Superluminal Signalling*

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Abstract

Special relativity is said to prohibit faster-than-light (superluminal) signalling, yet controversy regularly arises as to whether this or that physical phenomenon violates the prohibition. I argue that the controversy is a result of a lack of clarity as to what it means to 'signal', and I propose a criterion. I show that although we have no reason to think that one can send signals faster than light, this is not prohibited by special relativity.

1 Introduction

Special relativity originated as a way of accounting for the invariance of the laws of electromagnetism under the spatial and temporal coordinate transformations known as the Lorentz transformations. Whereas Lorentz understood length contraction and time dilation as changes in the properties of material bodies, Einstein was able to derive these transformations from two postulates: (1) the laws of nature look the same to all inertial (unaccelerated) observers; (2) the speed of light in a vacuum is constant, invariant under changes of reference frame. The former is simply a reaffirmation of Galileo's principle of relativity, while the latter appears to contradict it. It was Einstein's genius to see that these could be reconciled, and in fact *are* reconciled, by treating the Lorentz transformations as changes in the spatial and temporal coordinates associated with different inertial observers. One consequence of this is the relativity of simultaneity.

The existence of a finite, invariant speed of light in vacuum suggested early on that it would be impossible to send signals faster than light, and Einstein's attribution of this limit to the structure of space-time itself suggested that in fact *all* physical fields would be subject to this limitation. Yet arguments to this effect are nowhere to be found in Einstein's original work, which was primarily concerned with the propagation of electromagnetic radiation (light) and the dynamics of charged objects interacting with this radiation. Maxwell's equations do not place any restriction on the current, and one can ask, (as Sommerfeld (1905) did) though perhaps not definitively answer, what

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sort of field would be associated with a *superluminal* current. Though Einstein and others realized that the theory also implied that one could not accelerate massive objects up to or past the speed of light (due to the increase of mass with velocity), it was early on noted that it might be possible to have massive objects which *always* moved faster than light (Sommerfeld's 'tachyon').[1]

Nonetheless, it is commonly asserted that special relativity rules out the possibility of sending signals faster than light, of 'superluminal signalling.' However, it is well-known that there are physical phenomena perfectly compatible with special relativity in which 'something' travels faster than light. Thus accounts of such phenomena are usually accompanied by disclaimers explaining why the phenomenon in question cannot be used to send *signals* faster than light. In this the discussion has much in common with the discussion of Maxwell's Demon, a long-lived phantasm from the 19th-century whose activity would bring about violations of the second law of thermodynamics. In both cases, convictions run deep, but refutation is far from general. (See Leff & Rex (1990), Weinstein (2003)).

Perhaps the primary obstruction to attaining clarity on the relation between special relativity and the purported prohibition of superluminal signalling has to do with articulating just what a prohibition against superluminal signalling amounts to, while a secondary obstruction involves a clarification of the strictures imposed by special relativity. With regard to the latter, I will simply take special relativity to be the theory that says that the laws of nature are Lorentz-invariant. That is to say that all inertial frames are on an equal footing (as in Galilean relativity) and that the transformations between inertial frames are Lorentz transformations.

The characterization of superluminal signalling is less straightforward. There are a variety of approaches to the analysis of signalling in the literature. One school of thought is concerned with identifying physical objects or phenomena, e.g. "marks" (Reichenbach, 1958; Salmon, 1998) or wave-pulses (Brillouin, 1960; Jackson, *et al.*, 2001), which are understood to correspond to signals, and evaluating whether these objects can travel faster than light, i.e. whether their trajectories can be spacelike. Another school is primarily concerned with analyzing the correlations between signalling events and other, distant events, identifying whether relativistic constraints on such correlations preclude spacelike-separated transmission and reception. While the former approach suffers from a disregard for the connection (argued for below) between signalling and *intervention*, the latter suffers from a tendency to downplay the role of the equations of motion. The approach offered in this paper is something of a synthesis of the two, and may even strike some as a pedantic refinement of existing notions. However, the refinement allows one to see more clearly both the perspectival aspect of signalling (related to the subjectivity of 'intervention') and the absence of a

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[1] Here "the theory" includes the Lorentz force law, which gives the force exerted on an electric current by the field. This law is consistent with, but not directly derivable from, Maxwell's equations.

special relativity-derived prohibition on superluminal signalling.

2 Signals

A signal is often understood as some sort of disturbance that propagates through spacetime. Yet when we look at one or more fields in a single spacetime, how are we to identify the relevant disturbances? Suppose we wish to study the signal broadcast by a radio station. This is just electromagnetic radiation, and there is much electromagnetic radiation propagating through our atmosphere (other radio stations, GPS signals, etc.) and indeed through the cosmos (stellar radiation, galactic jets, microwave background). In practice, we extract 'the' signal using an antenna, which is sensitive to a limited range of wavelengths. Of course, this doesn't really work all the time – sunspot activity has a way of intruding on radio transmission, for example.

Even if we succeed in identifying some characteristic signal from amidst the background, we have to identify a moment of transmission and a moment of reception in order to define a velocity for that signal. (Of course, we should also identify the frame of reference.) If the transmission and the reception are spacelike, we say the signal has been transmitted superluminally; otherwise, not.[2] Viewed purely in terms of the signal, this is somewhat problematic. Ordinary signals are extended in space and time. Think of the word 'one', for instance – as a written symbol, it is spread out in space; as a soundwave or radio transmission, it is a wave-pulse extended in space and time (Hopfield & Brody, 2000, 2001). If we want to talk about the velocity of propagation of the signal associated with this pulse, we need to identify which part of the pulse at which time corresponds to the initiation or transmission of the signal, and similarly for the reception.

Let us simplify a bit and think of a smooth pulse in a single spatial dimension. One's intuition might be that it doesn't matter which part of the pulse one looks at, for as long as it is transmitted accurately, the entire structure will move as one. However, this is not the case, in general, for even if the pulse retains its shape, the velocity of the peak (the group velocity) need not equal the velocity of the leading edge. In other words, the pulse will generally spread or be otherwise distorted, unless it is a linear field propagating in a vacuum. Sommerfeld and Brillouin (both in Brillouin (1960)) noted that certain velocities associated with light propagation, e.g. the group velocity of a wave-packet in a *dispersive* medium, could in fact be *faster* than light. In recent years such phenomena have been realized in the laboratory (Wang, *et al.*, 2000), while all along it has been clear that there are many physical phenomena – for example, a shadow cast by a moving object on a distant surface – which can move faster than light.

If we are to settle on a candidate for the portion of the pulse that is to correspond to the

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[2] Signals that travel into the past lightcone are said to have negative but subluminal velocity.

transmission of a signal, we might well settle on the leading edge. Why? Because it corresponds to the initiation of the pulse, and we feel that this is the earliest time at which the signal could be said to have been induced. And indeed, this choice is salutary in that the leading edge of a light-pulse never travels faster than c.

A significant problem with this leading edge definition is the problem of noise. (See Garrison, *et al.* (1998)) Signals in the real world do not propagate against noiseless backgrounds. As a result, the leading edge of a pulse (or, for that matter, any part of the pulse) can be amplified, destroyed, or otherwise distorted by constructive or destructive interference. It is entirely unclear how to identify physically the leading edge through these various changes. In general, the issue here is whether there are suitable criteria of identity for wavelike phenomena.[3]

Even in the absence of noise, the leading edge definition tells us little of interest about cases in which the pulse is reflected or absorbed. Consider the following example. Take a laser pointer and point it at, say, the surface of the moon. Sweep it across the surface as fast as you can. If you do it in less than 1/30th of a second, then the spot will move across the face of the moon at greater than the speed of light.

If you point the laser at the moon and switch it on, this certainly may be understood as sending a signal, from the laser to the moon. The spot on the moon corresponds to the continuation of the signal, and the spot moves across the moon faster than light. Yet we do not say that the signal itself moves faster than light, that information moves faster than light, for this phenomenon apparently cannot be used to send information from one side of the moon to the other.

Now there is one line of thinking (Salmon, 1998; Steinberg, 2000) according to which the propagation of the spot is a ‘pseudopropagation’, ‘pseudo’ because a spot is (supposedly) not a real thing. However, it is difficult to conceive of a generic way to distinguish between real things and pseudo things in classical physics (and it is not much easier to conceive of such a distinction in quantum theory). In classical theory, one sometimes has particles with definite trajectories that allow one to identify the particles over time. But it is hard to see what to say about classical fields and the identity of waves and other disturbances over time.[4] So I think this approach is unprofitable.

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[3] A related problem for the leading edge definition has to do with the indefinability of the leading edge in cases of frequency modulation. Suppose we have a continuous coherent beam of red light, and we wish to send a signal by changing the frequency of light, so that it is blueshifted. (This is the sort of thing Reichenbach (1958) had in mind when he talked about the transmission of “marks”.) There is no particular point in the beam of light corresponding to the leading edge of the blueshifted pulse—there is no single point at which the light changes from red to blue.

[4] In quantum theory there are field quanta, but no associated trajectories, and furthermore there are various sorts of cases where the fundamental particle ontology is ambiguous. I am thinking here of (a) the Unruh effect, in which inertial and accelerating observers differ on whether there are particles in some region of space, and (b) the physics of the strong interaction, in which one may regard either quarks and gluons or hadrons as fundamental. See, e.g., Wald (1994) for the former, and Shifman (2001) for the latter.

3 Signalling

Recall that our study of signal propagation required identification of some event corresponding to the initiation of the signal. This suggests that, rather than following the trajectory of the signal, we should focus on the effects associated with the events that correspond to the initiation of a signal. Though this might seem to require a full-blown theory of causation, we will see that it does not.

Suppose you decide to use your laser pointer to send a message. In practice, there are any number of events that might be said to correspond to the initiation of the message. First, you 'form an intention,' then your finger moves, closing a switch, then the device warms up, then the laser light is emitted. Which of these events (in the nontechnical sense of 'spatially and temporally extended phenomena') corresponds to the initiation of the signal depends on just what physical system is deemed to be the medium of communication, and on what physical system corresponds to the user (animate or otherwise) of the medium. So for example one might consider the vacuum or the atmosphere the medium, and the laser the agent, or one might consider the laser and the vacuum (or the atmosphere) the medium, and the person the agent, and so on.

Whatever the medium is, its behavior will be understood to be deterministic, in a broad sense. That is, I will suppose that, given the state of the medium at some time, we will be able to predict the state at any future (or for that matter, past) time.[5] The medium need not be a closed system; a radio transmitter requires an external power source (hence it is an 'open' system), yet the composite system consisting of the transmitter plus empty space is, for my purposes, a perfectly good medium.

To send information, to signal, is to interact physically with the signalling medium. On the proposed analysis, a signal is simply a disturbance *of the medium*. A disturbance is understood to be an externally induced change in the state of the medium at some time and place. This is to say, it is a change which does not follow from what came before. The disturbance may be extended in time (speech) or space (think of dropping a rock into a pond), and may even occur at different times and places. The signal will generally be brought about via interaction with some external physical system, be it an animate or an inanimate object. However, the nature of this external system plays no role in our discussion - what is important is simply that it effects some sort of change in the signalling medium.[6]

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[5] More formally, this amounts to the requirement that the differential equations describing the evolution of the signalling medium have a well-posed initial value formulation.

[6] The technically-minded reader may think of a disturbance as the introduction of a forcing term into the Hamiltonian.

4 Superluminality

In order to judge whether a signal can be transmitted at superluminal speed, I propose that we do the following. Consider the time-development of the signalling medium on its own. This will naturally require:

- identification of the signalling medium, generally in terms of its degrees of freedom (e.g., field values; particle positions and momenta),
- specification of the equations of motion for these degrees of freedom (the dynamical laws), and
- specification of default initial data, i.e., values for these degrees of freedom at some time.

If there is a well-posed initial value formulation for the equations of motion, and if the initial data are appropriate,[7] then there will be a unique solution, which is to say a well-defined and unique future development of the undisturbed medium.

Note that the signalling medium and its default behavior is represented by a particular solution to a set of equations of motion. In the realm of media governed by Maxwell's equations, it may be a trivial solution such as the vacuum solution, or it may be a non-trivial solution, such as the carrier wave for a radio broadcast. A river flowing at some fixed rate might could be a signalling medium, as could a pond. (In the general case, one might wish to consider ensembles of initial data, and consequently ensembles of solutions.)

Now consider the time-development of a signalling medium which undergoes a disturbance. I.e., consider what happens when you make some (typically local) change in the initial data. As long as the new initial-value problem is again well-posed, the time development of the system will be unique, and will thus differ from that of the original system at various points in the future. If the system is made up of fields, then the set of points where the solutions first differ will be a 3-dimensional hypersurface which I will call the Surface of First Disturbance (*SFD*). (If the system is made up only of particles, then there will be a set of characteristic points in spacetime at which the particle trajectories differ from those in the undisturbed solution.) My proposal is that a classical theory allows superluminal signalling if and only if there is a signalling medium (a solution to the equations of motion) the disturbance of which gives rise to an *SFD* which contains at least *one* point that is spacelike to *all* points of the initial disturbance. (See Figures 1a and 1b) Conversely,

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[7] Proofs of the existence and uniqueness of solutions for systems of partial differential equations assume that the initial data and the solution have some degree or other of differentiability (e.g., C^3) (see Courant (1962)). What degree is deemed to be appropriate is a matter that I do not address in this article.

if no signalling medium exists that allows such a disturbance, then no superluminal signalling is possible.

Disturbing a signalling medium amounts to interfering in the time-development of the medium. We then determine whether a signal (an initial disturbance) can propagate faster than light by comparing the evolution of the perturbed intial data to the counterfactual evolution, identifying the 'effect' of the signal by comparing the actual evolution with what the evolution *would have been.* Ordinarily, such analyses of cause and effect are plagued by ambiguity, as one is hard-pressed to identify, in general, how things would have been had some event (the 'cause') not occurred. For instance, one might want to justify the claim that my dialing a certain number caused another telephone to ring by appealing to the intuition that had I *not* dialled the number, the phone would not have rung.[8] This is subject to the counterargument that the phone *would* have rung if someone else had dialled the number.

A common sort of response to this puzzle about counterfactual analyses of causality is to propose that, in determining what would have happened had the purported cause not taken place, one leave everything else the same. Thus one is explicitly blocked from considering a world in which someone else dials the same phone number. However, such a response is problematic if one is considering worlds in their entirety, because a world in which you did not dial the phone number is a world with a different past than the world you inhabit, insofar as you are a phyical object governed by deterministic laws. Though there are ways around even this objection, we will not consider them, because it is here that the counterfactual analysis of *signalling* differs from counterfactual analyses of *causation.* In the analysis of signalling, we identify certain parts of the world as evolving deterministically, and *other* parts of the world as intruding (or not) on this subsystem, and disturbing it. This buys us freedom from the ambiguities involved in evaluating counterfactuals, since we can hold the signalling medium fixed.

The price of this freedom is that the identification of the subsystem in any given situation is purely up to us, and thus any ontological conclusions are blocked. Although I am free to regard my picking up the phone as a signalling event, an event which brings about a disturbance of a signalling medium (the telephone system) including the ringing of a distant phone, I am precluded from definitively describing the dialling as a 'cause' of the ringing. Whereas the signalling claim is based on a conception of the world as comprising subsystems (particularly, signalling media) which are subject to external intervention (or, if you like, "control": see the Appendix for further discussion), a full causal analysis typically regards the world in its entirety, and attempts to attribute causal relations to events therein.[9]

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[8] Several good papers on the counterfactual analysis of causation are collected in Collins, *et al.* (2003).

[9] The necessity of identifying states of subsystems of the world, and subsequently analyzing various possible interventions, has much in common with the Copenhagen approach to quantum theory, whereby one regards state

The following sections discuss some important qualifications to the signalling criterion.

4.1 Localization of disturbance

Though the initial disturbance will typically be restricted to a finite spacetime region, we are free to consider local disturbances in several spatial regions, at the same or different times. If any point on the resulting *SFD* is spacelike to every point in all of these regions, then we say that a signal has been sent superluminally.

4.2 Initial value formulation

My characterization of signalling assumes that the initial data at some time determine the solution for all future times. Whether this actually is the case depends on the equations of motion.[10] For many generic sorts of matter with generic initial conditions, there is indeed a well-posed initial-value formulation. On the other hand, this is certainly not the case for all the types of matter that can be described in a special-relativistic context. (Indeed, gauge theories are counterexamples, though the non-uniqueness there is of a rather trivial sort.) For example, the equations of motion for 'dust' do not have a well-posed initial-value formulation, interestingly enough (see Geroch (1996)).

On the other hand, the *absence* of an initial value formulation indicates a breakdown in determinism for the system under consideration, and it is hard to see this as opening the door to the possibility of signalling, since signalling implies that the initial signal (disturbance) determines (perhaps probabilistically) the behavior at later times. A complete failure of predictability can be seen as *defeating* the possibility of signalling.[11]

The third and perhaps most intriguing possibility is that of a world in which Lorentz-invariant equations of motion have an initial value formulation, but in which the future (past) domain of dependence of a point on the initial data surface lies outside the future (past) lightcone at that point. An example of such a system is a relativistic perfect fluid with 'sound-speed' $v > c$ (where v is measured in the rest frame of the fluid). In this case, it is possible to find a spacelike surface (an 'instant of time') with respect to which the evolution of the system is well-defined. (One simply needs to find a frame of reference with respect to which the sound-speed is non-negative and use a surface of simultaneity associated with that frame.)

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preparations and measurement outcomes as being brought about by free manipulation of external, classical apparatus.

[10] It also depends on the initial data. (See previous footnote.)

[11] This is not meant to preclude the possibility of signalling media which obey probabilistic laws, such as those encountered in quantum mechanics. It is probably sufficient, but not necessary, for the evolution of the probabilities to be deterministic (as in quantum theory), though non-Markovian probabilities would seem to represent an interesting borderline case.

It is in the context of this sort of system (hyperbolic but non-causal, in the jargon of Geroch (1996)) that one should expect the possibility of superluminal signalling. In other words, if one were to describe the signalling medium as simply a perfect fluid with sound-speed $v > c$, then one would expect that the *SFD* would be spacelike to some initial disturbance.

4.3 Sufficiency and necessity

I have proposed a condition for superluminal signalling which I regard as uniquely sufficient. In light of the considerations just above, I am inclined to require the existence of a well-posed initial-value formulation as a *necessary* condition. That is, the question of whether or not superluminal signalling is possible does not even get off the ground in the absence of a medium whose state evolves in a predictable (even if stochastic) way. Taken together, these conditions constitute a kind of operational definition of superluminal signalling.

5 'No-go' theorem?

Given the criterion I have proposed, there is a clear sense in which special relativity does permit superluminal signalling, in that one can construct (deterministic), Lorentz-invariant equations of motion in Minkowski spacetime that describe the behavior of a signalling medium, and which have the property that the *SFD* resulting from a typical disturbance has points which are spacelike to all of the points in the disturbance. (Technically, this means that the characteristic surfaces are null or timelike.)

Not only does special relativity permit such fields; there are several sorts which have actually received extensive discussion in the physics literature. Least radical is ordinary quantum electrodynamics itself, considered in a curved background. There, it has been shown that vacuum polarization effects may induce corrections to the effective classical action such that photons propagate outside of the lightcone (Drummond & Hathrell, 1980; Shore, 1996). Then there are nonlinear modifications of electrodynamics, the most well-known of which is Born-Infeld (1934) theory, originally proposed as an alternative to ordinary Maxwell theory which did not suffer from the divergent self-energy associated with classical point sources. It was largely abandoned as a serious candidate for fundamental theory because of difficulties in quantization, but has recently re-emerged as an object of study in the context of string theory (Gibbons & Herdeiro, 2001). It has been well-known for some time (Plebanski, 1970; Boillat, 1970) that the theory admits superluminal propagation. More specifically, there are solutions to the Born-Infeld equations of motion which have perturbations that propagate outside the light cone. Therefore, if we take one such solution to be descriptive of a possible signalling medium, then there exist *SFD*s which are spacelike with respect to some set of initial disturbances.

Another class of relativistic theories allowing superluminal signalling are those derived from a *k-essence* Lagrangian (Armendariz-Picon, *et al.* (2001)). These describe scalar fields with a nonlinear kinetic term, and have been proposed in order to generate a time-dependent cosmological constant in an attempt to account for recent observations. Here, too, there are solutions to the field equations which exhibit superluminal propagation in the relevant sense. (Erickson, *et al.* (2002); Garriga & Mukhanov, 1999)

Can one give anything like a 'no-go' theorem for superluminal signalling? For a situation in which the signalling medium is just the free, classical Maxwell field, and in which the initial data are appropriately differentiable, one can show that no superluminal signalling (in the present sense) can take place. However, one might wonder about the solutions of Maxwell's equations for non-differentiable initial data (for example, from shock waves). One then enters the realm of so-called 'weak solutions' of the equations of motion, which are typically nonunique, and require additional 'entropy conditions' to single out a particular solution.

Furthermore, there are physical systems which generically develop singularities (perhaps shocks, perhaps not) in finite time which do not lend themselves to analysis in terms of weak solutions and entropy conditions. For instance, the equations for a three-dimensional compressible perfect fluid (the 'compressible Euler equations') generically give rise to shocks in finite time (see Sideris (1985)). For such systems, it may be impossible to predict their behavior after a finite time, and thus a general 'no-superluminal signalling' *proof* is impossible.[12]

In short, superluminal signalling, as understood in this paper, is compatible with special relativity. However, the relativistic equations of motion we are *most* familiar with, such as those for the electromagnetic field (described by Maxwell theory) and those for relativistic fluids, do not give any indication of allowing superluminal signalling.

6 Quantum Signalling

What then of quantum theory? Though it is often claimed that the postulates of relativistic quantum theory preclude superluminal signalling (Bell, 1975; Maudlin, 2002), the situation turns out to involve new subtleties. However, one can at least address the question using the basic framework discussed above, except that instead of describing the signalling medium as a classical system evolving under classical equations of motion, one should describe it as a quantum system evolving under quantum equations of motion. The relevant initial disturbances are now local

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[12] Investigating such systems in a Newtonian context, Earman (1986) concludes that such singular behavior corresponds to a failure of determinism.

operators on the initial state, and the question becomes whether the action of such operators brings about a change in the expectation value of any quantity defined over some region which is spacelike to the initial disturbance.

The question of superluminal signalling in quantum theory has been addressed in a variety of ways in the literature. One oft-cited paper by Ghirardi, *et al.* (1980) entitled 'A general argument against superluminal transmission through the quantum mechanical measurement process' does not really live up to the generality claimed in the title, but does provide an argument against the possibility of exploiting measurements on entangled particles to transmit information faster than light. The work of Shimony (1984) and Redhead (1986) is in a similar vein. All of these describe the possible manipulations of quantum systems by local unitary operators representing manipulations on individual, spatiotemporally isolated parts of the system under consideration. They do not, however, address at least two important issues.

One such issue has to do with dynamics. All of the treatments cited invoke the assumption that the entangled systems are non-interacting. This is a rather strong assumption, and one which is particularly out of place if one is inquiring into the possibility of signalling from one region to another. All of the *classical* signalling scenarios discussed above involve interacting systems. What then of interacting, relativistic quantum systems? Can one have a Lorentz-invariant quantum signalling medium which allows superluminal signalling? This is an open question, to my knowledge. Though standard relativistic quantum field theory incorporates 'causality' by requiring that spacelike observables commute, it is by no means obvious that this requirement is appropriate for, and even consistent with, equations of motion which exhibit superluminal propagation of disturbances.[13]

Given the assumption that there are no interactions between the two entangled particles, can one safely assert, in light of the proofs alluded to, that no measurements allow superluminal signalling? Surprisingly, the answer appears to be "no". Recent work of Beckman, *et al.* (2001), drawing on earlier work of Sorkin (1993), demonstrates that there exist quantities, represented by bounded self-adjoint operators, the measurement of which would allow superluminal signalling. Consider two observers, Alice and Bob, each equipped with a two-state quantum system (e.g. the two spin-states of an electron). Alice starts with $|0\rangle$, and Bob selects either $|0\rangle$ or $|1\rangle$ at time t_0. Thus the initial state is $|00\rangle$ or $|01\rangle$. At time $t_0+\epsilon$, a partial measurement is made on the system, represented by the projection operator onto the state $\psi = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. At time $t_0+2\epsilon$, Alice measures her particle. If Bob began with state $|1\rangle$, then Alice will obtain $|0\rangle$ with certainty. But if Bob prepared his

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[13] The problem here is that one requires the operators (in the Heisenberg picture) to satisfy the equations of motion for the field, and that this in turn implies that some operators at spacelike points may not commute if the equations of motion exhibit superluminal propagation. Simply *requiring* the operators at spacelike points to commute would seem to preclude satisfying the equations of motion. This dilemma is closely related to the problem of constructing a quantum theory of gravity, in which the causal structure is itself a dynamical variable.

particle in $|0\rangle$, then there is a 50% chance that Alice will obtain $|1\rangle$. Thus if such a measurement is possible, it would appear that Bob can (with 50% reliability) signal Alice instantaneously (in the limit $\epsilon \rightarrow 0$). Sorkin (1993) and Beckman, *et al.* (2002) both conclude that this indicates that relativistic quantum theory tolerates a much more restricted selection of observables than is normally assumed. I believe that this conclusion is incorrect; for further discussion, see Weinstein (2002).

7 Conclusion and Prospectus

The question of the possibility of superluminal signalling in classical, relativistic physics is here understood as an inquiry into the effects of various sorts of disturbance on a Lorentz-invariant signalling medium. The effects of disturbances are unambiguously ascertainable because the signalling medium itself is understood to be a subsystem of the universe, the undisturbed behavior of which is well-defined. Superluminal signalling is possible if there exist signalling media such that some (or all) disturbances of the medium result in an *SFD* which is spacelike to all points of the initial disturbance. The question of the compatibility of superluminal signalling and relativity theory is here understood as an inquiry into whether there exist (on paper) any such signalling media obeying Lorentz-invariant equations of motion. The answer is, "Yes."

To put the matter less technically, the idea in this paper is simply that evaluating the speed of signalling is a matter of evaluating the effects of kicking something. This 'something' is not a member of a distinct ontological category, 'signalling media'; the world does not contain a natural division between signalling media and the objects which disturb them. Like computers, signalling media are perhaps best regarded as physical systems over which we have some relevant (to *us*) level of control. I do not, however, think that there is any fact of the matter as to what we can and cannot control, and so unlike Bell (see Appendix), I do not think that there is any need for a "fragment of a [physical] theory of human beings." (Bell 1975, 60) Signalling is about what we can and cannot bring about, and thus the study of signalling relies on a conception of what is going on in the world that allows for agency. To the extent that one's conception is at odds with this, to the extent that one views agents and signalling media alike as parts of a deterministic machine, one cannot see signalling in nature at all.[14]

Though a point of view that requires a split between physical system and external agent may be anathema to many, it is well worth noting that something very similar is assumed when applying

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[14] Talk of signalling (and causation) in a cosmological context is, I would argue, predicated on an implicit split of the universe into signalling medium and perturbations external to the medium. For example, when we speak of the transit time for signals broadcast from a supernova in a distant galaxy, the 'undisturbed medium' is the intergalactic vacuum, and perhaps the other stars and galaxies, understood to be evolving in an uninteresting fashion.

both quantum mechanics and thermodynamics to actual physical situations. When applying quantum theory, one must make a conceptual split between the observer or measuring apparatus and the quantum system under study. The line between the two is movable, just as the line between external intervention and signalling medium is movable. The theory is ultimately about predictions of measurements on systems described quantum mechanically, and these measurement results are described classically. Similarly, thermodynamics is in large part about subsystems of the universe (thermodynamic systems!), and manipulations thereof, which may elicit a cost in work done or a benefit in work extracted, depending on whether the manipulation results in a decrease or increase in entropy. Assigning a quantum state to the entire universe, or assigning a temperature or an entropy to the universe as a whole, is arguably incoherent, just as regarding the entire universe as a signalling medium (kicked by what?) is incoherent.[15] I believe these analogies are highly suggestive, and worthy of further investigation.

8 Appendix: Maudlin's analysis

Tim Maudlin's (2002) book is an extensive discussion of the compatibility of special relativity and quantum theory, with a chapter dedicated to discussing superluminal signalling and relativity. Though he and I agree that relativity does not preclude superluminal signalling, our analyses are different in a non-trivial way.

Maudlin's position is that superluminal signalling does not constitute a violation of relativity unless it "would allow us to pick out a particular Lorentz frame as holding a privileged position in nature." (102) Here I am more or less in agreement, as it would seem that one could pick out a particular Lorentz frame if and only if the equations of motion of the signalling medium are not Lorentz-invariant. Maudlin goes on to say that whether or not this is the case "depends on the details of the superluminal transmission, on the exact connection between the emission of the signal and its reception."(102) I agree with this as well, but have a different sense of what these "details" amount to.

As in my treatment, Maudlin is primarily concerned to analyze the effects of signalling, rather than the trajectories of signals. More specifically, he looks at the transmission and the reception of the signal. What is a signal? According to Maudlin, "A signal requires a correlation between a controllable physical state and an observable one, the source of the signal being identified not by its position in time but by its controllability." (Maudlin 2002, 100) Maudlin offers as an example of a "signalling mechanism" a "button which can be pushed and a lamp which goes on and off."

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[15] An illuminating discussion of the dependence of entropy on the macroscopic description may be found in Jaynes (1992).

The signal is understood to be transmitted when the button is pressed, and received when the lamp goes on (or off). Little is said about how this is supposed to generalize, other than that Maudlin requires that "[t]he button can be treated as a free variable in the sense that it can be coupled to any manner of device which will determine its state." By "free variable", Maudlin "do[es] not mean to conjure up the idea that the button pushers must have free will in some deep, metaphysical sense." Rather, he means that the button can be coupled to "a mechanism whose workings are predictable and well understood." The mechanism then determines the state of the button.

One difficulty with this account is that it is unclear whether "controllability" is intended to pick out a unique event corresponding to the initiation of the signal. What corresponds to the moment of button-pushing when I sit down at my computer and type and send an email? This problem stems from the vagueness of the notion of controllability. Such vagueness might seem puzzling in a work explicitly inspired by the the work of John Bell, as Bell (1987) famously inveighed against "the unprofessionally vague character of conventional formulations of quantum field theory." (173), particularly with respect to the use of the term 'measurement'. Yet Bell (1975) himself is quite vague when exploring the compatibility of quantum field theory and the (supposed) relativistic prohibition against superluminal signalling. He writes,

> Can *we* then signal faster than light? To answer this we need at least a schematic theory of what *we* can do, a fragment of a theory of human beings. Suppose we can control variables like a and b above, but not those like A and B. I do not quite know what 'like' means here, but suppose that beables somehow fall into two classes, 'controllables' and 'uncontrollables'. The latter are of no use for *sending* signals, but can be used for *reception*. (60)

This is clearly the (vague) strategy followed by Maudlin (for whom signal reception is similarly broadly defined).

In contrast, the approach taken in this paper does not invoke a notion of controllability, nor of "predictable...mechanism." Rather, one simply considers all perturbations of a given, well-defined signalling medium. This approach is not immediately available to Maudlin because he does not discuss signalling media. However, I believe that it is in the spirit of his approach.

Because he does not discuss signalling media, *per se*, Maudlin, like Bell, does not explicitly consider the role of equations of motion, of dynamics. Thus although he appears to endorse Lorentz-invariance as the defining property of a special relativistic theory, and although he recognizes what many miss, that Lorentz invariance does not preclude superluminal signalling, his analysis is based on an analysis of whether certain kinds of signalling could be used to define a preferred reference frame. The analysis here, by contrast, construes special relativity as simply the demand for Lorentz-invariant equations of motion, and considers the types of signalling available with Lorentz-invariant signalling media.

Finally, it is somewhat curious that Maudlin does not discuss the various proofs to the effect that manipulation of entangled quantum systems cannot be used to signal faster than light. Here, again, it would seem that Maudlin nods to Bell, as they both cite the existence of equal-time commutation relations of relativistic field theory as evidence for the fact that one cannot send signals faster than light (see Bell, 1975, 61 and Maudlin, 2002, 86). However, this begs the (open) question as to the relevance of equal-time commutation relations to the quantization of a classical theory in which disturbances propagate outside the lightcone, not to mention the difficult questions raised by Beckman, *et al.* (2001) and Sorkin (1993) as to the "acausal" properties of certain quantum measurements.

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