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The Non-Signalling theorem in generalizations of Bell's theorem

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Abstract. Does "epistemic non-signalling" ensure the peaceful coexistence of special relativity and quantum nonlocality? The possibility of an affirmative answer is of great importance to deterministic approaches to quantum mechanics given recent developments towards generalizations of Bell's theorem. By generalizations of Bell's theorem we here mean efforts that seek to demonstrate the impossibility of any deterministic theories to obey the predictions of Bell's theorem, including not only local hidden-variables theories (LHVTs) but, critically, of nonlocal hidden-variables theories (NHVTs) also, such as de Broglie-Bohm theory. Naturally, in light of the well-established experimental findings from quantum physics, whether or not a deterministic approach to quantum mechanics, including an emergent quantum mechanics, is logically possible, depends on compatibility with the predictions of Bell's theorem. With respect to deterministic NHVTs, recent attempts to generalize Bell's theorem have claimed the impossibility of any such approaches to quantum mechanics. The present work offers arguments showing why such efforts towards generalization may fall short of their stated goal. In particular, we challenge the validity of the use of the non-signalling theorem as a conclusive argument in favor of the existence of free randomness, and therefore reject the use of the non-signalling theorem as an argument against the logical possibility of deterministic approaches. We here offer two distinct counter-arguments in support of the possibility of deterministic NHVTs: one argument exposes the circularity of the reasoning which is employed in recent claims, and a second argument is based on the inconclusive metaphysical status of the non-signalling theorem itself. We proceed by presenting an entirely informal treatment of key physical and metaphysical assumptions, and of their interrelationship, in attempts seeking to generalize Bell's theorem on the basis of an ontic, foundational interpretation of the non-signalling theorem. We here argue that the non-signalling theorem must instead be viewed as an epistemic, operational theorem i.e. one that refers exclusively to what epistemic agents can, or rather cannot, do. That is, we emphasize that the non-signalling theorem is a theorem about the operational inability of epistemic agents to signal information. In other words, as a proper principle, the non-signalling theorem may only be employed as an **epistemic**, **phenomenological**, or **operational** principle. Critically, our argument emphasizes that the non-signalling principle must not be used as an ontic principle about physical reality **as such**, i.e. as a theorem about the nature of physical reality independently of epistemic agents e.g. human observers. One major reason in favor of our conclusion is that any definition of signalling or of non-signalling invariably requires a reference to epistemic agents, and what these agents can actually measure and report. Otherwise, the non-signalling theorem would equal a general "no-influence" theorem. In conclusion, under the assumption that the non-signalling theorem is epistemic (i.e. "epistemic non-signalling"), the search for deterministic approaches to quantum mechanics, including NHVTs and an emergent quantum mechanics, continues to be a viable research program towards disclosing the foundations of physical reality at its smallest dimensions.

Introduction

Historically, the first successful attempt in fashioning a deterministic approach to quantum mechanics was the one now known as the de Broglie-Bohm theory, and that theory introduced the notion of "hidden variables" (Bohm [1]). In turn, Bohm's consideration that hidden variables might possibly underlie quantum phenomena, in conjunction with the earlier analysis by Einstein, Podolsky and Rosen [2], inspired John Bell to develop the theorem named after him (Bell [3]). 50 years on, it is widely accepted that Bell's groundbreaking theorem has proven beyond doubt that no (deterministic) quantum theory based on local hidden variables could account for the observations of quantum physics. However, while Bell's theorem ruled out as an explanation any local hidden-variables theory (LHVT), Bohm's original proposal of a nonlocal hidden-variables theory (NHVT) remained a viable possibility at least on logical grounds, even after Bell (e.g. Bell [4]).

In recent years, however, efforts have gained prominence that implied that **all** types of deterministic approaches to quantum mechanics, not only LHVTs, but also all forms of NHVTs such as de Broglie-Bohm theory, must be in violation of Bell's theorem. In the context of the present article, such efforts we will refer to as efforts seeking to generalize Bell's theorem. Recent publications with important implications for generalization, in the here proposed sense, of Bell's theorem are, for example, Colbeck and Renner [5, 6] and Gallego et al. [7]. (Their work builds on previous work that has similar implications such as Barrett et al. [8]; Kofler et al. [9]; Pironio et al. [10]). Both Colbeck and Renner [5, 6], and Gallego et al. [7], have argued that even those deterministic quantum theories, which are unconstrained by Bell's locality assumption (i.e. an NHVT such as de Broglie-Bohm theory), must necessarily violate the non-signalling theorem or principle. Gallego et al. [7] also argued that their own work had important "philosophical and physics-foundational implications". Because of their interest in foundational issues as well and also because this work is the most recent one we included in our analysis, we will use Gallego et al. [7] as the key reference in our exploration of basic physical and metaphysical assumptions concerning the non-signalling theorem. While in no way do we question the great technical achievements which are presented in the mentioned articles, we do question the finality of assumptions expressed therein concerning the possibility of deterministic approaches to quantum mechanics. Importantly, these authors, like many researchers in quantum physics in general, take for granted a foundational, ontic interpretation of the non-signalling theorem. By contrast, the present work will argue that for deterministic approaches to quantum mechanics an exclusively **epistemic**, **phenomenological**, or **operational**, interpretation of the non-signalling theorem does in fact ensure compatibility between special relativity and quantum nonlocality. Before proceeding with our analysis of the non-signalling theorem, and of possible assumptions underlying the theorem, we will start with a brief summary of quantum phenomenology as apparent from EPR-type experiments.

1. Quantum phenomenology of EPR-type experiments

What is the phenomenon that is in need of explanation by quantum-theoretical approaches whether by standard indeterminist or by unconventional determinist approaches? We here focus on quantum phenomenology, such as on nonlocal correlation phenomena, as apparent from EPR-type experiments (e.g. Aspect et al. [11, 12]; Weihs et al. [13]; Tittel et al. [14]; Ursin et al. [15]; Giustina et al. [16]). In the following sections (1.1. to 1.3.) we present a brief overview of different metaphysical interpretations of the same quantum-phenomenological observations.

1.1. Nonlocal, instantaneous correlations signify the existence of instantaneous influences

Orthodox quantum theory makes no claim regarding the nature of physical reality that might underlie the formation of nonlocal i.e. instantaneous correlations. Everyone agrees that the term 'correlation' merely represents a descriptive, epistemic term i.e. 'correlation' defines a state of

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knowledge only. Therefore, the use of the term neither implies underlying causal processes nor the existence of any fundamental physical elements or ontic structures in general. However, at the same time, we consider the fact to be non-controversial that instantaneous correlations manifest **physically** at the level of distant measuring devices. It goes without saying that lacking the power to manifest physically, instantaneous correlations would be beyond the capacity of epistemic agents to observe. Therefore, the fact that instantaneous correlations can indeed be observed as **physical effects** in concrete i.e. ontically-real systems, we take as evidence that some kind of "instantaneous" or "quasi-instantaneous" influence must be at work as part of the formation, between space-like separated quantum detectors, of nonlocal correlations. We here do not engage the difficult question of whether the existence of "nonlocal correlations" is evidence of nonlocal or superluminal **causation** (e.g. see Maudlin [17]). In fact, it is of no consequence for our subsequent argument that instantaneous influences – at a minimum – represent near-instantaneous superluminal influences, whether or not influences are assumed to be "nonlocally causal" (e.g. as an instantaneous "common cause"), or are characterized only as "a-causal" or "formal".

1.2. Instantaneous influences associated with nonlocal correlations are, at a minimum, near-instantaneous, superluminal influences

The instantaneous influences usually associated with observation in EPR-type experiments of nonlocal correlations would be influences, again whether causal or a-causal (see 1.1.), that operate, by definition, at an infinite velocity. However, as is well-known, the assumption of infinite velocity could never be proven experimentally. In other words, the question appears to be undecidable by any conceivable experiment of whether or not an observation, such as the appearance of nonlocal correlations, is in fact due to an infinite-velocity influence (i.e. an "instantaneous correlation"). By contrast, the generation of positive evidence for finite-velocity, yet superluminal, influences is possible by way of scientific experimentation, at least in principle (e.g. see Salart et al. [18]; Cocciaro et al. [19]). In any case, what can, and indeed has been, established by way of EPR-type experiments is that influences exist in nature which, if they are not instantaneous, then they at least must be superluminal (however, they must not be signalling, of course). Consequently, we here take a conservative position and assume that nonlocal correlations could either be instantaneous correlations or near-instantaneous, superluminal correlations; again, the reason is that proof of instantaneity is beyond scientific measurement.

1.3. Nonlocal correlations are unpredictable but not necessarily intrinsically random correlations

It is well-known to physicists that no mathematical proof exists which could decide "whether or not a given series of digits is in fact random or only seems random" (Chaitin [20]). This does not mean, of course, that powerful statistical tests are unavailable for demonstrating the lack of **certain** patterns in a digital sequence; nevertheless "no finite set of tests can ever be considered complete, as there may be patterns not covered by such tests" (Pironio et al. [10]). In short, it is undecidable – as a matter of principle again – whether a digital sequence, for example, a data sequence obtained from an EPR-type experiment, is genuinely random or merely pseudorandom. The principal undecidability of whether data sequences derived from quantum experiments are either random or merely pseudorandom has the following consequence: no experiment could refute the possibility that deterministic processes might rule at all levels of physical reality, including at the level of the quantum. Therefore, while indeterminism remains a metaphysical assumption which is greatly preferred over determinism by many quantum physicists, it must be noted also that indeterminism is neither a conclusive experimental fact nor a logical requirement on the basis of existing evidence. Importantly, in relation to EPR-type experimental findings, the two competing metaphysical assumptions – determinism and indeterminism – share an all-important feature: the **statistical unpredictability** of measurement outcomes. Therefore, given the above-described undecidability concerning the existence, or not, of free randomness, we here take again a conservative position, and we characterize EPR-type correlation phenomena as merely "unpredictable" instead of as a sure sign of "intrinsic randomness".

For example, statistical unpredictability may be the result of intrinsic complexity rather than intrinsic randomness. That is, unpredictability could be entirely a function of deterministic processes, i.e. at the level of individual events predictability would be impossible due to lack of precise knowledge. Famously, in deterministic chaos, (long-term) unpredictability of behavior is due to **intrinsic complexity**, and not due to intrinsic randomness. Therefore, in the case of complexly-structured, deterministic systems an assumption of free randomness is not required to account for the appearance of statistical unpredictability of measurement outcomes.

Therefore, it should remain an open question in quantum physics whether, or not, the correlations that are observed in EPR-type experiments do in fact represent **intrinsically random**, **instantaneous** correlations. From the alternative perspective of deterministic theory, we here argue that the quantum phenomenology as established by EPR-type experiments merely indicates that these correlations are **unpredictable**, not intrinsically random, and that they either may be **near-instantaneous**, **superluminal** or **instantaneous** (1.1. to 1.3.).

2. Evaluating the validity of the non-signalling theorem in generalizations of Bell's theorem

During the last decade, as was already mentioned in the Introduction, an argument has gained traction, especially in work concerning the foundations of quantum cryptography, which uses the validity of the non-signalling theorem, to generalize the predictions of Bell's theorem i.e. to rule out the possibility of NHVTs including de Broglie-Bohm theory. In summary, the argument has three stages: (1) assume the validity of the non-signalling theorem as a foundational principle concerning the nature of physical reality, (2) if so, then the unpredictability of nonlocal correlations as observed in EPR-type experiments is essentially due to intrinsic randomness, and therefore (3) deterministic approaches to quantum mechanics, including even NHVTs, are impossible. A critique of this argument will be the main topic for the remainder of this article.

2.1. On the use of the non-signalling theorem in the foundations of quantum cryptography

There is a wide-spread belief, or basic assumption, especially in the growing literature on quantum cryptography, that the non-signalling theorem guarantees the presence of "free randomness" i.e. of fundamental indeterminism. Conversely, the belief is wide-spread also that a deterministic approach, in combination with nonlocality, necessarily must imply superluminal signalling. For example, one representative statement from that literature reads "any state that is deterministic and nonlocal allows signalling" (e.g. Barrett et al. [8]). However, if that statement were true in an ultimate sense, then Bell's theorem would not only negate the possibility of LHVTs but also of any NHVTs such as de Broglie-Bohm theory. Traditionally, however, compatibility of NHVTs and the predictions of Bell's theorem had always been assumed (e.g. Bell [**?**]; Bohm and Hiley [21]; Holland [22]; Valentini [23]). Consequently, there now appears to have surfaced a fundamental contradiction between the well-known predictions of Bell's theorem, on the one hand, and the recent claims in the literature on quantum cryptography concerning the use of the non-signalling theorem as a foundational, instead of as an operational, principle. As evidence for the "new" incompatibility we will next discuss a number of statements by the authors who were mentioned in the Introduction already (Gallego et al. [7]). We will point out, in appropriate places, that the presumption of incompatibility results from the assumption that the non-signalling principle serves as an ontic, foundational principle, which, as we will explain, presents a view of the principle that has lost its essential connection to epistemological concerns.

According to Gallego et al. [7], the non-signalling principle "states that no instantaneous communication is possible, which in turn imposes a local structure on events, as in Einstein's special relativity." In other words, any kind of superluminal signalling or communication is prohibited, whether by instantaneous or quasi-instantaneous, superluminal influences. (For the remainder of this analysis we will only discuss possible consequences of instantaneous influences in the context of non-signalling.) We fully agree with Gallego et al. [7] that this indeed is the essential meaning of the non-signalling principle. Put differently, the impossibility by epistemic agents to signal each other by way of quantum nonlocality protects against violations of special relativity. However, we question the basic assumption by Gallego et al. [7] that the non-signalling principle applies also to instantaneous influences that are beyond control for the purposes of communication or signalling. Crucially, the non-signalling principle does not state "no instantaneous influences are possible", but it only states "no instantaneous communication is possible"; otherwise, for example, the formation of nonlocal correlations in EPR-type experiments would be impossible to account for, or even to talk about, in terms of possible explanations in physics (compare 1.1.). Importantly, we point out that as long as control is impossible of instantaneous influences, these influences, even if acting instantaneously, do not violate the non-signalling constraint. In other words, if such influences are informationally inaccessible to epistemic agents, i.e. if influences are genuinely "hidden influences" (e.g. "hidden variables"), then instantaneous influences by way of nonlocal hidden variables do not have to contradict special relativity. This is essentially what is implied by an epistemic, operational, or phenomenological interpretation of the non-signalling theorem.

Valentini [23], for example, showed that "all deterministic hidden-variable theories, that reproduce quantum theory for a 'quantum equilibrium' distribution of hidden variables, predict the existence of instantaneous signals at the statistical level for hypothetical 'nonequilibrium ensembles'." Crucially, however, the assumption of "instantaneous signals at the statistical level" for quantum theories sharing both determinism and nonlocality does not mean that such theories would have to contradict the non-signalling theorem. For example, after considering the possibility, between two distant members of a correlated pair of spin-$\frac{1}{2}$ particles, "of nonlocal information flow at the hidden-variable level", Valentini [23] explained: "Of course, in equilibrium this information flow is not visible at the statistical level, because as many outcomes flip from +1 to -1 as from -1 to +1." An epistemic, phenomenological interpretation of the non-signalling theorem is therefore implicit in the argument by Valentini [23]: "It is as if there is a conspiracy in the laws of physics that prevents us from using nonlocality for signalling. But another way of looking at the matter is to suppose that our universe is in a state of statistical equilibrium at the hidden-variable level, a special state in which nonlocality happens to be hidden. The physics we see is not fundamental; it is merely a phenomenological description of an equilibrium state."

However, it is apparent that Gallego et al. [7] have excluded, as of course have many others (e.g. Barrett et al. [8]; Kofler et al. [9]; Pironio et al. [10]; Colbeck and Renner [5, 6]), as a possibility an epistemic, phenomenological interpretation of the non-signalling constraint: "In fact, Bohm's theory is both deterministic and able to produce all quantum predictions, but it is **incompatible with no-signalling at the level of hidden variables**." And, they continue: "Thus, we assume throughout the validity of the no-signalling principle." From this last statement it becomes clear that these authors, like many before them, have committed to a view of the non-signalling theorem which has eliminated any vital reference to epistemic agents, and to what epistemic agents can or can't do; they have "ontologized", so to speak, a principle derived solely on the basis of epistemic considerations i.e. signalling or non-signalling. In consequence, the "non-signalling" principle was tacitly turned into a "no hidden-influence"

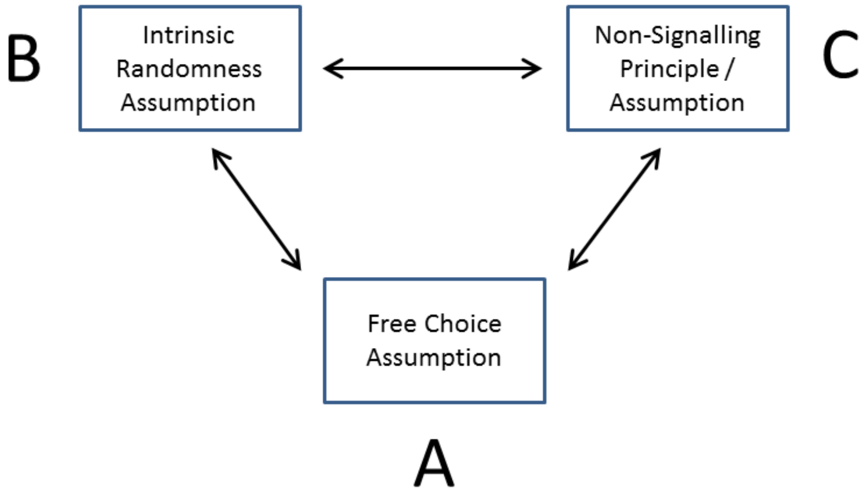

Figure 1. Relational diagram showing the interdependency of three basic assumptions (A–C) which are discussed, for example, in Colbeck and Renner [5, 6], and Gallego et al. [7]. The validity of each of these assumptions is central to the conclusion that deterministic theories, including those based upon nonlocal hidden variables (i.e. de Broglie-Bohm theory) are impossible because they contradict the non-signalling principle.

principle. The justification for this move and for transforming the very meaning of non-signalling has not yet been revealed. Is this a valid interpretation of the non-signalling principle? Can the notion of "non-signalling" really be reduced to a notion of "non-influencing"?

Regarding the problem of "non-signalling" versus "non-influencing", specifically in relation to NHVTs such as de Broglie-Bohm theory, for example, Holland [22] commented: "To summarize, the quantum potential implies that a certain kind of 'signalling' does, in fact, take place between the sites of distantly separated... particles in an entangled state, if one of the particles undergoes a local interaction. This transfer of information cannot, however, be extracted by any experiment which obeys the laws of quantum mechanics." This is in agreement with the above-cited position by Valentini [23] who explained that in the manifestation of nonlocal correlations "information flow is not visible at the statistical level"; therefore control of information flows by epistemic agents for the purposes of signalling is again prohibited. Finally, Holland [22] concluded that therefore "...the failure of quantum correlations to provide a signalling mechanism at the empirical level is consistent with the requirement of special relativity that no signal be transmitted faster than the speed of light."

2.2. Circular reasoning in the relationship between the non-signalling principle and the assumption of intrinsic randomness

We will next describe another argument against the use of the non-signalling principle as an ontic foundational principle in favor of the existence of intrinsic randomness, in addition to the argument already presented above (2.1.). This second argument is based on the following simple observations: it is exactly because standard quantum theory assumes the unpredictability of nonlocal correlations to be evidence of intrinsic randomness that these correlations are presumed to be "intrinsically non-signalling" in the first place; it is equally valid therefore to say that the non-signalling assumption (C in Fig. 1) is a consequence of the prior free (intrinsic) randomness assumption (B in Fig. 1).

Similarly to the first step of the argument by Gallego et al. [7] which did correctly recognize

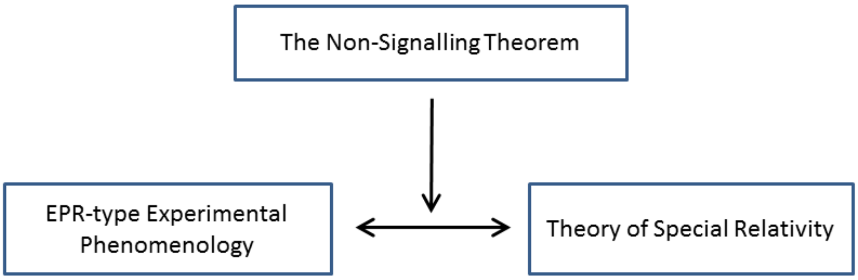

Figure 2. The non-signalling theorem or principle.

the inseparability, or relationality, of assumptions A and B (see bidirectional arrow between B and A in Fig. 1), the second step of their argument also, **as is pointed out in the present work only**, is equally characterized by an inseparability, or relationality, of assumptions B and C (see bidirectional arrow between C and B in Fig. 1). Therefore, it is questionable whether the non-signalling principle can be used to argue for the necessity of free randomness in nature, as only the **prior** assumption of intrinsic randomness could justify any foundational, physical implications of the non-signalling theorem to begin with. In the final section of this article (2.3), we will first provide a short (historical) overview of reasons for introducing the non-signalling principle, and then briefly return to discussion of the incomplete metaphysical status of the non-signalling principle.

2.3. The non-signalling theorem

The non-signalling theorem was introduced, of course, to acknowledge that EPR-type experiments, which indicate "instantaneous correlations" between space-like separated quantum detectors, do not violate special relativity (e.g. Eberhard [24]). Special relativity imposes a fundamental constraint on all physical phenomena whether quantum or classical. In particular, special relativity imposes a fundamental limit on the maximum speed of any physical influences existing in the vacuum of spacetime – the speed of light. Therefore, special relativity should outright prohibit the appearance in nature of any kind of "superluminal influences" whether infinite-velocity influences (i.e. instantaneous influences) or finite-velocity influences (e.g. near-instantaneous, superluminal influences). However, as was described before, EPR-type experiments have provided ample evidence for the existence of instantaneous, or at least, superluminal influences (see 1.3). Such influences are apparent from the measurement of physical effects which manifest – at velocities far exceeding the speed of light – between distant quantum detectors. Again, how could the existence of faster-than-light influences be compatible with special relativity? In regards to EPR-type experimental phenomenology, the tension which arises as a function of the **apparent** incompatibility between special relativity, on the one hand, and the observation of instantaneous, or at least, superluminal correlations, on the other hand, is relieved through the introduction of the non-signalling theorem or principle (see Fig. 2).

Clearly, the need to invoke non-signalling as a theorem for avoiding conflict with special relativity reveals just how extraordinary the phenomenology is of EPR-type experiments. This introduction is all the more remarkable as the theory of special relativity puts firm constraints already on the nature of allowable micro-causal processes, and yet the non-signalling principle itself does not refer to causal processes at all. The non-signalling principle refers to signals only, or rather their absence, i.e. to epistemic "states of knowledge" rather than to any ontic physical or causal states. The fact that an **epistemological** rather than an ontological argument

	Signalling / Non-signalling Influences	**Instantaneous Influences**
Basic relations:	Sender and Receiver	"Unknown relations" [1]
Operational ability:	Ability, or inability, by epistemic agents to control information transfers	Registering random events
Influence is:	Purposeful; a "message" is, or is not, conveyed	Not purposeful; blind
Available must be:	Epistemic agents **and** physical processes	Physical processes
Conceptual framework:	Epistemology **and** Ontology	Ontology

Table 1. Distinguishing signalling/non-signalling influences from instantaneous influences. [1]The reference in the Table to "unknown relations" only states the obvious namely the lack of scientific understanding of the **physical nature** of "instantaneous influences". For example, an instantaneous influence does neither imply "efficient causation" nor any kind of "action-reaction"-type scenarios unless when considering a wholly **operational** meaning of an "action-reaction" relation. For example, in the context of instantaneous influences, as part of an EPR-type experiment, an "action" may be the defining of a measurement setting in location A, whereas a "reaction" might refer to the physical measurement effect at the quantum detector in location B; again operationally only.

suffices to resolve the apparent incompatibility between special relativity and EPR-type data has astonished many thinkers on quantum foundations. This includes for example John Bell also who asked (Bell [25]):

"Do we then have to fall back on 'no signalling faster than light' as the expression of the fundamental causal structure of contemporary theoretical physics? This is hard for me to accept. For one thing we have lost the idea that correlations can be explained, or at least this idea awaits reformulation. More importantly, the 'no-signaling…' notion rests on concepts which are desperately vague, or vaguely applicable. The assertion that 'we cannot signal faster than light' immediately provokes the question: Who do **we** think we are? **We** who can make 'measurements', **we** who can manipulate 'external fields', **we** who can signal at all, even if not faster than light? Do we include chemists, or only physicists, plants, or only animals, pocket calculators, or only mainframe computers?"

We conclude that the metaphysical status of the non-signalling principle still remains a very much open question even today. For example, as was alluded to above many times already, it is still undecided whether the non-signalling principle is a foundational principle, or an operational, phenomenological one. We conclude that until this all-important question is answered, the argument, for example, by Gallego et al. [7] must be considered, at a minimum, to be incomplete concerning their claim that the non-signalling principle is a conclusive argument in favor of intrinsic randomness in nature (compare Fig. 1, B and C).

Importantly, our analysis maintains that while the non-signalling principle prohibits faster-than-light communication it does not prohibit the possibility of instantaneous influences. Put differently, in combination with the non-signalling principle, the meaning of special relativity is changed from an absolute "no influence can exist which is faster than the speed of light" to the less restrictive statement that "no instantaneous/ superluminal influence can exist **that can be controlled for signalling purposes**". Critically, the conflation in meaning of the notions of "signalling / non-signalling influence" and "instantaneous influence" has led to much confusion in the literature, and worse, to misleading conclusions. The Table summarizes differences for better overview.

The present work sought to argue against proposals that seek to construe the non-signalling theorem as a "non-influence theorem". Specifically, we have argued that the non-signalling theorem serves to eliminate only the capacity of epistemic agents to signal information by way of instantaneous, or near-instantaneous, influences. However, the non-signalling theorem does not equal a non-influence theorem, e.g. the non-signalling theorem does not prohibit the existence of instantaneous influences, for example, in the formation of nonlocal correlations as part of EPR-type experiments (see 1.1. to 1.3.).

Finally, we conclude that "epistemic non-signalling" is likely to be sufficient to ensure the peaceful coexistence of special relativity and quantum nonlocality. A major reason in favor of our conclusion is that any definition of signalling or non-signalling invariably requires a reference to epistemic agents, and what these agents can actually measure and report (see Table 1).

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