The No-Signalling Theorems: A Nitpicking Distinction

Kent A. Peacock[1]

> It seems to me that it is among the most sure-footed of quantum physicists, those who have it *in their bones*, that one finds the greatest impatience with the idea that the 'foundations of quantum mechanics' might need some attention. Knowing what is right by instinct, they can become a little impatient with nitpicking distinctions between theorems and assumptions.
>
> —John Stewart Bell [4, p. 33]

> Pronouncements by experts to the effect that something cannot be done have always annoyed me.
>
> —Leo Szilard [20, p. 28]

Shortly before his untimely death, John Stewart Bell remarked that his famous theorem tells us "that maybe there must be something happening faster than light, *although it pains me even to say that much*" [emphasis added] [14, p. 90]. Bell's reaction to his own momentous discovery is puzzling: why should it have *pained* him or anyone else? Should we not be excited and fascinated by the possibility of superluminality, and want to learn as much about it as possible—instead of trying to deny its reality or minimize its importance? I'll return to this question later in this paper; first, I want to critically review the orthodox argument for what Abner Shimony has called "peaceful coexistence" between quantum mechanics and relativity [23]. The term peaceful coexistence was used by Shimony ironically[2] and was meant to suggest that while quantum mechanics apparently subscribes to a nonlocal ideology, it does not threaten the standard interpretation of special relativity because quantum mechanics does not permit the exploitation of nonlocality for *controllable* faster-than-light signalling. Thus, according to this doctrine, a compromise is possible which (like some kind of analgesic) masks the metaphysical pain occasioned in many physicists by nonlocality, even if it does not correct the underlying pathology.

There are numerous no-signalling proofs in the literature. Recently, an especially clear review of the problem has been given by Clare Hewitt-Horsmann, who claims that no-signalling (which she calls "statistical locality") relies on "only one prior assumption" namely that the probability distribution is given by Born's Rule, $|\langle\Psi|\Psi\rangle|^2$. Because this is such a "foundational part of quantum mechanics," Hewitt-Horsmann says "it is safe to say that the conclusion that statistical locality must be obeyed is an extremely strong one" [11, p. 886]. As a general methodological rule, one should be suspicious of mathematical rigor in physical arguments, especially when they are arguments designed to *exclude* a possibility. Rigor may indeed be a sign of the operation of a principle of great generality (such as Born's Rule). However, it can also be a sign that crucial physical factors have been ignored, or even a mere consequence of a problem having been defined in such a way as to guarantee a preconceived result. As Bertrand Russell once sardonically remarked, "It is one of the chief merits of proofs that they instil a certain scepticism as to the result proved" (quoted in [13, p. 48]). The point is hardly that one should eschew rigor, but rather that one should ensure that one has proven what was actually to have been proven. I will argue here that despite their apparent rigor the widely accepted arguments for peaceful coexistence do not establish what most people think they establish and do not investigate the questions that actually need to be investigated.

The Problem

Let us illustrate the problem of signalling with the assistance of the ubiquitous experimenters Alice and Bob. We will place Alice and Bob at some distance apart, and between them there will be a source emitting pairs of entangled particles. To avoid relativistic complications we will assume that Alice, Bob, their detectors, and the particle source are all mutually at rest in an inertial frame (the "lab" frame). Pair after pair of particles are emitted by the source and detected by Alice and Bob's apparatuses, who record their results. Alice and Bob are free to alter the angle of their detectors with each run of the apparatus.

What each experimenter will record is an apparently random sequence of ups and downs, like the results of an honest coin repeatedly tossed; and yet, when they compare results afterward, they will note that certain correlations, generally sinusoidal in form, stand between their results. For example, if the particles are spin-1/2 fermions, and if Alice and Bob are measuring spin in a particular direction, then the correlation between their results will be $-\cos\theta_{AB}$, where θ_{AB} is the angle between Alice and Bob's detectors. Sinusoidal correlations like these readily violate mathematical inequalities such as those defined by Bell [2]. Itamar Pitowsky [19] showed that the Bell Inequalities are examples of "conditions of possible experience" first written down by George Boole; these are consistency conditions between measurement results on the assumption that the results of one measurement and the way it is carried out does not influence the measurement of the other particle *at the time of measurement*. This means that the particular sequence of results that Alice and Bob get at their respective detectors could not have been encoded in the particles at the source; for some relative angles their results are too well correlated or anti-correlated for them to be due to local causes built into both particles when they were emitted.

If Alice and Bob are siblings they likely would resemble each other more than they tend to resemble other people chosen at random from the general population. This is due simply to the fact that they had the same parents and thus have more similar DNA than two people picked at random. Einstein, Podolsky, and Rosen [9] thought it was beyond discussion that there had to be some sort of "quantum DNA" carried by elementary particles that would cause them to obey the correlations predicted by quantum mechanics. Since the work of Bell in 1964 [2] we know this is mathematically impossible: there is no "DNA" that can account for the correlations of results in entangled states. Pitowsky [19] emphasized that if one insists that there be an explanation for the violation of the Bell/Boole inequalities there are very few mathematical options other than some sort of "measurement bias"—an influence of one measurement on the outcome of the other. And given that Alice and Bob make their measurements at a spacelike separation, the influence, whatever it may be, has to operate faster than the speed of light.

Now, what will happen if Alice decides that she would like to exploit this mysterious influence to send messages in code to Bob faster than light? Suppose she tries to do this by varying her detector angle from run to run of the apparatus, hoping that this will impose a signal on Bob's local results. It won't work as Alice hoped, for both she and Bob will continue to record sequences of results that look entirely random. However, what Alice can indeed do—and this is a most interesting accomplishment in itself—is encode a message in the *correlations*, for the correlations, as noted, are a function of relative detector angle. This phenomenon is the basis for quantum cryptography, which is likely the most theoretically secure form of encryption; because both experimenters' local results are random the message cannot be decoded from one set of results alone, but each set of results serves as a key in combination with the other.

Alice is still not satisfied, however, and now she tries to *force* her particles to go either up or down in her detector. She could likely do this by interposing additional electromagnetic fields in just the right way. But she still won't be able to signal to Bob, for she will discover that she has destroyed the nonlocality: if Alice forces her particles to go one way or the other, not only will Bob's local results stay random, but the correlations between her results and Bob's will obey a Bell Inequality.

Alice's inability to control her local results without washing out the nonlocal correlations seems to be just a technical problem; surely, Alice might think, if she could simply interact with her particles more *gently* or if there were some way to make the nonlocal connection between the particles *stronger*, then she ought to be able to influence Bob's local statistics. The authors of the no-signalling proofs insist that Alice's problems are not merely technical; instead, they say, there are deep reasons of principle why Alice, no matter how carefully she may interact with her particles, cannot hope to influence Bob's local statistics.

The "Proofs"

Many papers have been published setting forth alleged proofs that there is nothing Alice can do to influence Bob's local statistics, and there is not space here to review them all. (See [17, 12, 18].) They fall into two broad categories, those that use the tools of non-relativistic quantum mechanics, and those within local quantum field theory.

Non-Relativistic No-Signalling Proofs We'll look at non-relativistic no-signalling arguments first, since this is the type of proof cited by Hewitt-Horsman [11]. There are many algebraic variants of these proofs but they depend upon essentially the same physical assumptions. Hewitt-Horsman is correct that these arguments use key elements of the basic formalism of quantum mechanics, such as the Born Rule. However, they also depend upon a crucial physical assumption that many authors, apparently including Hewitt-Horsman, think is so natural that it does not even need to be acknowledged as a special assumption. Let $\mathcal{O}_{AB}$ be the operator representing the effect of Alice's measurement procedure upon the Hilbert space of the combined entangled system (that is, the tensor product space representing Bob's distant particle as well as Alice's). Let $\mathcal{O}_A$ be the operator representing Alice's measurement in the subspace of her particle, and let $\mathbf{1}_B$ be the identity operator in Bob's subspace. The crucial *physical* assumption that drives the non-relativistic no-signalling arguments is that Alice's measurement operation acts only trivially on Bob's subspace:

$$\mathcal{O}_{AB} = \mathcal{O}_A \otimes \mathbf{1}_B. \tag{1}$$

With this assumption in hand, Bob's local statistics remain the same regardless of what choice of measurement parameters Alice makes when interacting with her particle. It is fairly straightforward to demonstrate this result, although some no-signalling papers accomplish the task by means of some truly impressive algebraic machinery. Machinery notwithstanding, what is going on in these arguments is very simple: one *assumes* that Alice does not have a physical effect on Bob's side of the system, and then shows that a *confirmation* of this assumption can be extracted from the quantum mechanical formalism. Viewed uncharitably, such no-signalling arguments amount to little more than trivial consistency checks of the formalism, for all they say is that an operator that is *assumed* to not act in a subspace does not change the statistics in that subspace. Such arguments are completely powerless to tell us whether anything that Alice can do to her particle does *in fact* have a superluminal physical effect on Bob's particle. But surely, *that* is what we really need to find out.

It is possible to view such no-signalling arguments in a slightly more positive light, for one can say they do at least demonstrate that Alice could not influence Bob's local statistics *without* the aid of some sort of superluminal dynamics. We can't get controllable signalling in quantum mechanics without actually expending some free energy on the receiving device any more than we can with any other kind of signalling; one could say, then, that the conventional no-signalling arguments also amount to a confirmation of the Second Law of Thermodynamics in the sense that no transmission of information can be accomplished without the expenditure of free energy. But again, the standard no-signalling arguments do not *prove* that there is no such superluminal dynamics, but instead *assume* that proposition.

A few papers attempt to establish no-signalling in non-relativistic quantum systems by directly assuming that the Hamiltonian of the combined system of experimenters and particles is local [21, 22, 18]. This means that the total Hamiltonian of the combined entangled state together with Alice and Bob's detectors is simply the sum of the Hamiltonian on Alice's side and the Hamiltonian on Bob's side:

$$\mathcal{H}_{AB} = \mathcal{H}_A + \mathcal{H}_B. \tag{2}$$

The authors of such proofs thereby take it that the Hamiltonians of multiparticle systems are never entangled even if the states of the system, expressed in terms of other observables on the system, are entangled—for entangled states of any observable, including energy, in general cannot be represented as a simple sum of local properties of individual particles.

This line of argument at least has the merit of not being quite so obviously question-begging, in that it makes explicit its assumptions about the dynamics of the system. But it also rests upon essentially the same unproven assumption as the algebraic approaches described above, for there is no proof that in general all of the energy states of an entangled system are local. Indeed, there are good reasons to think that energy in quantum systems is nonlocal, or at least has a nonlocal component [18]. To see this, one need only think of the energy of an atomic orbital, which cannot be said to be localized until a portion of it is emitted in an atomic transition. Bohm's quantum potential is an explicitly nonlocal form of energy, and it can be shown to be entangled for entangled states [7]. Energy-entangled states appear in recent studies of nonlocal interferometry [10]. The requirements of symmetrization based on the fact that all particles obey either Bose-Einstein or Fermi-Dirac statistics also point to terms in the Hamiltonians of multi-particle systems that do not break down neatly into localizable parts [18]. There is also a thermodynamic argument for the nonlocality of energy in entangled states: if a number of particles interact and thereby become nonlocally correlated, the entropy of the ensemble decreases (equivalently, its mutual information increases) and this is only possible if there is energy associated with the mutual information of the system above and beyond the local energies of the particles in it. Finally, lurking behind modern theoretical physics is the puzzle of the nonlocality of gravitational energy in general relativity, which is a consequence of the Equivalence Principle [15]. It remains to be seen whether the nonlocality of gravitational energy has anything to do with quantum mechanics, but it gives further support to the idea that nonlocal energy must be taken seriously. In view of such considerations, there is no basis for assuming without argument that the energy of entangled states is entirely local to the particles of which it is composed, and thus no basis for a no-signalling proof on this assumption—except, possibly, when fluctuations in the system are such that its *effective* Hamiltonian has the form (2).

Field-Theoretic Proofs The other major strategy used in no-signalling proofs is to appeal to a principle of local quantum field theory (LQFT) called microcausality or (in some books) local commutativity. This is a postulate that all observables acting at a spacelike separation commute, even if they are observables (such as position and momentum) that would not commute if they were acting on the same system locally. It is fairly straightforward to arrive at a no-signalling result given microcausality [8]. Most, but not all, authors of such proofs are careful to assert that all they really meant to prove is that within LQFT microcausality is equivalent to no-signalling. The possibility certainly exists of a nonlocal quantum field theory either in which microcausality could be derived without the expedient of bare postulation or in which one would find circumstances in which it was violated. But the historical fact remains that microcausality was *written into* LQFT by its founders (such as Pauli) precisely in order to preempt predictions of signalling. Microcausality can therefore be thought of as a sort of security patch, downloaded, as it were, into the structure of field theory in order to prevent conflict with the orthodox interpretation of relativity, and any presumption that it provides for a completely general prohibition on signalling is question-begging [17, 16].

Some History of the Dissenting Literature on Signalling The literature on the signalling problem is huge, and I can't hope to do justice to it here, even its heretical branches. As far as I know, the first author to publish doubts about the conventional wisdom regarding signalling was P. J. Bussey [6], who in 1987 suggested that the standard no-signalling proofs are "ad hoc." I published a short review of the problem in 1992 [17] in which I outlined a taxonomy of the various methods that have been used to demonstrate no-signalling, and argued that they are all question-begging. A longer and more detailed treatment was published by J. B. Kennedy in 1995 [12], and in 1998 Peter Mittelstaedt published much the same conclusions as Kennedy and myself about the circularity of the local field theoretic arguments [16]. Similar worries are expressed in a recent paper by Steve Weinstein [25].

Where the Investigation of Signalling Might Go

Even if practical superluminal communication as such is never feasible, controllable nonlocality may have other possible applications, and I shall briefly mention two that are not as far-fetched as they might immediately seem. First, it has not been appreciated that a quantum computer would amount to a superluminal communication device in the sense that both have to do the same thing: extract information from an entangled state without collapsing the state. As with Alice's communicator, reasonable approaches to explore would include the use of protective, or non-demolition measurements, and finding ways of pumping up the coupling strength of the nonlocal interaction. One can imagine that this could also have applications to the search for high T_c superconductors. There, the barrier has been that quantum coherence is disrupted by thermal randomness, and again the solution could be to find a way—conceivably *via* some sort of resonance phenomenon—to strengthen the nonlocal interaction.

Aharonov *et al.* [1] published a signalling scheme in 2004 based on the notion that protective measurements could allow a way of extracting information from an entangled state without collapsing it. Their scheme would only allow for signalling under limited conditions but it is quite immune to the assumptions used in the standard no-signalling arguments. If anything like what Aharonov and his colleagues propose could be made to work, then nonlocality is normally uncontrollable only because the nonlocal dynamics of entangled states are very weak and thereby easily perturbed by standard measurement procedures. Perhaps Alice was right after all: the key to signalling would be either to create very robust entangled states (perhaps by using a large number of phase-coherent particles as in a Bose-Einstein condensate) or (as in Aharonov *et al.*'s scheme) by using a very gentle measurement interaction. Every effort should be made to find out whether it is actually possible to build an apparatus such as that envisioned by Aharonov *et al.*

A Historical Perspective

I have been describing the conventional approach to the signalling problem as if it were a methodological error, and it is, but it is helpful to see it in the context of the history of modern physics. This is also somewhat fairer to those who have advocated peaceful coexistence, for the approach they have taken, although *now* clearly outmoded, was reasonable given the challenges and priorities faced by physicists in the early years of quantum mechanics and quantum field theory.

In the very early years of quantum mechanics, even before Heisenberg enunciated his uncertainty relations in 1927, physicists such as Max Born speculated that the very notion of a classical spacetime would break down in the face of quantum discontinuities. The question opened by a few far-seeing physicists, even at this time, was whether ways could be found of constructing spacetime *from* quantum mechanics. As it became increasingly apparent that in some sense all physics is quantum physics, it began to seem natural to some to suppose that the whole relativistic theory of spacetime might be merely a classical approximation or limiting case of a deeper quantum theory of spacetime—a quantum theory of gravity. The relation between the theory of relativity and quantum gravity might be something like the relation between the classical and quantum theory of liquids. It soon became apparent, however, that constructing a quantum theory of gravitation or spacetime was just too difficult, especially when, in the 1930s and 1940s, physicists were faced with the more immediate crisis of the infinities of quantum electrodynamics and the burgeoning "particle zoo." Physicists found it necessary to adopt a much more conservative approach. They accepted Einstein's view that special relativity is a "principle theory"—a background into which other theories should fit. Add to this a general suspicion, probably endemic to physicists all the way back to the time of Newton, of the notion of action at a distance, and it seemed eminently reasonable to the framers of the brash new theory of quantum mechanics to assume that relativity is logically prior to it and that it should therefore not contradict relativity. As they attempted to axiomatize quantum mechanics and the field theory that was growing out of it, they deliberately restricted the generality of quantum theory by imposing the postulate of microcausality and (even in the face of entanglement) the assumption that spacelike separation guaranteed dynamic separability. This approach was reinforced by the dominance of the Copenhagen interpretation of quantum mechanics, which held that the classical level of description is (in some obscure sense) independent of the quantum level.

This conservative approach, in which quantum processes are taken to occur against a classical, locally-Minkowski background, allowed for the development of very powerful and predictively effective quantum field theories. However, as Lee Smolin and other proponents of quantum gravity have argued [24], the conservative approach is no longer open to us since the task now is to show how to construct spacetime out of quantum mechanics—not shoehorn quantum mechanics into spacetime. The problem of peaceful coexistence therefore bears on very current and contentious debates about how to construct quantum gravity in a background-independent way, and how much of the classical picture of spacetime will be left when that large task is accomplished. I do not take lightly the task of constructing a genuinely nonlocal quantum field theory that would actually work and would contain present local quantum theory and relativity as limiting cases. There is no reason to suppose that when this large task is accomplished, however, that the familiar, almost comforting, causal structure of Minkowski space will be anything more than a (frequently useful) approximation. There can no longer be any justification for assuming *without argument* that the predictions of quantum mechanics must not conflict with relativity.

Causal Paradoxes and the 'Spirit of Relativity'

Part of the metaphysical pain occasioned in many physicists by nonlocality stems from the fact that it seems to violate something called the "spirit of relativity." I have never seen a precise explanation of the scientific meaning of this phrase, and it seems to be not much more than a vague prejudice against talk of spacelike causality.

Bell himself had more specific worries about the causal paradoxes that would apparently arise if superluminal effects could be controlled [5]. It is easy to show that if Alice and Bob can send signals at arbitrary velocities then causal paradoxes can be set up. The causal paradoxes of superluminality are a genuine problem to which I do not have a complete answer. We can say enough, however, to show that worries about causation should not be sufficient to lead us to rule the possibility of superluminal effects out of court *ab initio*.

There are two kinds of causal paradoxes that are connected with superluminality, *one-way* and *two-way* or *closed-loop* paradoxes. In a one-way paradox, Alice sends a superluminal signal to Bob. In some frames of reference Bob receives the signal at an earlier time coordinate than when Alice launches it. The "paradox" is that this conflicts with our familiar sense that causation always runs forward in time. In a two-way paradox, Bob sends a response back to Alice in such a way that she receives it at an earlier proper time on her worldline than when she sent her message. This seems to open the door to outright *logical* paradox, because presumably Bob could send a message that would negate Alice's initial transmission.

Whatever causation may be, it is clearly something that goes along particle worldlines. For causal connections inside and on the light cone, the direction of causation is the same for all worldlines, and with a suitable choice of conventions it can be made the same as the direction of time in all Lorentz frames. For causal connections outside the light cone, if any, the direction of causation may differ from the direction of time in some Lorentz frames. Bell thought this was unacceptable [5], but I submit that this is merely an odd effect; one-way paradoxes are not logical, but merely involve a conflict with essentially Newtonian (and thus outmoded) intuitions about causation.

Now let us suppose that there is some way in which Alice and Bob can exchange superluminal messages *via* a spatially-extensive entangled state. Bell himself was well aware that we can avoid closed-loop paradoxes if the velocity of the messages, although superluminal, has an upper limit such that Bob's return message to Alice always hits Alice's worldline at a later proper time than when she sent her initial message. Bell was deeply troubled by the notion that all nonlocal quantum interactions might have a maximum velocity, since he feared it would imply that there is a "preferred frame" whose existence would violate the Principle of Relativity.

The idea that all particles in the universe are entangled in a completely consistent way is not unreasonable, given that something like the Big Bang theory is probably true. But this does not imply a violation of the Principle of Relativity any more than does the existence of the cosmic background radiation (CBR) rest frame. That is the state of motion in which there is no Doppler shift in the cosmic background radiation. It defines a sort of *de facto* standard of rest for the whole universe but it does not violate the Principle of Relativity in any way since the CBR rest frame is defined by cosmological history, not by some violation of frame-equivalence in fundamental law. It is well known that history can break fundamental symmetries. There is almost certainly something similar going on in the case of quantum nonlocality. Quantum nonlocality should not be an occasion for metaphysical or logical pain, but it is still going to take some getting used to.

The Limits of the Possible

The quest to define the limits of the physically possible is, of course, a legitimate and indeed necessary scientific enterprise. But we have to take care that we really have surveyed all relevant possibilities. The history of science is littered with the wreckage of failed impossibility "proofs." Bell has warned us that "what is usually demonstrated by impossibility proofs is a lack of imagination" [3]. Bell was not talking specifically about the signalling problem when he wrote these words, but they apply to it. It seems highly likely that a few things really are just impossible, but perhaps not as many as one thinks in a quantum world, where "impossible" often means nothing more than "highly improbable" or "usually highly improbable." The problem of quantum signalling is of interest not only in itself, but also as a case study in the larger problem of determining when an apparent limit in nature is a genuine limit or merely the result of an attempt to define an awkward phenomenon out of existence. I claim that the latter is precisely what has happened around the signalling problem. As Bell pointedly remarked, nature is telling us that something is going faster than light in quantum mechanically entangled systems, and to date there is *no* proof either that Bell was wrong about this or that such superluminal effects could not be controlled in ways that so far we can only sketchily imagine. If nonlocality *can* be controlled we need to learn as much as we can about how to do it, *soon*. If the doctrine of peaceful coexistence is correct after all and nonlocality *cannot* be controlled, we need to prove this from the first principles of a theory of quantum gravity, when they are finally available, and not merely build it into physical theory as an assumption.

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Notes

[1] Department of Philosophy, University of Lethbridge, 4401 University Drive, Lethbridge, Alberta, Canada. T1K 3M4. Email: kent.peacock@uleth.ca.

[2] Private communication.

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