sort would be inconsistent with special relativity for the following three reasons: (i) they would imply the existence of a 'distinguished' frame; (ii) they would allow the detection of absolute motion; and (iii) they would violate the relativity of simultaneity. This paper shows that the first two objections rest upon very elementary misunderstandings of Minkowski geometry and on lingering Newtonian intuitions about instantaneity. The third objection has a basis, but rather than invalidating the notion of faster-than-light influences it points the way to more general conceptions of simultaneity that could allow for quantum nonlocality in a natural way.

## 1 – Alleged troubles with superluminal effects and influences

There are at least two good reasons to take seriously the possibility of superluminal influences. First, they are arguably though controversially implicated in the violations of locality found in quantum mechanics.[1] Second, it is not at all clear whether special relativity as it is usually formulated actually *excludes* superluminal influences or simply *fails to describe them properly*.[2] To some knowledgeable observers these two claims will seem obvious, to others they will seem to be 'not even wrong.' I will not attempt a detailed explication or advocacy of them in this paper, although it will become clear where my sympathies lie. The major purpose of this note is two-fold. First, it will attend to a job of undergrowth clearance, which is to defend the notion of superluminality against certain too-common misconceptions which stem from misunderstan-

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1 - *See, e. g., Maudlin (2002) for a defence of this view.*

2 - *In support of the latter possibility I can only cite the large but admittedly inconclusive body of literature exploring the possibility of tachyons, superluminal frames, and extended relativity. It is not possible to do a comprehensive review of this literature here. The modern era of tachyon theory began in the 1960s, and papers from that era by G. Feinberg (1967) and O.-M. Bilaniuk and E. C. G. Sudarshan (1969) are widely cited; see also Bilaniuk, Deshpande, and Sudarshan (1962). E. Recami insightfully advocated the significance of tachyons in several publications; see his (1986) for comprehensive review. A neglected paper by R. I. Sutherland and J. R. Shepanski (1986) is an important milestone: their approach is different than the orthodox treatment of tachyons given by most authors. The orthodox approach is to substitute the condition $v > c$ into the usual Lorentz transformations; this gives an imaginary Lorentz factor $1/\sqrt{1 - v^2/c^2}$ leading to many difficulties of interpretation. Sutherland and Shepanski show that by re-deriving Lorentz-like transformations for the superluminal case (rather than merely substituting the condition $v > c$ into the subluminal transformations) one arrives at a Lorentz factor $1/\sqrt{v^2/c^2 - 1}$ which makes all proper quantities real-valued for superluminal frames. M. Fayngold's recent review monograph (2002) on superluminal physics is very useful, but it does not take account of Sutherland and Shepanski's important innovation. Very recently, J. M. Hill and B. J. Cox (2012), and R. S. Vieira (2012) have developed 'extended' versions of special relativity that use the same real-valued Lorentz factor as Sutherland and Shepanski's for $v > c$. These approaches merit further study and development.*

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dings of Minkowski geometry and from lingering Newtonian intuitions about simultaneity. Second, it will sketch a notion of simultaneity which (properly developed) could allow for quantum mechanical superluminal influences in a natural way. This paper is propaedeutic to a larger project being undertaken by this author that is aimed at defining generalized conceptions of simultaneity which would be adequate to the fact that we live in a quantum universe.

Some of the misunderstandings I will criticize here were dealt with rather clearly by Frank Arntzenius (1990) over twenty years ago. However, they continue to appear in the professional literature, and so it seems necessary to respond to them yet again. Let's begin with Barry Dainton, since the particular problems he cites will be useful talking-points for my discussion. Dainton, in his *Time and Space* (2010), begins by quoting J. R. Lucas (1990, pp. 9-10), who said,

> if some superluminal velocity of transmission of causal influence were discovered, we should be able to distinguish frames of reference, and say which were at rest absolutely and which were moving.

Dainton (p. 339) agrees, saying,

> [a]nd in this he [Lucas] is surely right. Were we to discover that a truly instantaneous connection exists between objects at different places in space, then assuming the connection has some detectable effects, not only would the notion of absolute simultaneity have a real application, but we would have a way of determining which frames of reference are at absolute rest and which are not: *it is only with respect to frames truly* [sic] a*t rest that the relative changes would occur at precisely the same time*. [Emphasis added.]

Adán Cabello, a distinguished researcher in quantum information theory, has worries about instantaneity similar to Dainton's. In *Nature* Cabello reviewed recent findings on quantum-mechanical correlations, and expressed his objection to instantaneous influences in quantum mechanics as follows:

> ... the decision of what test is performed in one location cannot influence the outcome of the test performed in the other location, unless there is an instantaneous influence of the two tests on each other. ... But this is too high a price to pay, *because it is impossible to fit instantaneous influences into any theory in which such influences travel at a finite speed* [emphasis added] (2011, p. 456).

Views like these have been held by other notable authors. Wesley Salmon, for instance, argued that

> [a]rbitrarily fast signals yield absolute simultaneity of the strongest sort; the presence of the relativity of simultaneity in special relativity hinges crucially upon the existence of a finite upper speed limit on the propagation of causal processes and signals (1980, p. 122).

Nicholas Maxwell (1985, p. 38) seems to suggest that the *mere existence* of a superluminal effect would conflict with the Principle of Relativity. He cites his own interpretation of quantum mechanics, which postulates the superluminal collapse of spatially extended 'propensitons' which, he argues, would explain quantum correlations. Maxwell insists that his own theory

> irreparably contradicts special relativity. For special relativity asserts that all inertial reference frames are physically equivalent. In only one reference frame, however, will any given probabilistic collapse of propensiton state be instantaneous; in other, relatively moving frames the collapse will not, according to special relativity, be instantaneous (though always faster-than-light).

From these remarks we can tease out four closely-related charges against superluminality. Before stating them, though, it will be helpful to settle on terminology:

- A superluminal *effect* will be any physical process that involves the faster-than-light propagation of a geometric locus such as the intersection point between a beam of light and a background, without presuming that this involves the transmission of any sort of influence or information faster than light. A widely-discussed example is the searchlight-beam effect (Rothman 1960; Weinstein 2006): a beam of light from a rotating point source will track across a distant screen faster than light if the screen is at a sufficient distance. Another example of a superluminal effect would be a string of flashbulbs or firecrackers set to go off simultaneously in a given inertial frame. In all other inertial frames the sequence of flashes or detonations will propagate superluminally; we'll return to the spacetime kinematics of such processes shortly. It is usually taken that there is no question of the searchlight beam effect or strings of firecrackers transmitting *influences* superluminally along their trajectories but it should not be assumed that the searchlight beam effect is unproblematic.[3]

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3 - *Rothman (1960) dismisses the possibility that the searchlight beam effect could transmit information along the trajectory of the intersection point, but Weinstein's wording (2006) is more cautious, suggesting that the problem needs more investigation. H. Ardavan (1984a) considered a scenario in which a rotating beam of electromagnetic radiation (such as that from a pulsar) traces a superluminal locus over a conductive surface (such as a layer of plasma spread through the solar system). The beam of radiation will cause charge separation in the plasma and thereby induce electromagnetic radiation from the surface at the intersection locus. Ardavan carried out a rigorous calculation showing that if the locus orbits superluminally in a circular pattern then the induced field will diverge. Ardavan further showed (1984b) that the gravitational field induced by the searchlight beam effect in such scenarios will also diverge. Ardavan left it open whether these results indicate the high-field breakdown of classical electromagnetic and gravitational field theory, or some sort of otherwise-implausible prohibition on the searchlight beam effect. The important questions raised by Ardavan's work remain open.*

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- A superluminal *influence* would be a hypothetical superluminal process in which some sort of causation passes faster than light from one point to another distant point. I'd like to leave it as open as possible how superluminal influences, if any, would be constituted.
- A *tachyon* is a hypothetical faster-than-light particle, where we think of a particle as an entity that can be localized, at least under some circumstances. I'll take a tachyon to be a form of superluminal influence, and I will sometimes use these terms interchangeably.[4]
- I will occasionally refer to superluminal influences, superluminal effects, and tachyons collectively as forms of *superluminal propagation* when the difference between them doesn't matter.
- Some papers in this literature (e.g., Sutherland and Shepanski (1986) and references therein) speak of *superluminal reference frames*, which would be hypothetical faster-than-light Lorentzian physical systems which could be transformed *to* in some versions of superluminal kinematics.
- I'll also prefer the adjective 'invariant' ('same in all frames of reference') to 'absolute' or 'truly' because that is more in keeping with standard usage in current relativity literature, and because it avoids dubious philosophical connotations.

Here are the Troubles with Superluminality with which we shall be concerned:

TS1: There is no way to reconcile instantaneous influences with 'any theory in which such influences travel at a finite speed' (Cabello).

TS2: The existence of a superluminal physical influence (such as Maxwell's propensiton collapse) would imply the existence of a distinguished frame of reference and thereby violate the Principle of Relativity (Lucas, Dainton, Maxwell).

TS3: If a superluminal influence could be used to transmit information controllably then it would be possible to detect absolute states of motion and again thereby violate the Principle of Relativity (Lucas, Dainton).

TS4: If a superluminal influence were detectable or could be used to transmit information controllably, it would allow violations of the relativity of simultaneity (Dainton, Salmon).

I will show that TS1-3 rest upon elementary but surprisingly widespread misconceptions about how superluminal motion would be represented in Minkowski geometry. As to the fourth (and much more interesting) problem, I will have to respond *guilty as charged*, but I will argue (though not as conclusively as with TS1-3) that the charge is not nearly as damaging as most people suppose, and that it may in fact open a door to interesting new physics.

## 2 – Superluminal propagation does not imply a distinguished frame

Before we address the implications of the detectability of superluminal influences, let's review some basics of superluminal kinematics in special relativity. Consider a familiar spacetime diagram, restricted to 2-dimensional ($x,t$) space for simplicity:
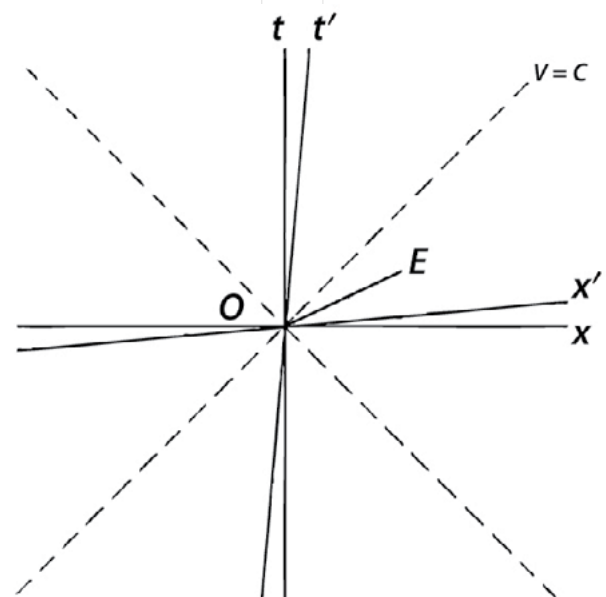


Figure 1

We'll take the $x$ and $t$ axes to be the space and time axes respectively of the 'lab' frame $S$ and the $x'$ and $t'$ axes to be the space and time axes of another inertial frame $S'$ moving subluminally to the right. We've chosen units such that the light cone is at 45° with respect to the $x$ and $t$ axes, and the line $OE$ is the trajectory of something propagating with constant superluminal velocity to the right. Geometrically, what defines any form of superluminal propagation is merely that its spacetime trajectory is outside the light cone as shown. The line $OE$ therefore need not be the worldline of an exotic hypothetical particle, a collapsing propensiton, or the Starship *Enterprise* moving at warp speed; it could simply be a string of flashbulbs timed to go off simultaneously in some inertial frame. If the relative velocity of the moving ($x',t'$) frame steadily increases, the $x'$ and $t'$ axes rotate uniformly toward the light cone in order to preserve the invariance of the speed of light for both frames. (Of course, the proprietors of the ($x'$,

4 - R. Sigal and A. Shamaly (1974, p. 2358) state, 'we use the term tachyon to describe any propagation outside the light cone,' and this could include both of what I have called superluminal effects and influences. Sigal and Shamaly's usage is not unusual in the literature; however, I will in this paper follow my narrower usage of 'tachyon' because the three-fold distinction I sketch between different types of superluminal propagations allows me to make certain claims with less risk of misunderstanding.

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*t'*) frame are perfectly entitled to draw *their* axes as orthogonal and the axes of the lab frame as rotating away from the light cone.) Recall that the spatial hyperplanes of a Lorentz frame serve as its hyperplanes of simultaneity when simultaneity is defined according to Einstein's clock synchronization convention (see Taylor and Wheeler 1966). Any string of events along a line parallel to the *x*-axis of *S* is simultaneous in *S*, though not in any frame moving with respect to *S*. As the *x'*-axis rotates toward the light cone, there will be exactly one relative velocity between lab and moving frames at which the spatial axis of the moving frame coincides with *OE*, and just as Maxwell says, in this frame *and this frame only* the propagation along *OE* will be instantaneous (though it is superluminal in all frames). Indeed, if *u* is the velocity of a superluminal propagation with respect to the lab frame, then this propagation moves infinitely fast not in a frame 'truly at rest' as Dainton has it, but in a frame moving with velocity $v = c^2/u$ with respect to the lab frame.[5]

There are thus two salient facts about instantaneity in special relativity: first, instantaneity with respect to a frame of reference is a perfectly admissible concept; second, there is no invariant concept of instantaneity if 'instantaneous' means 'traversing a distance with no lapse of coordinate time'. (The frame-dependence of instantaneity is merely the relativity of time-coordinate simultaneity in different words.) There is no question that the frame-dependence of infinite velocity clashes with Newtonian intuitions that are hard to dislodge. However, because instantaneity (or equivalently infinite velocity) is a frame-dependent concept, there is no way that any form of superluminal propagation (even though it is necessarily infinitely fast in some frame, as shown in Fig. 1) could define an absolute rest frame, a notion that cannot even be represented in the mathematics of special relativity (let alone on a spacetime diagram).

Another way to look at it is to note that any ordinary object moving at some velocity less than the speed of light defines a special frame as well, namely its local co-moving rest frame. No one supposes that the fact that every subluminal object is at rest in its own private inertial frame picks out a 'privileged' frame whose existence threatens the Principle of Relativity. The local co-moving frame of a subluminal particle is determined by the contingent details of that particle's history, and is not by itself a universal law of physics. Similarly, no one need suppose that if there is so much as one instance of superluminal propagation in the universe then its existence would pose a threat to the Principle of Relativity just because its motion is instantaneous in a particular frame of reference. Again—any such frame of instantaneity would be picked out not as a matter of universal law but as a consequence of the accidents of the dynamical history which led to that particular propagation.

It is essential to grasp that while the Principle of Relativity requires that there be a covariant description of every possible physical process, it does not imply that everything looks the same in every admissible state of motion.[6] As noted, any discrete object is at rest only in its own local co-moving rest frame. Another pertinent example is the electromagnetic field; it has a covariant description (see, e. g., Misner, Thorne, and Wheeler 1973, §3.4) but this surely does not mean that any given electromagnetic field looks the same in all states of motion. For example, the field of a point charge in its own rest frame has no non-zero magnetic components, but this hardly implies that the rest frame of a charge is 'privileged' (even though when doing electromagnetic theory it is often useful to simplify a problem by finding a frame, if one can, in which some components of the field vanish). Similarly, *pace* Maxwell, the fact that any superluminal influence is infinitely fast in one but only one frame does not contradict the Principle of Relativity.

There is a subtle fact about relative velocities that is not always explicitly mentioned in books on relativity, and a failure to grasp this subtle fact may be a cause of some of the confusion about superluminal motion. In special relativity all velocities (except for the velocity of light itself) are relative, *including* zero and infinite velocity. However, it is an *invariant* fact whether or not two physical systems have a certain *relative* velocity. Thus it would be an invariant fact whether or not a certain tachyon beam is instantaneous relative to a certain inertial frame. Perhaps this is part of what has puzzled those who apparently believe that the mere existence of superluminality would imply the existence of an invariant or 'absolute' state of motion other than the motion of light itself. Dainton *et al.* possibly have confused the *invariant* fact that any superluminal propagation has infinite velocity relative to one frame (which one depends on the spacetime trajectory of the superluminal effect) with the notion (not correct) that any superluminal propagation would be invariantly infinite for *all* frames.

When Dainton speaks of 'truly' instantaneous connections his usage is ambiguous. No connection outside the light cone is instantaneous in more than one physical frame although in that frame it is 'truly' instantaneous. Which frame it is depends upon initial conditions and is not some law of nature. And since any instantaneous connection is *superluminal* in all frames the question of instantaneity is a red herring; the real question is what we are to make of superluminal influences.

Let's go back to Cabello's worries about Bell correlations. There is no question that if they are due to any sort of causal influence it must be superluminal, and if it is superluminal in one frame it is superluminal in all. However, that hardly implies that such superluminal influences would be instan-

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5 - *This follows from the Lorentz transformation for time:* $\Delta t' = 0 = (\Delta t - u\Delta x/c^2)$ *implies* $\Delta x/\Delta t = v = c^2/u$. *See Rindler (1979), especially pp. 90-91.*

6 - *What I say here does not add much to the very clear argument given by F. A. Muller (1992).*

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taneous in *any* given frame. In which frames they happen to be instantaneous would depend upon the initial and boundary conditions of the experiment. Thus, there certainly is a theory that allows for influences which are instantaneous in one frame and finite (though superluminal) in all others: it is called 'special relativity.'

## 3 – Superluminal influences would not allow detection of absolute motion

In order to address TS3, let's consider a slightly more complicated scenario. In Fig. 2, Alice and Bob are localized observers moving through spacetime. They were initially coincident at O and at that point they synchronized their local co-moving standard clocks. As the diagram suggests, they undergo varying accelerations in their careers through spacetime. If they are brought back into coincidence at a much later point it will be found that in general their elapsed proper times (given by the readings on their co-moving clocks) will differ. This is the much-debated Twin Paradox, which is based on the fact that elapsed proper time is path-dependent but invariant while coordinate time (as defined by Einstein's clock synchronization convention) is global but frame-dependent. (See Marder 1971, Arthur 2008, and H. R. Brown's lucid discussion of clocks as the `waywisers' of spacetime, in Brown 2006, p. 95.)
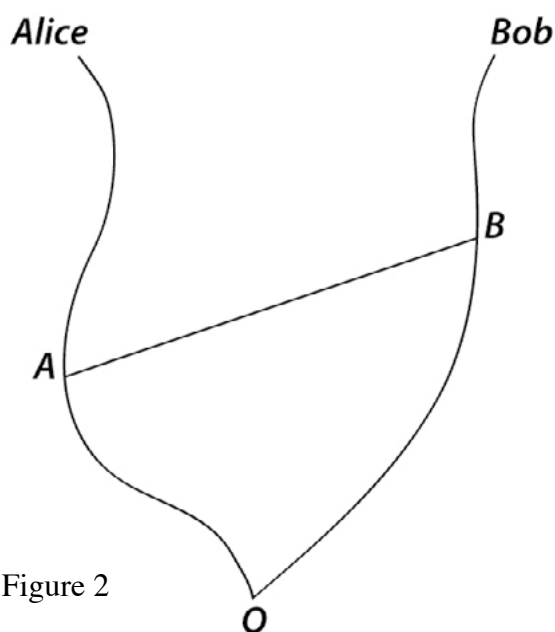


Figure 2

Suppose that Alice emits a tachyon beam at *A* which moves with constant superluminal velocity until it happens to inter-

sect Bob's worldline at his world point *B*. I say 'happens to' since I'm not appealing here to any speculative theory that would give rules governing the motion of tachyons; for all we know, Alice's tachyon beam could have been emitted in a random direction in spacetime and the fact that it intersects Bob's worldline at *B* could be pure chance. Nevertheless, it is invariant that the beam intersects Alice's worldline at *A* and Bob's at *B* and that it follows a certain trajectory through spacetime between these world points. The ordering of *A* and *B* with respect to a global time coordinate is frame-dependent, but the fact that these points are connected by the tachyon beam is not.

If Alice and Bob happen to be (even momentarily) at rest with respect to each other at the points *A* and *B*, then they share a common inertial frame, which can be defined so that the line *AB* is its spatial *x*-axis. The tachyon connecting *A* and *B* will be instantaneous in this frame (and, strictly speaking, in any frame related to it by mere translation). This, at the risk of repetition, is certainly an invariant fact. But if Alice and Bob are linked by a tachyon beam which is instantaneous in their mutual rest frame, that does not in the slightest degree imply that Alice and Bob are 'absolutely' at rest, as Lucas and Dainton seem to think. The invariance of a state of relative rest does not imply the existence of a globally invariant state of rest any more than does the invariance of the fact that Alice and Bob could be moving at some non-zero finite velocity *v* with respect to each other imply that *v* is an absolute velocity in any sense that would have interested Newton. Again, the mere fact that Alice and Bob might be connected by a tachyon beam---or for that matter a string of flashbulbs which happen to have been arranged so as to pop off simultaneously in Alice and Bob's mutual rest frame because *kinematically* these things are equivalent—surely does not by itself imply that they are at rest in any 'absolute' sense. This is despite the fact that it could be an invariant fact that they are *relatively* at rest.

Now, what about detectability? Let us imagine what some might say would be the worst case scenario, which would be that Alice can 'ping' Bob by means of a readable tachyon signal along *AB* and Bob can bounce a readable response back to Alice along *BA* with no lapse of proper time for her[7] between transmission and reception, and with a complete picture of Bob's local physical state at *B* encoded in the return signal to Alice. The tachyon probe would make it as if Alice at *A* could be momentarily coincident with Bob at *B*. Alice can therefore learn exactly as much but no more from the tachyon signal than she could if she and Bob's worldlines happen to cross at *A* and *B*. Even with this much information about Bob, the very most that Alice could know about Bob's velocity at *B* is his *relative* velocity with respect to her at *A*. Why? Because

7- *I have not said anything about the elapsed proper time for the tachyon between A and B. On the orthodox reading of special relativity, proper time for spacelike propagations is imaginary since $ds^2 < 0$ outside the light cone. However, in the superluminal kinematics developed by Sutherland and Shepanski (1986) $ds^2 \geq 0$ for all intervals, spacelike and otherwise. It is beyond the scope of this paper to adjudicate between their view and the orthodox view. How we parameterize proper time along the tachyon's path is not relevant to our discussion here.*

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that is all the information about Bob's state of motion there is to be had—Bob doesn't *have* an absolute velocity. Alice can use the tachyon beam to determine the *invariant* fact of her *relative* velocity with respect to Bob, but if she understands relativity theory she will not be confused by the fact that it is invariant whether she and Bob are relatively at rest at certain points.

Indeed, Alice need not have used tachyon beams at all to know her state of motion with respect to Bob's at *A* and *B*, for she and Bob (when they were coincident at *O*) could have arranged in advance that they would follow acceleration schedules such that they would be relatively at rest at points *A* and *B*. No one would dream of suggesting that the fact that they could do this would define an absolute state of rest that would violate the Principle of Relativity. There is no good reason at all to suppose that the mere fact that Alice and Bob can somehow infer that they are mutually at rest at some spacetime points or others implies the existence of an absolute or invariant state of rest, and this fact is independent of whether they are connected by a tachyon that happens to be instantaneous in their mutual rest frame, whether the 'connection has some detectable effects,' or whether Alice at *A* and Bob at *B* have any way at all of measuring directly or inferring each other's states of motion.

There's another way of looking at it. Suppose the point *O* is at rest in the 'lab' frame, and suppose as before that Alice and Bob are momentarily at rest with respect to each other at points *A* and *B*. At those points they could be moving at any velocity from zero to arbitrarily close to but not equal to *c* with respect to the lab frame. There are therefore indefinitely many velocities with respect to the lab frame at which Alice and Bob could be at rest with respect to each other. Hence the fact that they can be at rest with respect to each other can hardly define a unique state of rest, which would surely have to be unique if it were indeed 'absolute.' Again, this is completely independent of whether or not Alice or Bob could use tachyons or any other means to tell that they were relatively at rest at *A* and *B*.

These observations help to explicate a remark made by Arntzenius (1990, pp. 229-230):

> When W. Salmon [claims] that tachyons, if they could be used as signals, could establish absolute simultaneity, he does not indicate how one could do this. Assuming the frame-independence of the speed of light, and the frame dependence of the speed of tachyons this in fact appears to be a hopeless project: which tachyons exactly are to be used to establish absolute simultaneity?

What I am mostly doing here in my response to TS3 is to spell out in almost painful detail this point made by Arntzenius in 1990.[8] With apologies to Arntzenius, it seems that this point needs to be made again, with as much clarity as can be mustered. Again, if I may: *Any* tachyon is instantaneous with respect to *some* frame and there is no basis on which to pick one tachyon as definitive of an invariant state of rest. Conversely, for *any* inertial frame there is a trajectory which is instantaneous in that frame; which of the indefinitely many such frames do we pick as privileged?

# 4 – Superluminal influences would not conflict with Einstein's relativity of simultaneity

It should be clear that TS1-3 can be obviated by a bit of careful thought about how spacetime diagrams work. But now we must say something about Dainton's worry (TS4) about distant clock synchronization, which raises much more interesting difficulties—and possibilities. Precisely what can Alice and Bob do with tachyons that they cannot do with light signals?

First, if a readable signal, *per impossibile* perhaps, could be imposed on a tachyon beam, then Alice and Bob could momentarily synchronize their local clocks at the points *A* and *B*. What I mean is that if Alice can send her local clock reading at point *A* to Bob at point *B* then Bob could set his local clock reading at *B* to agree with Alice's local reading at *A*. Our Newtonian intuitions prompt us to think that the distant clocks are synchronized only if they have the same reading *at the same global time coordinate*. However, this has no invariant meaning in special relativity, whereas it is invariant whether the local readings at *A* and *B* are equalized as described. Whether or not the local clock readings are equal at *A* and *B* is therefore independent of whether or not *A* and *B* are at the same global time coordinate in some inertial frame or other.

Distant clocks in special relativity can be synchronized using light signals but it takes a certain minimum amount of time to do that in *every* frame. The new thing that Bob and Alice could do with controllable tachyons is synchronize their distant clocks so that there exists an inertial frame in which the process takes *no* time. It could be done by picking the frame in which *AB* is a spatial axis connecting Bob and Alice. The events *A* and *B* are at the same time *in this frame* and the tachyon signal will be instantaneous *in this frame*. But whether or not the clocks at *A* and *B* are synchronized by tachyons interchanged between *A* and *B* is completely unaffected by any choice of inertial frame in which the process is described.

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8 - *Arntzenius' paper 'Causal Paradoxes in Special Relativity' (1990) is still an essential prerequisite for anyone who wishes to investigate the puzzles arising from the possibility of causal looping in special relativity. Where we can go beyond Arntzenius today is that more is known about entanglement and extended versions of quantum mechanics such as the two-state formalism; these topics, which open the door to decidedly non-classical notions of causation, are discussed briefly in later sections of the present paper.*

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I said that Alice and Bob could synchronize their clocks 'momentarily' because unless they happen to remain at rest with respect to each other their local clocks would get out of synchrony again as they continue their careers through spacetime. On the other hand, if Alice and Bob continue to stay at rest with respect to each other then their clocks, once synchronized by tachyons at $A$ and $B$, would stay in synchrony.

The crucial point of this story is that Alice and Bob's ability to synchronize their clocks using tachyons would not violate the relativity of simultaneity defined as equality of a global time coordinate, because the latter is based upon Einstein's considerations about how one could synchronize clocks using light rays given that the speed of light is both finite and invariant. Einstein's way of defining time-coordinate simultaneity neither assumes nor requires that light signals be either the fastest or the only way of communicating between distant events; it's only about what can be accomplished with light signals.[9] Alice and Bob could have tachyon-based radios and yet still go ahead and set up a coordinate system using ordinary laser beams and Einstein's synchronization procedures (as in, e. g., Wheeler and Taylor 1966), and all the strictures identified by Einstein would continue to apply to the latter. The possibility of tachyon signals makes no difference to the relativity of time-coordinate simultaneity, for it simply would give *another way* of coordinating distant events than by means of electromagnetic signals. This point was made by G. Nerlich quite some time ago (1982) but it seems that it must be made again.

Thus Salmon's statement that 'the relativity of simultaneity... hinges crucially upon the existence of a finite upper speed limit on the propagation of causal processes and signals' (1980, p. 122) is simply incorrect. The relativity of time-coordinate simultaneity (where times are defined using the synchronization procedure recommended by Einstein in 1905), and indeed the entire mathematical structure of special relativity, is dependent upon the assumption that the vacuum speed of light is a finite *invariant*, not necessarily a maximum. It seems clear that Einstein himself believed that $c$ is a universal speed limit, and it is also clear that many authors would *prefer* that this were the case,[10] but that assumption is not ma-

thematically required in order to derive the Lorentz transformations. To confirm this, review Einstein's own derivation of the transformations (1905), or see any standard presentation of special relativity (e.g., Wheeler and Taylor 1966).

If there are, indeed, superluminal influences or connections of some sort, then there is no good reason to think that they could not peacefully coexist in parallel with Einstein's time-coordinate simultaneity.[11]

# 5 – But superluminal influences might allow alternative concepts of simultaneity

What would superluminal influences, controllable or otherwise, add to our understanding of simultaneity? Is there any sense in speaking of superluminal influences as definitive of simultaneity-like relations on spacelike-separate events?

The problem is that even though everyone knows that simultaneity defined in terms of global a time coordinate is frame-dependent, almost everyone still wants time-coordinate simultaneity to do the same metaphysical work that absolute-time simultaneity does in Newton's universe. Newton's absolute time is the great steady heartbeat of his universe, and all physical changes in that universe are with respect to it. In Einstein's universe there are indefinitely many ways of coordinatizing events; none are metaphysically privileged though some may be preferable for practical reasons. Einstein's procedure for setting up space and time coordinates using light signals and standard measuring rods is, to be sure, very useful (in large part because it nicely reduces to the Newtonian picture in the limit of low relative velocities), but it is only one possible way of painting coordinates onto events; general covariance tells us that no coordinatization of events is privileged in any physical or metaphysical sense (Rovelli 2004).[12] It is therefore not automatically given that any physical connectivity or equivalence between spacelike separate events must be described in reference to hyperplanes of

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[9] - *The persistent belief that relativity is based upon the assumption that light is a 'first signal' (as in Reichenbach, 1957) is arguably an instance of what John Woods (2003, p. 153) has described as the* Heuristic Fallacy:

> *Let H be a body of heuristics with respect to the construction of some theory T. Then if P is a belief from H, which is indispensable to the construction of T, then the inference that T is incomplete unless it sanctions the derivation of P is a fallacy.*

*(Woods goes on (p. 154) to explain diplomatically that many fallacies are errors 'that even the attentive and intelligent are routinely disposed to make.') While the notion that c is a limiting velocity certainly played a key historical role in motivating the construction of special relativity by Einstein and Poincaré, this notion is not formally used as a premise of the theory, and it is only debatably a theorem of special relativity.*

[10] - *An important example is J. S. Bell, who said that by his theorem 'maybe there must be something happening faster than light,* although it pains me even to say that much' *[emphasis added] (Mann and Crease 1988, p. 90).*

[11] - *In this paper I have entirely skirted the large and subtle literature on the conventionality of simultaneity, because that problem is about what can be accomplished with light signals—an important question that is orthogonal to my interest here, which is to explore what could be accomplished with other sorts of signals than light. For an up-to-date review of the conventionality of simultaneity, see (Brown 2006, pp. 95-105).*

[12] - *In many relativistic cosmologies, such as Robertson-Walker universes, there can be a global time, but it is* history-dependent *and does not conflict with general covariance. See, e.g., (Weinberg 2008).*

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constant time coordinate.

This, by the way, is the blind spot that has dogged discussions of the problem of finding a covariant description of quantum state reduction. Even the best-informed authors in this literature (e.g., Aharonov and Albert 1980, 1981) assume that wave function collapse has to occur over hypersurfaces of constant time coordinate, which leads to the immediate conclusion that there is no covariant description of the process, if it is a physical process at all.[13] If one were to seek a covariant description of state reduction, one would want to see if this can be done in terms of covariant properties of the wave function.[14] An obvious candidate is *phase*:  it is far more natural to think of wave functions as reducing over hypersurfaces of constant phase, and this automatically gives a covariant picture; given appropriate initial conditions, it may also be possible to describe state reduction in terms of constant *action* (Rietdijk 1985; Peacock 2006). These proposals require much technical development but, from the spacetime point of view advocated in this paper, the conventional assumption that state reduction is linked to hypersurfaces of constant time coordinate seems to be among the *least* promising approaches to the problem.

Returning to the problem of simultaneity, consider Fig. 2, and again suppose there is some sort of connection or influence outside the light cone between points *A* and *B*. This would most likely be quantum mechanical in its basis, but to see the point I want to make we need not worry about the precise nature or origin of this connection; whether or not there are such influences or connections is an empirical question which cannot be settled on an *a priori* basis from the postulates of special relativity as they presently stand.  Whatever the details of the dynamics may be, the *kinematics* of such connections is clear in the following respect:  the connection between *A* and *B* is *factual* in the sense that all observers in all states of motion will agree that it is *those* two points, *A* and *B*, which are connected in this particular way; the fact that these points are connected is relativistically invariant. As we have seen, *A* and *B* will be at the same time in one and

only one frame, which (again) is 'distinguished' only by its dynamical history and not by some law of nature. In all other frames *A* and *B* will be at different time coordinates, and so whether or not two spacetime events are connected in this peculiar invariant but history-dependent way has nothing to do with whether or not they are at the same time in some Lorentz frame.

I would now like to suggest that if such connections do exist it is meaningful to say that they define a kind of simultaneity relation between *A* and *B*—though obviously not the sort of simultaneity defined by Einstein, which is based on equality of a global time coordinate.  A full treatment of this question is beyond the scope of this paper, but I'll try to say enough to show where this inquiry could go.

The key is that the modern usage of the term 'simultaneity' equivocates on two distinct senses of the term.  According to Max Jammer (2006, p. 11), the etymological root of 'simultaneity'

> is, of course, the Latin "simul," which in turn derives from the Sanskrit "sem" (or "sema"), meaning "together," both in the sense "together in space" and "together in time".

The *Oxford Latin Dictionary* (Souter *et al.* 1968) tells us that the Latin *simul* has two distinct senses: two events may be *simul* if they occur at the same time, but events may also be judged *simul* if they are in some way *together* or *in joint process*—that is, part of some larger or more extensive coherent whole. Our events *A* and *B* are *simul* in the second sense in all frames of reference, but *simul* in the first sense in only one. The notion of simultaneity as joint process is an epistemically more primitive sense of simultaneity than simultaneity in terms of time coordinate, since judgements of time are built up from judgements of coincidence (localized joint process) between clock readings and localized events. In a Newtonian universe it is natural to assume that events in joint process are at the same absolute time, but this does not follow in an Einsteinian universe.[15]

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13 - According to Aharonov and Albert (1980, p. 3322),

> [i]n the nonrelativistic case a measurement is taken to set initial conditions for the propagator over the equal-time hypersurface of the measurement event... In the relativistic case, however, different observers will in general have different definitions of this hypersurface... different observers may derive different sets of probabilities.

They go on to explain that there is, after all, a consistent way of predicting the probabilities of local measurement results, with the aid of microcausality, but 'a description of the physical system in terms of its observables simply cannot consistently be written down' (1980, p. 3324).  But if state reduction is superluminal, which it must be, then for the elementary kinematic reasons explained in this paper there is only one frame in which it could reset probabilities over an equal-time hypersurface. Therefore, it is just a mistake to suppose that every observer would describe the reduction process as instantaneous.

14 - It is important ton say what sort of wave function we are discussing when we talk of the problem of finding a covariant description of wave function collapse. The wave function is not necessarily an object living in configuration space.  A wave function in general is simply the projection of the state function into a continuous representative (see Cohen-Tannoudji, Diu, and Laloë 1977, Ch. II, §E) which could be configuration space, ordinary spacetime, or momentum-energy space. What I am talking about here, and what most of this literature concerns itself with, is the de Broglie wave packet, which is a projection of the state function into Minkowski space; see (Dirac 1958, §30) for a succinct review of the de Broglie wave.

15 - A small number of authors have explored the notion that there are distinct senses of simultaneity.  Adolph Grünbaum (1973, p. 203) defined what he called topological simultaneity:  events simultaneous in this sense are those that cannot be connected causally.  Since he thought that any sort of spacelike causal connections are excluded by relativity theory, all events spacelike separate from A are topologically simultaneous with respect to it. Whether or not events are

# Would superluminal influences violate the principle of relativity?

In orthodox relativity the notion of invariant joint process is accepted so long as the events are coincident. In Einstein's words (1916, p. 115),

> We assume the possibility of verifying 'simultaneity' for events immediately proximate in space, or—to speak more precisely—for immediate proximity or coincidence in space-time, without giving a definition of this fundamental concept.

But even in his earliest writings on the theory of relativity Einstein was well aware that the notion of the coincidence of two presumably point-like events is neither mathematically nor physically clear:

> We shall not here discuss the inexactitude which lurks in the concept of simultaneity of two events at approximately the same place, which can only be removed by an abstraction (1905, p. 39).

Up to now I have been largely concerned with pointing out the respects in which superluminal influences are consistent with relativistic kinematics as presently understood. We now reach a boundary beyond which one must consider ways in which relativity needs to be expanded to take account of quantum mechanics. Physics can no longer avoid addressing the 'lurking inexactitude' cited by Einstein.

In classical relativity the ambiguity in the notion of infinitesimal closeness is simply ignored; spacetime is taken to be built up out of point-like events and if these are spacelike separate they are presumed to be causally disjoint (except insofar as they can be linked by backwards and forwards light cones). Therefore, from the point of view of quantum mechanics the concept of an event in classical relativity is ambiguous in two respects. First, the physical meaning of coincidence or infinitesimal closeness is unclear. This is partially because of the Uncertainty Relations; also, some current approaches to quantum gravity (e.g., Ali, Das, and Vagenas 2009) open up the possibility that space and time may be discrete at the Planck scale. If spacetime is discrete then even events separated by one quantum of length are spacelike separate and, by the classical criteria, could not be considered coincident. Second, and most pertinent to the theme of this paper, is the vexing question of whether events outside each other's light cones are causally disjoint. No one doubts that any collection of events can be associated by convention in an essentially arbitrary way; the question is whether it makes any sense to speak of *distant* events as being in 'joint process' in a causal or dynamical way that is somehow demanded by the physics of the situation.

There is increasing evidence that quantum mechanics shows that distant particles, especially if they are entangled, may be nonseparable or form or partake in a unity in surprising ways. It may therefore be sensible to generalize the conception of an event to allow for events and states that are extended throughout spacetime in an invariant way.

A dramatic example of the inseparability of spatially extended quantum states appears in a recent experiment by K. C. Lee *et al.* (2011). These experimenters used a complicated interferometric apparatus in which two 3 mm diamond chips separated by 30 cm were put into entangled phonon states (phonons are quanta of vibrations) and then 'pinged' by an ultra-high frequency laser. The key point for our discussion here is that the diamond chips were demonstrably put into a *single* quantum state despite their spatial separation. As Lisa Grossman explains (2011),

> [t]o show that the diamonds were truly entangled, the researchers hit them with a second laser pulse just 350 femtoseconds after the first. The second pulse picked up the energy the first pulse left behind, and reached the detector as an extra-energetic photon. If the system were classical, the second photon should pick up extra energy only half the time—only if it happened to hit the diamond where the energy was deposited in the first place. But in 200 trillion trials, the team found that the second photon picked up extra energy every time. That means that the energy was not localized in one diamond or the other, but that they shared the same vibrational state.

It is as if quantum mechanics simply does not know or care that the two diamond chips are 30 cm apart. Lee *et al.* do not attempt a covariant description of their nonlocal energy states but their result is an example of the sort of scenario we discuss here: at certain proper times along their world-lines, the two diamond chips share a certain common energy state. Whatever the detailed spacetime description may be (this remains to be worked out) it has to be an invariant fact that *those* points on their world-lines are linked in *that* particular invariant and nonseparable manner. Most important, the single nonlocal energy state shared by the two distinct diamond chips is demonstrably not reducible to two local energy states possessed by the two chips. That's an important part of what it means to say that the state is entangled: it is not separable into distinct and localizable sub-states. To be sure, the diamond chips have other physical properties that are localizable in the normal way, but their non-separable, spatially-extended energy state seems to be a very natural candidate for an entity that is *simul* in the second sense. One cannot avoid speaking of it as being in 'joint process' because

topologically simultaneous is an invariant distinction. Brent Mundy (1986) similarly defined what he called causal *simultaneity as the absence of any possible causal connection*, but unlike Grünbaum he argued that relativity does not logically exclude the possibility of spacelike causal connections; therefore, on Mundy's view, the sets of causally simultaneous events might not comprise the whole region outside the light cone. The synchronization of distant clocks according to Einstein's clock synchronization convention was called by Mundy optical *simultaneity*. Mundy argued that the presentations of relativity by Grünbaum and Reichenbach (1957) are reconstructions, based on the unnecessarily strong assumption that light is a 'first signal,' which distort the meaning of the theory and drastically limit its scope.

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it cannot even be analyzed into distinct localized parts.

It is quite likely that such alternative notions of simultaneity as suggested here—invariant but history-dependent—would violate some people's intuitions about a vaguely-defined 'Spirit of Relativity,' but it is not obvious that they are not allowed by the mathematical structure of relativity and they seem to be demanded by quantum physics. While relativity is far more amenable to superluminal influences that has been generally supposed, ultimately it is classical relativity that must adapt itself to the quantum (Chang and Cartwright 1993; Peacock 1998).

To summarize: if we grant that there could be invariant connections between spacelike separate events, likely quantum mechanical in their basis, then it is reasonable to call it a kind of simultaneity relation because it answers to the notion of distant events as being part of a single process. Quantum mechanics *prima facie* demands that we disambiguate the two key senses of simultaneity that have been conflated since the time of Newton.

## 6 – Are 'causal' accounts of quantum mechanics consistent with the Principle of Relativity?

An anonymous referee for this paper made a very helpful observation:

> [T]here are theories that are phenomenologically compatible with special relativity in which superluminal propagation does pick out a preferred frame. Bohmian mechanics (also referred to as 'pilot-wave' theory or de Broglie-Bohm theory) has a preferred frame of reference. Perhaps theories like these are feeding the intuitions of those making claims akin to TS2...

This is quite likely right. For instance, Maudlin (2002) argues that Bell's Theorem could force us to concede that there is a special frame which is preferred although *undetectably* so. Thus one must ask whether any theory that attempts to underpin quantum statistics by means of nonlocal dynamics is *necessarily* in conflict with Lorentz invariance. Or to turn the question around, can there be a *covariant* theory of nonlocal dynamics?

Bohm's 'hidden variable' theory of 1952 (Bohm 1952; Cushing 1994) is Galilean-invariant because Bohm never intended it to be otherwise; his aim was to show that non-relativistic wave mechanics could be underpinned by a causal (though unavoidably superluminal) dynamics in which particles apparently have definite trajectories. Hence it is reasonable to investigate whether a relativistic generalization of Bohm's

theory is possible. Bohm himself apparently thought not: he and Basil Hiley state that 'it would be extremely surprising to obtain a Lorentz invariant theory of particles that were connected nonlocally' (Bohm and Hiley 1993, p. 282). They consider two spacelike separate particles A and B, 'both at rest in the laboratory frame' at worldpoints a and b respectively, and then remark,

> [i]f there is a nonlocal connection of the kind implied by our guidance condition, then it follows that, for example, points a and b instantaneously affect each other. But if the theory is covariant, there should be similar instantaneous connections in every Lorentz frame.

Their accompanying figure shows connections from a to other points on B's worldline. Although their language is unclear, Bohm and Hiley do seem to grasp that each possible spacelike connection between a and the points along the worldline of B would be instantaneous in one and only one Lorentz frame; there is no covariant sense in which *all* are instantaneous. However, they go on to say that from the fact that there could be instantaneous connections between a and earlier points on A's own worldline via points on B's worldline, it would be possible to set up a typical closed-loop causal paradox in which an influence from a could interfere with A's own history at an earlier worldpoint along A's worldline in such a way as to prevent the influence from being emitted at a.

Closed causal loops are a genuine problem for superluminal theories, but the risk of a closed causal loop has nothing to do with whether or not the connections are instantaneous in some frame or other, for that is a frame-dependent concept. To this extent, Bohm and Hiley suffer from confusions about instantaneity similar to those I have criticized elsewhere in this paper. Rather, the risk of closed-loop paradox has to do with the invariant fact that points in spacetime can sometimes be connected in a closed loop by means of the presumed superluminal influences; the problem, if any, arises from the fact that the influences would be superluminal (and thus outside the light cones of both A and B), not that they would be instantaneous. So the question that matters is whether any putative superluminal theories should be rejected *just because* they may open up the possibility of closed causal loops. I'll return to this point below.

While Bohm's theory is the best-developed causal alternative to conventional quantum mechanics, it is not the only possible such theory. Late in his life Louis de Broglie was inspired by Bohm to revisit his own early attempts at a causal version of quantum mechanics (1960, 1970). De Broglie's late causal theory, though incomplete in many respects (for instance, it applies only to spin-0 particles), is fully Lorentz-covariant. Bohm and Hiley themselves were not comfortable with theories like de Broglie's later approach (see their 1993, p. 238) because such theories imply that any particle inte-

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racts *via* the four-dimensional wave field with other particles both past and future throughout spacetime. Bohm and Hiley seem to have thought that this was simply too strong a violation of classical intuitions or expectations about causality. This is why they rejected the possibility of covariant pictures of nonlocality (such as de Broglie's), *not* because such theories are technically out of the question.

The need to revise our intuitions about causality could be the price to be paid for any causal interpretation of quantum mechanics that satisfies the Principle of Relativity. In particular, a four-dimensional picture of the wave field could be the answer to worries about paradoxical closed causal loops: if such loops are mediated by a genuinely covariant quantum field then it simply would not be possible to write a description of a self-contradictory loop in the language of the theory, any more than any other sort of quantum state vector can be validly written in manifestly contradictory terms. That is, while there may well be amplitudes for past-future-past loops, each possible amplitude could only be for sequences of events (more precisely, measurement outcomes) that are mutually consistent. Thus, while such a theory such as de Broglie's would certainly do violence to classical intuitions (prejudices?) about the proper order of cause and effect it is quite likely that it would *not* allow for outright logical paradoxes of the kind that worried Bohm and Hiley.

A similar picture arises in the two-vector formalism studied by Aharonov, Popescu and Tollaksen (2010). Their theory is not explicitly a causal interpretation of quantum mechanics, but it also considers amplitudes from both the past and the future. It could be worthwhile to investigate parallels between de Broglie's Lorentz covariant causal theory and the two-vector formalism. Although there are closed loops in the two-vector formalism, there is no risk of paradox for the reason outlined above: no single looped amplitude is, in itself, inconsistent. Like the possible states of Schrödinger's cat, the possible classical outcomes may well be inconsistent with each other, but each possible outcome set is internally consistent—*and only one is ever observed.* In versions of quantum mechanics that allow for future-to-past amplitudes, the mystery of causal looping is therefore subsumed into the larger mystery of understanding the relation between the quantum mechanical descriptions of physics in terms of

amplitudes and the outcomes that are actually observed. These possibilities require much further study, but enough is known now to show that one should not *automatically* reject a version of quantum mechanics because it allows for causal loops.[16]

There is a larger question: Lorentz invariance itself fails to satisfy the Principle of Relativity in a certain crucial respect, since the Lorentz transformations are divergent at a critical velocity (the velocity of light in vacuum). Sutherland and Shepanski (1986) point to this as the key factor hindering the extension of the principle of relativity to all relative velocities, since it makes it impossible to cover all of spacetime, both inside and outside the light cone, with a single group of continuous transformations. It is thus impossible to transform *to* a frame moving with velocity *c* and this fact arguably violates the presumption of the equivalence of all frames. It is conceivable that a deeper theory which avoids this problem (possibly by allowing for quantum effects which would suppress the divergence at velocities very close to *c*) will obey some invariance principle more general than Lorentz invariance. Let us call such a to-be-written principle *Planck covariance*. Presumably it would would reduce to Lorentz invariance in suitable limits just as Lorentz-covariant theories reduce to Galilean theories in the limit of low relative velocities.

I have indulged in some reasonably well-founded speculations in this section. However, what is not speculative is that (as the example of de Broglie's theory shows) it is not necessarily the case that any account of quantum mechanics in terms of some more general physical principles would demand the return to Galilean covariance and a preferred frame; rather, the move to a fully quantized theory of relativity will probably take us even farther from Galilean covariance than does special relativity.

# 7 – Summary and what must lie ahead

A lot more needs to be said before anyone has any business being entirely comfortable with the notion of superluminal influences, quantum mechanical or otherwise.[17] But a neces-

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16 - *There is a large literature exploring the puzzle of closed causal loops that could arise given the possibility of time travel or backwards causation (not necessarily in the context of quantum mechanics). Some notable papers in this genre include Arntzenius (1990), Brown (1992), and Smith (1997). The upshot of these investigations is that it is by no means* obvious *that a physical theory should be automatically excluded because it allows for the possibility of causal looping.*

17 - *Further problems with superluminality include but are not necessarily limited to the following:*
- *The temporal order of spacelike separate events is frame-dependent; this may require the abandonment of causal order as a global invariant.*
- *With some combinations of relative velocities, superluminal trajectories can form closed causal loops, apparently allowing for logical paradoxes.*
- *Rest mass diverges at v = c, apparently precluding the acceleration of massive bodies through the speed of light.*
- *There are problems with reconciling superluminal motion with local quantum field theory as it is presently understood.*
- *In some but not all versions of superluminal or 'extended' relativity proper quantities are imaginary.*
- *It is widely though controversially held that quantum mechanical entanglement cannot be exploited for controllable superluminal signalling. (For the orthodox view of quantum signalling, see, e.g., Eberhard and Ross (1989) and Shimony (1983). For critical responses to this orthodoxy, see Peacock (1992, Kennedy (1995), and Mittelstaedt (1998).)*

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sary prerequisite to the analysis of any of the substantial problems with superluminality is to grasp the kinematics of propagation outside the light cone.

The following points are elementary even though they have been persistently misunderstood by professionals working in this field:

- Trajectories outside the light cone have a natural description in the kinematics of special relativity.
- Infinite velocity (equivalently, instantaneity) is a frame-dependent concept, and thus any form of superluminal propagation is instantaneous in one and only one frame.
- The mere existence of some form of superluminal propagation, even if it is controllable, does not imply the existence, much less the detectability, of any supposititious absolute state of motion.

It is perhaps less immediately obvious, but still clear enough, that the possibility of distant clock synchronization *via* superluminal influences does not invalidate the frame-dependence of time-coordinate simultaneity—because the latter is simply not about what one could do with superluminal signals. And finally it is arguable, though not conclusively at this stage, that the increasing evidence of dynamic inseparability in a wide variety of quantum mechanical experiments (such as the recent dramatic results by Lee *et al.* 2011) points to the cogency of notions of invariant simultaneity-like relations between spacelike separate entities (or portions of entities) that are much in the spirit of the ancient notion of simultaneity as a kind of jointness, wholeness, or coherence of possibly spatially-extensive events. The task remaining is to articulate these possibilities in a precise and testable way.

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- *The existence of space-like influences or connections demands a rethinking of the postulate of microcausality which is one of the building blocks of local quantum field theory.*

*There are candidate responses to all of these problems but they require discussion that would go far beyond the issues considered in this paper, which are prerequisites for those discussions.*

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**CONTACT ET COORDONNÉES :**

Kent A. Peacock
Department of Philosophy
University Lethbridge
4401 University Drive
Lethbridge AB Canada
T1K 3M4
kent.peacock@uleth.ca