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SUPERLUMINAL SIGNALING AND RELATIVITY

ABSTRACT. Special relativity is said to prohibit faster-than-light (superluminal) signaling, 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 according to this criterion, superluminal signaling 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 flow of charge, and one can ask, (Sommerfeld, 1905) though perhaps not definitively answer, what 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

Synthese (2006) 148: 381–399
DOI 10.1007/s11229-004-6231-5

light (due to the increase of mass with velocity), it was noted early on 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 signaling'. 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*. 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 and Rex (1990) for an overview of the history of the Demon, and Earman and Norton (1998, 1999) and Weinstein (2003) for critical discussion).

Perhaps the primary obstruction to attaining clarity on the relation between special relativity and the purported prohibition of superluminal signaling has to do with articulating just what a prohibition against superluminal signaling 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 spacetime structure is Minkowskian, and the laws of nature respect the symmetries of that structure (i.e., they are Lorentz-invariant), so that there is no dynamically distinguished frame of reference.

The characterization of superluminal signaling is less straightforward. There are a variety of approaches to the analysis of signaling 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 (Maudlin, 2002) is primarily concerned with analyzing the correlations between signaling 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 signaling 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 role of intervention and the absence of a special relativity-derived prohibition on superluminal signaling.

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. (And of course we will need a frame of reference as well, since temporal intervals will, in general, be frame-dependent.) 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 and 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 described by 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 other physical phenomena – for example, a shadow cast by a moving object on a distant surface – that 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 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 (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). When dealing with classical particles one sometimes deals with particles, and these have 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, in which we try to identify the trajectory of a "signal", is unprofitable.

3. SIGNALING

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 'agent' (animate or otherwise) manipulating 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, I will *assume* that its behavior is in a broad sense deterministic. That is, I will suppose that, given the state of the medium at some time, the state of the medium at any future time will be determined, presumably by the equations of motion.[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 signaling 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, that is to say 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 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 signaling medium.[6]

3.1. *criteria for superluminal signaling*

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 signaling medium on its own. This will naturally require:

- identification of the signaling 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 default behavior of the signaling medium is represented by a particular solution to the medium's 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 could be a signaling 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 signaling medium which undergoes a disturbance. That is, consider what happens when one makes a local change in the initial data.[8] 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 spacetime points in the future.[9] I will call the set of spacetime points where the solution first differs from the undisturbed solution the 'Set of First Disturbance', or *SFD*. If the system is made up of fields, then the *SFD* will typically be a 3-dimensional hypersurface. If the system is made up only of particles (e.g., dust), 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 signaling if and only if there is a signaling 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, if no signaling medium exists that allows such a disturbance, then no superluminal signaling is possible.

Disturbing a signaling medium amounts to interfering with the time-development of the medium. We then determine whether a signal (an initial

Figure 1a. Undisturbed medium (particles).

disturbance) can propagate faster than light by comparing the evolution of the perturbed initial data to the unperturbed 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* dialed the number, the phone would not have rung.[10] This is subject to the counterargument that the phone *would* have rung if someone else had dialed the number.

A common sort of response to this puzzle about such counterfactual analyses of causality is to propose that, in determining what would have happened had the purported cause not taken place, one simply 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,

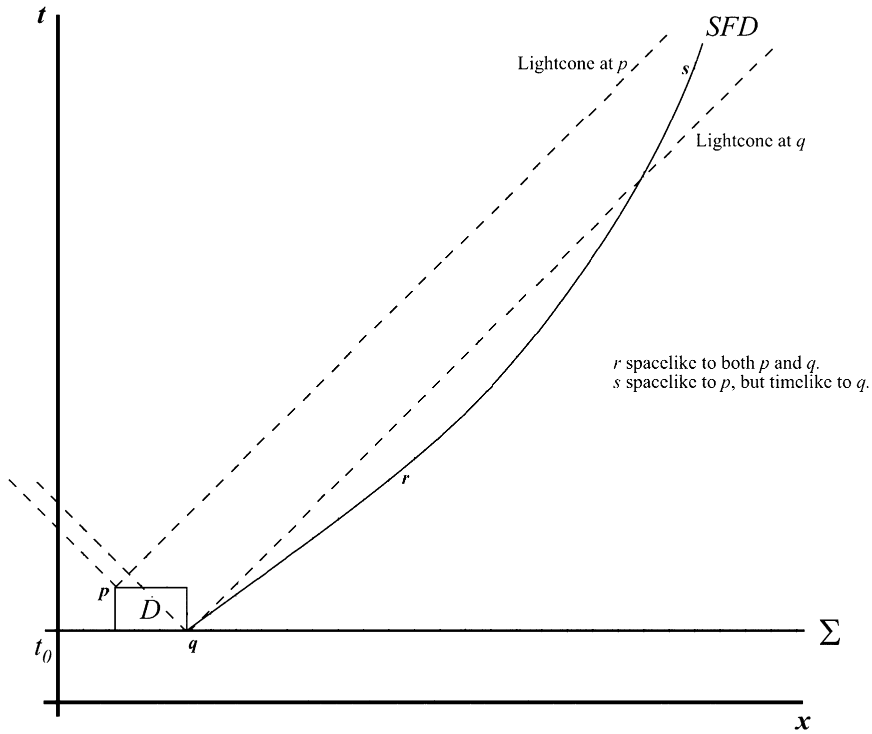

Figure 1b. Disturbed medium. *D*: Initial disturbance; *SFD*: Set of first disturbance. This is a case of superluminal signaling because *r* is spacelike to all points on *D*.

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 physical 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 *signaling* differs from counterfactual analyses of *causation*. In the analysis of signaling offered here, 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 hold the signaling 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 and dialing it as a signaling event, an event which brings about a disturbance of a signaling medium (the telephone system) including the ringing of a distant phone, the signaling analysis neither dictates nor requires that the dialing is the *cause* of the ringing – it is entirely compatible with a Humean eliminativism about causation. Whereas the signaling claim is based on a conception of the world as comprising subsystems (particularly, signaling 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 then attempts to attribute causal relations to events therein.[11]

3.2. *Remarks on the Role of Determinism*

My characterization of signaling 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.[12] For many generic sorts of matter with generic initial conditions, there is indeed a well-posed initial-value formulation. However, this is certainly not the case for all the types of matter that can be described in a special-relativistic context.[13] For example, the equations of motion for 'dust' do not have a well-posed initial-value formulation, interestingly enough (Geroch 1996).

The *absence* of an initial value formulation indicates a breakdown in determinism for the system under consideration. It is hard to see this as opening the door to the possibility of signaling, since signaling 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 signaling.[14]

4. SUPERLUMINAL SIGNALING

Suppose we have a relativistic perfect fluid, which is to say a perfect fluid obeying Lorentz-invariant equations of motion. This has a well-posed initial-value formulation, and is therefore a candidate signaling medium. Suppose, further, that the 'sound-speed' v of the fluid (measured in the rest frame of the fluid) is greater than the speed of light c. (In the jargon of Geroch (1996), this is a hyperbolic but non-causal system.) Then one can send signals faster than light by disturbing the fluid.

More precisely, the scenario for superluminal signaling involves comparing the evolution of the undisturbed fluid with the evolution disturbed fluid. One valid initial state for the fluid is simply the state in which the fluid is at rest in some inertial reference frame. The evolution of this system is of course trivial: it is static. One can then calculate the effects of a localized disturbance of the fluid (a "kick"), and evaluate the *SFD* (set of first disturbance) by determining the first points (with respect to the time in that frame) at which the solutions differ. If $v > c$, then there will be points on the *SFD* which are spacelike-related, satisfying our criterion for superluminal signaling.

There are reasons to think that no realistic fluid has an equation of state for which $v > c$. However, there are several more physically-motivated sorts of field with similar propagation properties 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 and 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 does 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 and Herdeiro 2001). It has been well-known for some time (Plebanski 1970; Boillat 1970) that the theory admits superluminal propagation and thus superluminal signaling in the sense discussed here. 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 signaling medium, then there exist *SFD*s that contain points spacelike with respect to some initial disturbances.

Another class of relativistic theories allowing superluminal signaling 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 and Mukhanov 1999).

Can one give anything like a 'no-go' theorem for superluminal signaling? For a situation in which the signaling medium is just the free, classical Maxwell field, and in which the initial data are appropriately differentiable, one can show that no superluminal signaling (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 unique 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 (Sideris 1985). For such systems, it may be impossible to predict their behavior after a finite time, and thus a general 'no-superluminal signaling' *proof* is impossible.[15]

In short, superluminal signaling, 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 signaling.

5. QUANTUM SIGNALING

What, then, of quantum theory? Though it is often claimed that the postulates of relativistic quantum theory preclude superluminal signaling (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 signaling 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 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 signaling 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' while not quite as general as the title suggests, 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 of individual, spatiotemporally isolated parts of the system under consideration. They do not, however, address at least two important issues, having to do with dynamics and measurement.

With regard to 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 signaling from one region to another.[16] All of the *classical* signaling scenarios discussed above involve interacting systems. What then of interacting, relativistic quantum systems? Can one have a Lorentz-invariant quantum signaling medium which allows superluminal signaling? This is an open question, to my knowledge. Though standard relativistic quantum field theory nominally 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.[17] In other words, it is largely an open question how to quantize relativistic media of the sort discussed above, media which permit superluminal signaling given appropriate initial conditions.

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 signaling? 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 signaling. 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 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 $\epsilon \to 0$).

It is important to note that the example above assumes that ideal measurements of observables are instantaneous. Sorkin (1993) and Beckman et al. (2002) make this assumption, and conclude that the fact that some measurements permit superluminal signaling indicates that relativistic quantum theory tolerates a much more restricted selection of observables than the full set of Hermitian operators. On the other hand, one might simply argue that the idealization of measurement as instantaneous is invalid, either in general or in cases in which one is projecting onto entangled states. A definitive resolution of this issue is beyond the scope of this paper.

6. CONCLUSION AND PROSPECTUS

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

More simply, the analysis in this paper is based on the idea that evaluating the speed of signaling is a matter of evaluating the effects of kicking something. There is, however, no unique division of the world into signaling media and external agents that disturb them. What counts as an agent, and what counts as a kick, depends in part on one's perspective. In particular, agents need not be human; radio transmitters will do as well. Thus, Bell (see Appendix), I do not think that an analysis of signaling requires a "fragment of a [physical] theory of human beings" (Bell 1975, 60). Signaling is about what we can and cannot bring about, and thus the study of signaling 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 signaling in nature at all.[18]

Although 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 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 signaling 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 signaling medium (kicked by what?) is incoherent.[19] I believe these analogies are highly suggestive, and worthy of further investigation.

7. APPENDIX: MAUDLIN'S ANALYSIS

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

Maudlin's position is that superluminal signaling 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 only if the equations of motion of the signaling 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 signaling, 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 "signaling mechanism" a "button which can be pushed and a lamp which goes on and off". 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 work of John Bell, who famously inveighed against "the unprofessionally vague character of conventional formulations of quantum field theory" (Bell 1987, 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 signaling. 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 signaling medium. This approach is not immediately available to Maudlin because he does not discuss signaling media. However, I believe that it is in the spirit of his approach.

Because he does not discuss signaling 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 signaling, his analysis is based on an analysis of whether certain kinds of signaling 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 signaling available with Lorentz-invariant signaling 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 (Bell, 1975, 61; 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.

ACKNOWLEDGEMENTS

I would like to thank Adam Elga and Bob Geroch for helpful discussions.

NOTES

[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.

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

[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.

[5] More formally, this amounts to the requirement that the differential equations describing the evolution of the signaling 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.

[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) (Courant 1962). What degree is deemed to be appropriate is a matter that I do not address in this article.

[8] The analysis of signaling offered here does not get off the ground if one cannot make local changes. It is an interesting open question how to analyze signaling in the context of interactions propagating with infinite speed in Newtonian space-time (e.g., Newtonian gravity). In such a case, a purportedly local change would actually affect all points in space at once, and thus be a global change.

[9] Here I am assuming an 'arrow of time', in that I am assuming that the disturbance does not affect any points in the past of the initial hypersurface.

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

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

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

[13] Indeed, gauge theories are counterexamples. Although the non-uniqueness there might seem to be of a rather trivial sort, eliminable by gauge-fixing or by moving to the 'reduced phase space', these present additional problems of some interest. They will be addressed in Weinstein (2004).

[14] This is not meant to preclude the possibility of signaling 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.

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

[16] More extensive discussion of the importance of considering interacting systems may be found in Kennedy (1995) and Peacock (1998).

[17] 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.

[18] Talk of signaling (and causation) in a cosmological context is, I would argue, predicated on an implicit split of the universe into signaling 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.

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

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