A critique of the quantum no-communication theorems

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Abstract

The no-communication theorem (NCT) is the thesis that it is impossible to employ quantum entanglement to send signals in a controllable fashion to a spacelike separate observer. The numerous proofs of an NCT that have been published all depend on the physical assumption that whatever effect Alice may have on an entangled system is dynamically local and thus cannot impose a signal on the local statistics that Bob will observe. I and other authors have argued that it is question-begging to assume from the outset that all dynamics within an entangled system are local, since the context of the inquiry should be to investigate that very possibility. I report on an illuminating conversation with Abner Shimony in 1993 and argue that there are good physical reasons to think that the dynamics of entangled states is in general nonlocal. On this view, therefore, the question of controllable communication in entangled states remains open.

An Awkward Question

- Conventional wisdom: it is impossible to use quantum entanglement to signal controllably faster than the vacuum speed of light.
- I and a few others have questioned the conventional wisdom, and in this talk I will try to explain why.
  - P. J. Bussey (1987) [4]
  - J. B. Kennedy Jr (1995) [10]
  - P. Mittelstaedt (1998) [13]
  - K. P. (1991, 1998) [14, 15, 16]
  - K. P. and B. Hepburn [17]
    - See also my collection *Quantum Heresies*. College Publications, 2018. (Available through Amazon.)

The Problem: Is There ‘Peaceful Coexistence’ Between SR and QM?

- Central question: How should we understand the relationship between quantum mechanics (QM) and the special theory of relativity (SR)?
  - Since the 1920s or earlier the working assumption has been that SR is what Einstein called a ‘principle theory’, a framework within which other physical theories are to be formulated.
- Problem: it was apparent very early on that quantum mechanics (QM) exhibited evidence of what Einstein sarcastically dubbed ‘spooky actions at a distance,’ which *prima facie* would violate SR.
- The response was to assume that QM should not conflict with relativity, and certain technical assumptions were ‘patched’ into QM to ensure that this would be the case.

Limitations of SR

- Relativity (both special and general) is a classical theory.
  - It takes no account of quantization of action, non-commutativity, interference effects, entanglement, or the irreducible effect of observation on the observed system.
- Hence, it can be argued that relativity is emergent from QM, a classical (and hence approximate) limiting case of some more general quantum theory of space and time (which we don't yet have) [16, 11].
  - Most physicists do not feel ready to 'go there'.
  - However, the problem has not gone away!

The Bell Sounds...

- The possible conflict between SR and QM came to a head with Bell's Theorem [1] and its (by now) wide experimental confirmation [22].
  - It is clear that in some (still debatable) sense, QM is nonlocal.
- However (!), numerous authors from the late 1970s onward published 'proofs' that one cannot use quantum nonlocality to violate the relativistic proscription against superluminal messaging.
- The philosopher-physicist Abner Shimony proposed that SR and QM stand in a relationship of 'peaceful coexistence,' based on the no-controllable-communication claim [19].
  - QM and SR go to different churches, but they obey the same traffic laws.

Who Has the Burden of Proof?

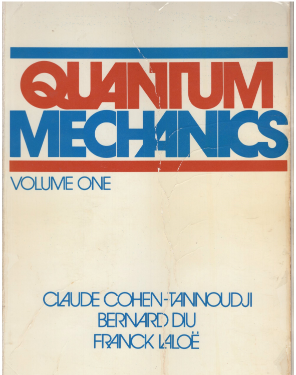
- Prevailing view was that QM has to show that it is compatible with relativity.
  - My view (and a few others): we should *challenge relativity* and find out if it is compatible with QM, because the latter in so many ways seems to be a more general theory.
- However, most authors in the no-communications literature were more concerned with showing that QM does not threaten relativity.
- The critics (including me) say that this has led to a reliance on circular reasoning and arguably an incorrect description of the dynamics of entangled states.

A Triviality?

- The point to be made was put bluntly by Bussey (1987):
  - "Non-communication in EPR experiments in standard formulations of quantum theory is obtained trivially by means of ... *ad hoc* assumptions about the behaviour of multiparticle amplitudes, rather than as a consequence of basic physical principles." [4]
- Some background needed to see where this is coming from...

"Get a Good Text" (J. S. Bell)

- In the following, I assume some knowledge of basic quantum mechanics, although not very much.
  - Excellent reference: C. Cohen-Tannoudji, B. Diu, K. Laloë, *Quantum Mechanics* Volume I. Wiley, 1977. [5]
  - Very good on mathematics of entangled states, *aka* nonfactorizable or tensor product states.



Entangled vs. Product States

- Suppose p_1 and p_2 are particles (of whatever kind you like...).
- Each has a state vector ("qubit") that "lives" in an associated Hilbert Space, which is a complex-valued vector space.
- What is their *combined* state vector?
  - If the particles never interact in any way, we write the *product state*:

    $$\psi_{12} = c\psi_1\psi_2 \quad (c \text{ is a complex constant}). \tag{1}$$

    Such particles evolve independently.
  - If the particles may have interacted in any way whatsoever, we must write the tensor product state:

    $$\psi_{12} = \Sigma_i c_i \psi_1 \psi_2. \tag{2}$$

    where the c_i are complex coefficients.

Non-Factorizability

- Important example is the *singlet state*:

$$|\Psi_S\rangle = 1/\sqrt{2}(|+-\rangle - |-+\rangle) \tag{3}$$

  - *It is mathematically impossible to factor this into states belonging entirely to each particle*.
- Such states are said to be *entangled*, a term introduced by Schrödinger [18].
- Mathematically, the existence of entangled (non-factorizable) states is a consequence of the superposition principle: every linear combination of allowed states is an allowed state.

Quantum Correlations

- Entangled systems exhibit correlations between measurements made upon them, generally sinusoidal in form.
  - For the singlet, the correlation is

$$P(1, 2) = -\cos\theta_{12} \tag{4}$$

where θ_{12} is the *relative* angle between detectors acting on particles 1 and 2 respectively.

Bell's Theorem

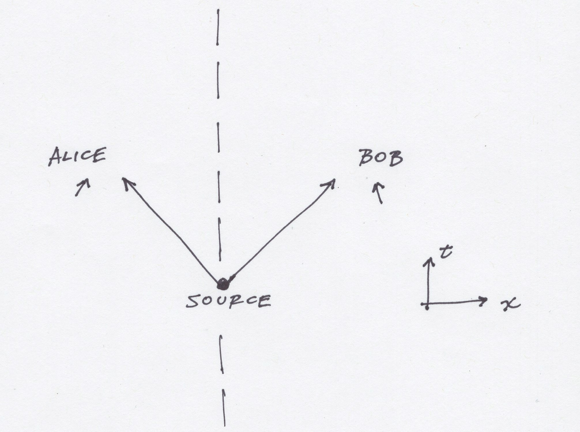
- Described by H. P. Stapp as "the most profound result of modern science" [21].
- Very short version:
  - Einstein's firm belief was that the quantum correlations were the sign of information/structure *encoded* in the particles at the source, because he thought it was absurd that there could be any sort of direct influence of one particle upon another at the time of measurement [8].
  - Bell called this the "genetic" interpretation of quantum mechanics [3].

Bell's Pain

- Bell showed that if the genetic interpretation is correct, then quantum correlations must obey certain inequalities; however, it is readily shown that entangled systems violate these inequalities [1].
  - Bell's Theorem: *There is no quantum DNA.*
- Bell: the theorem says that "maybe there must be something happening faster than light, although it pains me even to say that much" [2].
  - Why the pain?

Einstein-Podolsky-Rosen

Discussion of quantum signalling are usually framed in context of the Einstein-Podolsky-Rosen thought experiment [8].



What Can Alice and Bob Do?

- Suppose a sequence of correlated pairs are emitted from the source.
- Alice and Bob each locally see an apparently random sequence of $+$ and -.
- Alice could vary her detector angle so as to build a message into the *correlations*.
- However, to read the message one needs both Alice and Bob's strings of results.
  - This is the basis of quantum cryptography.
- Could Alice send a message that would show up in Bob's local statistics?

What Quantum Signalling Would Demand

- Suppose Alice has a way of forcing her particle to go in a particular direction, which she could do with magnets, etc.
- If she could do this *while maintaining the correlations* she could controllably (and superluminally) signal to Bob.
  - Problem: if she tries to do this, the state will collapse into a product state and it will be no more correlated than a product state!
  - (Product states can of course be correlated but the signal has to be built into them at the source.)
- As far as I know (!), no one has, as a matter of *practical* fact, been able to do this—but it *sounds* like a mere engineering problem.
- The no-communication theorem is the claim that it is impossible *in principle* for Alice to control her local results without disrupting the quantum correlations.

Quantum Signalling and Quantum Computing

- The problem of quantum signalling is essentially the same as quantum computing.
  - In both cases, we want to extract information from a coherent state *without* collapsing the state.
- Main difference is that in quantum computing we want to extract the information at one location, and in signalling we want to extract the information in two locations!

The ‘Proofs’

- There are numerous papers claiming to demonstrate the no-controllable-signalling theorem, some within non-relativistic quantum mechanics, some within quantum field theory.
  - The gist: in one way or another, they all *assume* that whatever Alice can do to her particle, it has no dynamic interaction with Bob’s particle—whatever she does is entirely local to her particle.
- So: no signalling, controllable or otherwise, because there is no dynamic interactions between the particles at all!
- But isn’t that what we should be trying to *prove*?

A Big Assumption

- Many no-signalling proofs depend directly or indirectly on the assumption of additivity of system Hamiltonian for entangled states (e.g., [20]):
$$H_{\text{total}} = H_1 + H_2 \tag{5}$$
- This is the basis, implicitly or explicitly, of many standard “no-signalling” arguments in the literature, and also essential in Local Quantum Field Theory.
  - Crucial point: *it’s just an assumption*.
- This assumption is made because physicists would *prefer* that relativity and QM be on an equal logical footing.
- But is it, in fact, correct?

The Nasty Cross-Terms

- How do we know that there are not cross-terms in the Hamiltonian for entangled states?

$$H_{\text{total}} = H_1 + H_2 + H_1 \, H_2 \tag{6}$$

- Abner Shimony (in a shocked voice): "But then we could violate Parameter Independence [no-controllable-signalling]!"
  - What does the physics demand?

Entangled Dynamics in Quantum Information Theory

- Dür *et al.* (2002) give the general Hamiltonian for an entangled (Bell) state of two particles as

$$H_{AB} = \sum_{i=1}^{3} \alpha_i \sigma_i^A \otimes \mathbb{I}_B + \sum_{j=1}^{3} \beta_j \mathbb{I}_A \otimes \sigma_j^B + \sum_{i,j=1}^{3} \gamma_{i,j} \sigma_i^A \otimes \sigma_j^B .$$

- Dür and colleagues [6] thought this was so obvious that they did not even have to state the derivation in their paper.
  - (It follows from the fact that any 2×2 complex matrix can be expanded as a linear combination of the Pauli spin matrices plus the identity matrix.)

Direct Experimental Evidence for Nonlocal Energy States

- Lee *et al.* (2011) [12, 9] show that two 3 mm diamond chips can be put into the *same* phonon state for a few picoseconds even though they are 30 cm apart.
- People who work on foundations do not seem to have noticed this result *at all*.

Cognitive Dissonance?

- In sum: It is well known, both theoretically and experimentally, that entangled quantum systems are not always dynamically local.
  - I have not even mentioned Bohm's quantum potential!
- And yet this has not penetrated into foundational discussions, which are still bent on showing that quantum mechanics is somehow local, despite Bell and all this other evidence.

Could the Hamiltonian for a Tensor Product State *Ever* be Additive?

- I will now sketch a *reductio* argument against the additivity hypothesis for entangled states.
- It is well known that subsystems of a tensor product (entangled) state cannot be pure states:
  - "It can be shown... that an interaction between the two systems transforms an initial state which is a product into one which is no longer a product: any interaction between two systems therefore introduces, in general, correlations between them. ... This question is very important since, in general, every physical system has interacted with others in the past ... *it is not possible to associate a state vector* $|\phi(1)\rangle$ *[a pure state] with system (1) alone.*" [5, p. 293].

Reductio Argument for Additivity for Entangled States

- Suppose that it is possible to associate a Hamiltonian H_1 with a particle p_1 that is a member of an entangled state.
- The Hamiltonian is an observable, and every observable associated with a state $|\psi\rangle$ has a set of eigenstates which define a basis for $|\psi\rangle$ [5].
- Therefore, if this particle "has" a Hamiltonian, it is possible to write the state of that particle as an expansion of the form

$$|\phi(p_1)\rangle = \sum_i c_i |e_i\rangle \tag{7}$$

where $\{|e_i\rangle\}$ are the energy eigenstates of the particle p_1 with respect to H_1, and c_i are complex coefficients.

The Rub

- But — *this is a pure state.*
- However, because p_1 is taken to be a member of an entangled state, it cannot, by itself, itself be represented as a pure state.
- Hence, there cannot exist a Hamiltonian that can be associated with p_1 in this way.
  - Hence any no-signalling argument that depends upon the assumption of additivity (or any other expression of dynamic localizability) is merely a trivial demonstration of no-signalling for *product states* (which *do* have additive dynamics).

What About Microcausality?

- Another major method used to demonstrate no-controllable-communication is the principle of *microcausality*, used in quantum field theory.
  - Microcausality (local commutativity): all observables at a spacelike separation commute (even if they would fail to commute if they were taken on the same local system).
- Problem: microcausality was introduced to quantum field theory as a 'patch' explicitly *in order to prevent conflict with relativity*.
  - By appealing to microcausality in order to demonstrate no-communications, we are arguable, therefore, assuming what we needed to prove [13].
- (I don't have the space here to treat this question properly.)

In Sum. . .

- To summarize the orthodox no-communication arguments (not entirely precisely but memorably):
  - "There's no signalling because there's no signalling, dammit!"
- I do not know whether it is, in fact, possible to design a device that could use entanglement to signal in a controllable manner.
- But it seems clear that most or all of the standard proofs that this is impossible do not do the job!
- If there is a sound proof of no-signalling in quantum entangled systems, it must use another method than merely *assuming* dynamic locality.
  - IMHO, the question of controllable quantum signalling remains open.

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