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Article

Nonlocality or Superposition? The Source of Quantum Contextuality

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Abstract: Euclidean theorems are indisputable in flat spaces, but do not hold in curved spaces. Likewise, Bell's Theorem is true for jointly distributed variables in Kolmogorov probability spaces. Yet, quantum spin variables are not jointly distributed and cannot coexist in Kolmogorov spaces. They have different qualities and operate by different rules. Therefore, Bell's Theorem does not entail that quantum theory is non-local. The question remains: what is the origin of quantum contextuality? Other theories (not quantum theory) need nonlocality or super-determinism to make similar predictions, because they cannot violate Bell-type inequalities, but why is quantum theory different? The answer is found in the analysis of quantum superposition, in the context of a much older debate about the ontology of linear wave superposition.

Keywords: quantum superposition; EPR paradox; nonlocality; Bell's Theorem; contextuality

1. Introduction

Quantum theory is often described as "nonlocal" because it predicts violations of Bell's inequality [1-8]. EPR-type experiments – old and new – are also announced as tests of locality [9-18], but why is that happening? As shown by John Bell [3], hidden variable theories need nonlocality (or super-determinism, or parallel universes) to reproduce the predictions of quantum theory. Yet, quantum theory itself is not a hidden variable theory. Furthermore, if quantum theory is assumed to be complete, then hidden variables cannot exist. This makes them irrelevant for any discussion about quantum behavior. Conversely, if quantum theory is assumed to be incomplete, then hidden variables – though real – remain unobservable by definition. It does not matter if they can or cannot violate some rule, because quantum theory predicts such violations for observable properties. How can we claim that some properties are real or not real, and that they require or do not require metaphysical factors, if we are measuring other (unrelated) properties? Indeed, quantum predictions apply to measurement contexts where Bell violations are naturally possible, in the same way in which they are naturally impossible for the so-called hidden variables. Accordingly, there is no logically valid scenario in which quantum correlations require metaphysical explanations.

To clarify the problem by analogy, let us consider a well-known theorem from Euclidean geometry: the sum of all angles in a triangle is equal to 180°. An established theorem must be treated as a statement of fact, until proven otherwise. Accordingly, it is a practical law that the sum of all angles in any Euclidean triangle is equal to 180°. Yet, this is only valid as long as analysis is confined to Euclidean spaces, with flat curvature. In other spaces, the same sum can be much more or much less than 180°, depending on the curvature of the relevant context. This is also a statement of fact. Yet, the two facts do not invalidate each other. They merely define each other's boundary of validity. Just because non-Euclidean spaces exist, Euclidean theorems do not stop being accurate in their domain. Similarly, it is true that jointly distributed variables cannot violate Bell's inequality [19]. If such a violation was found, one would be justified in questioning the nature of reality, locality, or other fundamental category. However, quantum spin variables are not jointly distributed. Therefore, they are immune to the conclusions of Bell's theorem, in the

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same way in which triangles in curved spaces are immune to the conclusions of Euclid's theorems.

Still, what is the meaning of Bell's Theorem in quantum mechanics? The scientific aspect of this argument is straightforward [20-22]. Some theories are based on variables with fixed values that are not affected by measurement choices. Such theories cannot explain quantum observations. Yet, this is where the scientific significance ends. If these inadequate theories are modified to include magical parameters (such as nonlocality, super-determinism, or other metaphysical concepts), then they stop being "theories with fixed values for their variables". Indulging in metaphysical speculation cannot change the conclusion that such theories, as defined, are unfit for the analysis of quantum phenomena. More importantly, these speculations shift the focus of research away from the topic that really matters. Namely, how does quantum theory work? What makes it able to predict the well-known violations of Bell-type inequalities, unlike those other models? As will be shown below, the true difference between co-called "classical" approaches and quantum approaches concerns the ontology of propagating waves. This is particularly clear in the interpretation of the double-slit experiment. Classical models assume that wave components maintain their objective existence during overlap and propagate through each other unperturbed [23-26]. This is the basis for beliefs about "path knowledge" after interference. Quantum models assume the opposite: that the vector sum of superposed components is physically real. Single quanta express all the relevant spectral components of a wavefunction at the same time. At first sight, the two approaches are quantitatively equivalent, due to their identical implications at the group level. However, at the level of individual events, the two approaches make different predictions, especially about correlated observables. Accordingly, Bell violations tell us that quantum superposition is ontologically valid, and that traditional classical interpretations are false. However, the true significance of this conclusion requires a deeper understanding of quantum behavior than currently allowed by non-physical interpretations with "instantaneous collapse". This problem is explored in depth in the following sections. At first, the concept of superposition is explained in its historical and ontological context. Then, the conclusions of this analysis are used to illuminate some ignored aspects of the EPR paradox and carried over to the mechanism behind Bell violations in quantum mechanics.

2. The central problem of modern physics

Observable physical entities display corporeal integrity in spacetime without exception. They move in only one direction at a time and cannot be in two different places at the same time. In contrast, unobservable quantum objects are often presumed to display a different type of behavior, without spatial and temporal continuity. The reasons for this distinction seem compelling, given the known features of quantum superposition. Who hasn't heard about the double-slit experiment? Accordingly, it is common practice today to describe macroscopic objects as "intuitive" and microscopic objects as "counterintuitive". Yet, this division cannot be justified on the basis of principled analysis. As will be shown below, quantum mechanics uncovered a deep flaw in the interpretation of classical waves. It is classical physics that promoted a non-classical ontology with regard to linear superposition [25]. This picture was falsified at the beginning of the 20ty century. Therefore, quantum mechanics should have ushered in a return to classical interpretations. Unfortunately, the old paradigm was perceived as unquestionable. Instead, the adopted conclusion was that Nature is "weirder than anyone expected". As a result, quantum behavior is currently seen through a distorted prism, and new discoveries are misinterpreted to fit a non-classical ontology. This process cannot be stopped until the problem is acknowledged. For this reason, the physical interpretation of linear wave superposition is the central problem of modern physics.

So, what is the matter, in a nutshell? Complex wave profiles can be decomposed into simple spectral components in classical mechanics. This is true both physically and mathematically [27]. Yet, the challenge is to decide what happens when these components

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overlap in free space. Do they maintain their physical individuality, or do they exist merely as virtual elements? The crucial detail here is that waves are not objects. They are patterns of vibration in elastic media. Furthermore, a point in an elastic medium is functionally similar to a solid object under the influence of multiple force vectors. In classical mechanics, it can only move in one direction at a time. It cannot be in different places at the same time. Therefore, to assume that wave components do not merge in joint action is to invoke a fundamentally non-classical picture of the Universe. On the other hand, macroscopic waves always look as if they propagate through each other unperturbed. The evidence for that is practically omnipresent. Accordingly, classical wave theory evolved with the rule of thumb that wave components are always real [25]. In particular, this entailed that wave interference was just a macroscopic appearance [26]. When two waves overlap, their amplitudes may reinforce each other or cancel out locally, but no energy redistribution was assumed to take place at the microscopic level (Figure 1a). This expectation was contradicted by quantum theory, as seen in the double-slit experiment. Yet, instead of correcting an old misperception and returning wave interpretation back to a classical picture, the new conclusion was that "nothing is real". Bohr's complementarity principle was used to argue that waves still go through each other unperturbed when nobody is looking [28]. Moreover, interference was described as "real" only when the microscopic aspects of wave propagation were made observable. Thus, quantum behavior emerged as something "weird", as if it was contradicting classical principles of physical interaction [29]. As will be shown below, "quantum weirdness" is not a property of quantum theory and is not required by the experimental data. It is merely a byproduct of the ongoing confusion about the nature of wave-like phenomena at various level of analysis.

To set things in context, let us take a brief historical detour. In the year 1678, Christiaan Huygens proposed a theory of wave propagation in terms of microscopic wavelets, originating at every point of a wavefront [30]. His insight was reportedly based on the observation of water waves, but the molecular structure of water was not known at the time. Therefore, his proposal was perceived as non-physical. More importantly, Huygens' model had a big problem, due to the fact that it could not account for many details of wave diffraction. Many years later, in 1818, Augustin-Jean Fresnel introduced a correction to this model, by postulating that microscopic wavelets interfere when they overlap and that their relative phase and amplitudes are important for this process [31]. Accordingly, the profile of a subsequent wavefront would have to be determined by the net state of superposition between the wavelets from the preceding wavefront, at each increment of propagation. Again, Fresnel's correction was accepted as a good tool, but widely perceived as non-physical. Yet, from a modern perspective, this method captures the physics of water waves very intuitively. If two water molecules are "pressed into" a third molecule from different directions, then the recipient molecule cannot move in two directions at the same time (Figure 1b). It must be displaced in the direction of the vector sum of all the local forces, and this displacement will determine its future impact on other molecules. In plain language, ocean waves exist because water molecules are displaced. When two waves overlap, the only observable aspect is a single bigger wave. Indeed, it would be strange to suggest that water molecules do not move in the same way at the microscopic level. Classical objects cannot move in two directions at the same time. Therefore, elementary constituents of water cannot express virtual components of waves. They should be presumed to express the vector sum of all the local forces acting on them, just as observed for macroscopic objects. In short, Huygens had a correct insight, but his model failed because he assumed that wavelets could go through each other unperturbed. Fresnel's correction solved the problem and placed the model on a solid ontological footing, compatible with the principles of classical mechanics. Unfortunately, this model was ahead of its time and was widely perceived as "non-physical" – a label that became unquestionable over time.

The Huygens-Fresnel method was a big advancement in the formal analysis of wave behavior. Furthermore, it gave the answer to a very important ontological problem. When two waves overlap, they seem to become hopelessly scrambled in the volume of overlap. Yet, after this process of interference, they propagate forward as if nothing ever happened.

If wave interference is real and energy redistribution takes place indeed, how is it possible for the output projections to emerge unperturbed? If two input profiles are assumed to be destroyed during interference, it seems magical for them to suddenly reemerge with no trace of interaction. Yet, the magic vanishes when the process is analyzed with the Huygens-Fresnel method. If a pattern of interference is assumed to be real, then any point in the cross-section of a wavefront can be treated as an oscillating molecule. The amplitude and phase of oscillation of these wavelets is determined by the vector sum of the preceding influences at each point. If a wavefront from an interference volume is time-evolved, it predicts the emergence of two individual beams that look unperturbed, as if interference never happened. In short, there is nothing magical going on. The underlying symmetry of perfectly elastic interactions, together with the principle of momentum conservation, provide a satisfactory explanation for the full process. Two waves overlap, they really experience energy redistribution, but then the output waves become reconstituted at the macroscopic level, with no sign of interaction [25]. In short, it is possible to explain wave behavior without invoking magical non-classical assumptions.

This conclusion seems natural in retrospect. Yet, the fact remains that it was not incorporated into classical wave theory. This became a problem when electromagnetic waves were discovered. The calculus of wavelet integration is hard without supercomputers. Yet, geometrical models provided a simple solution to most practical problems, especially in the study of optics. Accordingly, the intuitive understanding of electromagnetic waves was not shaped by the wave model of Huygens and Fresnel, but rather by a particle model based on rectilinear ray tracing [32]. For example, when two coherent projections overlap, a pattern of (Young) interference fringes can be observed. Yet, the details of these fringes could be predicted by drawing rectilinear rays that pass through each other (Figure 1a). At the locations where two rays intersected in phase, constructive interference was observed [23]. At the locations where such rays were out of phase, interference was destructive. Accordingly, the established perception was that optical interference was a macroscopic illusion. At the microscopic level, the presumed physical reality was that wave components pass through each other unperturbed [26]. If it was possible to observe this reality, one would see two groups of "wave-packets" propagating along rectilinear trajectories. In the volume of interference, these particles were presumed to be uniformly distributed across wavefronts. It was only the joint effect of wave-packets from different components that resulted in the appearance of bright and dark fringes. Consequently, when quanta of light were discovered, the expectation was that a two-slit experiment would confirm the details of this "physical reality". Yet, when Young interferometry was performed with attenuated light beams, the observation was that quanta "bunched" into bright fringes, and stayed out of dark fringes. This was a big surprise that quantum theoreticians were supposed to explain. How is it possible for light to be actually redistributed into fringes, and then to emerge into separated unperturbed output projections? As shown above, this was a great opportunity to reconsider the flaws of dominant interpretations about wave behavior. Fresnel propagation offered a simple solution to this mystery [33, 34]. Yet, this is not what happened. In retrospect, the Copenhagen interpretation was successful because scientists heard what they wanted to hear. They were susceptible to the solution offered by Bohr's complementarity, because they strongly believed that wave interference does not happen when beams overlap. The emergence of unperturbed projections seemed decisive. Though, had they been aware of the ontological problems of dominant classical interpretations, the history of quantum mechanics might have been radically different.

As currently explained in textbooks, the fundamental problem of quantum interference is that quanta propagate one at a time and that they appear to interfere with themselves [35, 36]. Yet, this is not something that is based on the facts of quantum mechanics. This problem is simply a side-effect of the so-called wave-particle complementarity, which is a postulate that was imposed onto existing knowledge. If we assume that a particle transforms into a wave and vice-versa, we create a magical mechanics that produces magical outcomes. Yet, such assumptions were not necessary. Quantum theory predicted

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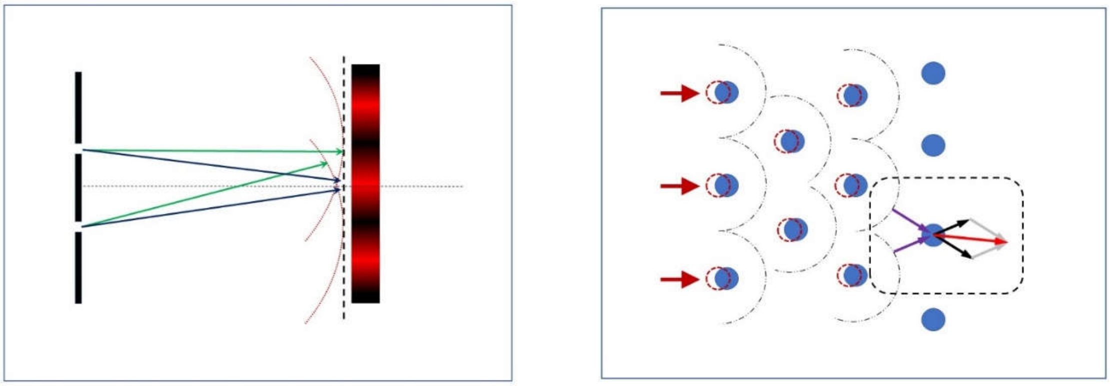
the probability of finding a quantum "somewhere", with a wavefunction. It did not require the existence of a single entity "everywhere". Indeed, Louis de Broglie proposed the pilot-wave theory of quantum behavior already in 1924, which later inspired Schrodinger's quantum wave theory [37]. The evidence supports the reality of both waves and particles, with the caveat that waves are the only ones governing the observable dynamics, but particles are the only ones that are observable. Thus, it is plausible to suggest that some kind of discrete entities surf an underlying wave pattern. This would entail that higher amplitudes produce a higher probability of finding a particle (such as, in bright fringes), while null amplitudes would yield the lowest probability of finding a particle (as seen in dark fringes). By implication, the problem of "which-way" knowledge might have some relevance for some problems, but it is not a fundamental topic of concern. The point remains that Bohr's complementarity was used to solve a non-existent problem. It was not a mystery that interference fringes are real, and their reality did not preclude the possibility of separated projections after interference. This could have been explained with what was already known in classical wave theory, if only the problem was investigated with more patience, to allow for non-mystical solutions to come up.



(**a**) (**b**)

Figure 1. Two models of wave interference. Classical waves display unmistakable signs of interference during overlap, yet also appear to go through each other unperturbed. It is impossible for both of these appearances to be correct, but which one is ontologically true? (**a**) Geometrical ray tracing supports the assumption that wave components go through each other unperturbed. Interference is described as a macroscopic illusion, due to the joint effect of overlapping "wave-packets": in-phase (constructive interference) or out-of-phase (destructive interference). (**b**) Fresnel propagation with Huygens wavelets describes interference as fundamentally real. For example, sound waves can be described as air molecules undergoing elastic interactions. When a single molecule is pushed from two directions, it cannot move in two directions at the same time. Only the vector sum of all the inputs can be real, just as seen in quantum theory. In this case it is an illusion that waves go through each other unperturbed. The macroscopic profiles are recreated by this process of interference at the output, but the microscopic source of energy is uncertain. There can be no "path knowledge", as one might expect from geometrical analysis. Accordingly, quantum wavefunctions are currently interpreted with mixed concepts, merging the two approaches incoherently.

The next chapter in this saga is that David Bohm rediscovered the pilot-wave solution in 1952 and developed a very influential theory on the basis of this approach [38, 39]. His model included particles with real trajectories that are guided by associated pilot-waves, according to the quantum potential of standard wavefunctions. However, Bohmian mechanics was still bound to the dominant pseudo-classical view that wave components should pass through each other unperturbed, allowing for "path knowledge" after interference. Therefore, the resulting mechanics was again puzzling, especially with regard to quantum trajectories that ended up in the "wrong" paths. This resulted in debates as to whether Bohmian trajectories can be real, or if they should be described as "surreal" instead [40-42]. In short, history is repeating itself. We rediscovered that wave propagation requires vector-sum effects, but this proposal is dismissed as "non-physical" or "surreal", because we do not know how it is possible. The overlooked detail is that vector-sum realism is the only assumption that can be real in a classical ontology. Granted, we do not know how pilot-waves can exist in real life. Yet, even if there are some sort of mysterious "probability" waves, the point remains that quantum behavior is compatible with the effect of unobservable spatially extended wavefronts that determine the statistics of observable discrete entities. A major point of confusion is that quantum experiments detect particles, and therefore it is tempting to assume that quantum theory predicts particle properties. In actuality, quantum theory is a wave theory. Particles are never inspected directly in quantum experiments. They are only counted, and their distributions provide information about the corresponding wave amplitudes. All the variables of quantum theory are wave variables. Accordingly, the only relevant ontological aspect is the mechanism of wave propagation: do wave components go through each other unperturbed? The simple answer is that wave interference must be real in classical physics. Assuming otherwise leads to magical conclusions. Yet, such is the appeal of particle models of wave propagation that scientists kept returning to them despite all the reasons to the contrary.

To sum up, quantum superposition is not "weird". It is artificially made to look strange, because of the perceived need to safeguard the principle of non-interference. Classical wave analysis is dominated by particle models. In this approach, waves are described as entities that magically propagate through matter, rather than physical attributes of matter. Accordingly, wave interference is not described as a process of energy redistribution, but rather as a macroscopic appearance. This results in a non-local ontology with incorrect microscopic predictions. When quantum mechanics falsified this approach, the correct solution would have been to acknowledge the reality of wave interference. Instead, the founders of quantum mechanics decided to incorporate the old ideas into a new ontology. By insisting that wave interference still didn't happen unless directly observed, quantum interpretations distorted the analysis of wave propagation into an "even weirder" picture. This misunderstanding influenced the interpretation of other quantum phenomena that express quantum superposition, including the EPR paradox and Bell's Theorem. In the following chapters, it will be shown that quantum behavior can be explained without paradoxes and without violations of Realism or Locality. All the known manifestations of quantum entanglement can be intuitively explained if the interpretation of linear wave superposition is corrected and adequately applied.

3. What is the EPR argument about?

The problem of quantum entanglement is better understood in its historical context. In the early years of quantum mechanics, it became apparent that some microscopic properties are inseparable from their context of measurement. Therefore, it was not possible to argue that observable properties correspond to unobserved objective properties. By implication, quantum observables could not be interpreted as indicative of the true physical reality outside of human measurement. Yet, as it is well known, some scientists took an additional leap by arguing that physical reality does not exist at all [43]. This development inspired other scientists to look for counterarguments, culminating with the notorious paper by Einstein, Podolsky and Rosen (EPR), published in 1935 [44]. The EPR argument was that some quantum properties must be described as real because they can be predicted with certainty without direct measurement. When two quanta are highly correlated, it is enough to measure one of them in order to obtain well-defined information about both of them. Furthermore, it did not sound reasonable to suggest that measuring quantum #1 causes a property of quantum #2 to become real, because this would require instantaneous action at a distance. Though, if two quantum properties are independently real, and cannot be produced by the act of measurement, does it mean that they are jointly pre-determined? The answer to this question was given by John Bell in 1964 [3]. If quantum properties are assumed to be jointly well-defined at the source, then they must obey

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Bell's inequality. If so, the only way for them to produce the known quantum correlations is by – again – allowing for instantaneous action at a distance.

As a corollary of the above, an inescapable conundrum appears to emerge: quantum properties cannot be caused by the act of observation (or else they are nonlocal) and cannot be well-defined before measurement (or else they are again nonlocal). It should be noted that the word "nonlocal" means "impossible" in this context of analysis. Action-at-a-distance may appear questionable because faster-than-light effects contradict the theory of relativity. Though, from a philosophical point of view, the fundamental problem is that nonlocality implies the reality of physical effects without direct physical causes. This sort of behavior contradicts the basic principles of modern science. Belief in nonlocality is akin to belief in magic and is therefore unproductive in the pursuit of scientific knowledge. Furthermore, in the context of Bell's Theorem, the concept of nonlocality does not have a matching mathematical component. Jointly distributed Kolmogorov variables are naturally found in classical systems, as seen for example in the statistics of playing cards, light bulbs, or various articles of clothing. By default, these properties cannot have coefficients of correlation that violate Bell's inequality. If something were to change and these properties were able to produce such violations, then they would no longer be jointly distributed Kolmogorov variables. Ontologically speaking, one could speculate about physical anomalies that change the nature of physical properties, from Kolmogorov to non-Kolmogorov statistics. Yet, there was never any evidence of classical properties suddenly becoming different in this manner. Therefore, there is no reason for such speculations. In short, suggesting that non-contextual properties require nonlocality for Bell violations is just a figure of speech, meant to suggest that such manifestations are impossible. In contrast, it is possible for quantum variables to violate such inequalities because they are contextual. (This will be explained in greater detail in the next section).

With this in mind, the apparent paradox of quantum behavior is not that it requires nonlocal influences, but rather that it seems inherently self-contradictory. If a property cannot exist before the measurement and also cannot be produced by the act of measurement, then how can it be real at all? On closer inspection, this is not a valid problem because we are dealing with a false dichotomy. The two alternatives for interpreting quantum observables are not "pre-existing" *or* "recorded", but rather "pre-existing" *or* "contextually produced". Quantum theory does not predict quantum properties as a consequence of some intellectual act of knowledge acquisition. Quite the opposite: quantum observables are expected to reflect the local profile of the wavefunction that governs their dynamics. In turn, the wavefunction is expected to follow a process of physical evolution that can be manipulated in preparation for intended observations. For example, the *gedankenexperiment* described in the EPR paper was eventually realized with modern equipment, by studying pairs of non-commuting variables with entangled photons [45]. This produced a visually instructive demonstration of quantum behavior. To review, optical vectors with parallel directions converge onto sharp points in the focal plane of a convex lens. At the same time, optical vectors with common source points converge in the image plane of such a lens (Figure 1 below). This means that an observation of "momentum information" requires the detection of photons in the focal plane. The observation of "position information" requires the detection of photons in a plane that "images" the plane of emission. Accordingly, the EPR experiment works by measuring two entangled photons in the focal plane (or the image plane) of their corresponding lenses, producing high correlations. In contrast, if one photon is measured in the focal plane and the other in the image plane, then coincidences become random. As suggested by EPR, it is possible to predict the value of a quantum variable with certainty. Yet, this is only true in the eventuality that the targeted quantum is measured at the correct location. Non-commuting properties materialize in different planes of detection, and only in such planes. Ergo, it is not necessary to speculate about quanta that "know" quantum theory. Instead, it is the observers who decide whether to keep a detector in the focal plane or to move it to the image plane on the same optical table. Though, it is not enough to consider the geometrical aspect of this problem, because it leads to incorrect conclusions.

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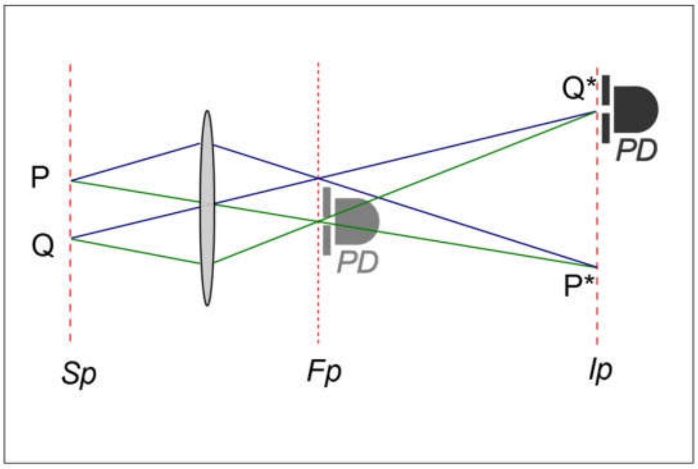

Figure 2. The geometry of wavefunction momentum and position. Quantum momentum and position cannot be simultaneously sharp in quantum mechanics. This is similar to the manifestation of classical wave momentum and position as part of propagating wavefronts. Momentum vectors are sharply resolved in the focal plane of a lens *Fp*. Position vectors are sharply resolved in the image plane *Ip*. This illustration appears to resolve the EPR paradox. It is possible for quantum properties to be objectively sharp, without being observable at the same time. Yet, the geometry of this process is ambiguous with regard to the underlying ontology. Do momentum and position values become *observable* in these two planes, or do they become *real* at such locations? In other words, are they permanent qualities that obey Bell's inequality, or transient features that do not?

Let us imagine a billiard ball rolling on a smooth surface. At any point in its observable history, the ball has a well-defined value of "momentum" and a well-defined value of "position". It would be unnatural to suggest otherwise. This picture, whether acknowledged or not, is the reason for interpreting non-commuting quantum variables as "weird", even when such variables are explicitly assigned to wave-like phenomena. How is it possible for "momentum" and "position" to exist only when measured? For a deeper understanding, consider the geometry of an optical projection passing through a lens. As seen in Figures 2 and 3, individual source points are associated with spherical wavefronts. Therefore, they are represented by a set of wave vectors pointing in every possible forward direction. During passage through a lens, these "rays" are refracted, but then continue indefinitely, tracing rectilinear paths. The curious thing is that some rays have parallel direction at the input, and they end up converging onto single points in the focal plane of the lens. Hence, every coordinate in the focal plane of the lens corresponds to a sharp value of "momentum". After passing through the lens, the input wave is decomposed into well-defined momentum components. Though, if these rays are allowed to pass unobserved, they go on in their different directions. The second curiosity is that the same rays end up converging according to a different rule at a later stage. All the rays that start at a common source-point end up converging onto a common point in the image plane, where it is possible to extract "position" information. According to this description, classical waves can be described as collections of microscopic "billiard balls". These particles follow rectilinear trajectories and have simultaneous sharp values for "momentum" and "position" (Figure 3a). The apparent problem is that such properties cannot be observed, except when the wave is adequately decomposed. According to this approach, the focal plane of a lens is merely a special location where particle momentum is revealed (because all the entities at the same coordinate have the same value). In the same vein, the image plane is merely a special location where the particle position is revealed. This is the intuitive basis for rejecting the claims of quantum theory with regard to non-commutativity. Yet, as shown in the previous section, this interpretation is fundamentally non-classical. If applied to classical oscillations, it entails that single objects can move in several directions at the same time. It is also non-local, because wave energy has to vanish in areas

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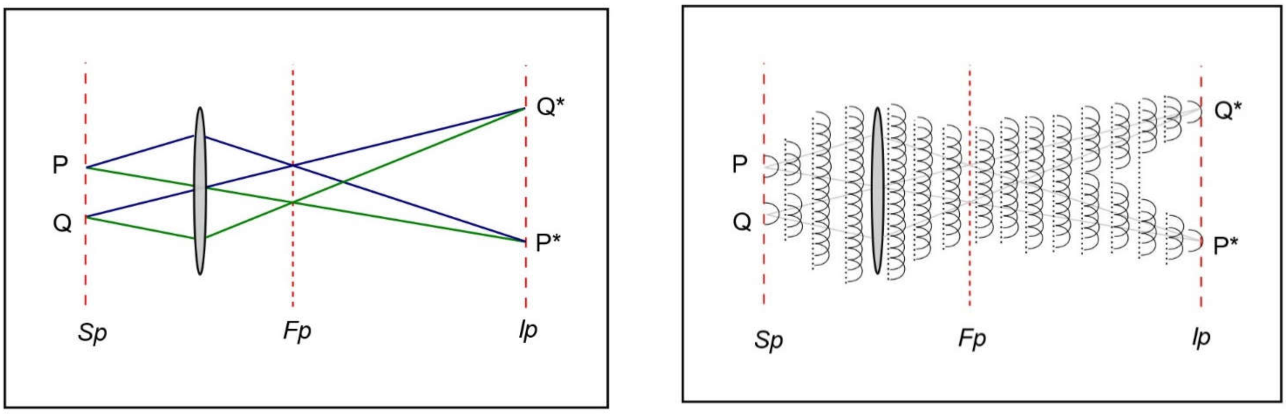
with destructive interference and magically appear in areas with constructive interference, at least at the macroscopic level. As a corollary, quantum superposition and its implications about non-commuting properties are not intrinsically weird. They only seem strange when wave-like phenomena are interpreted with particle models.



(**a**) (**b**)

Figure 3. Two models of non-commutativity. In classical wave mechanics, geometrical rays are assigned to presumed physical entities ("wave-packets?), while Huygens wavelets are described as non-physical. This tradition is conflict with quantum mechanics. (**a**) Wave vectors can be imagined as trajectories of particles with well-defined momentum and position at all times. The values of these variables are typically uncertain because they cannot be resolved, except in adequate planes of observation (momentum values in the focal plane *Fp*, and position values in the image plane *Ip*). (**b**) The same behavior can be explained with Fresnel propagation. In this case, wavefronts have *imaginary* spectral components, but only the net state of interference is *real* at every stage of propagation. Accordingly, the focal plane is a region where "momentum" states emerge in sharp form, as transient properties. Likewise, sharp images are *created* in the image plane, rather than merely *revealed*. Of these two models, only the second one leads to correct predictions for every aspect of wave behavior. It also entails local explanations for quantum behavior.

A different picture emerges if wave-like phenomena are interpreted with wave-based models. Rectilinear ray tracing may capture the macroscopic structure of a wavefront, due to the underlying symmetries, but it fails as a model of underlying reality. Instead, if wave propagation is analyzed in terms of Huygens wavelets with Fresnel interference, then wave diffraction can be predicted with precision [33, 34], and overall interpretations become both "classical" and "intuitive". In particular, every step of wave propagation must be interpreted as a process of wavelet interference (Figure 3b). Therefore, every new wavefront is a new physical context, and every observable property is a new property. It is also the vector sum of all wavelet forces onto a single point that determines the physical reality at that point. Accordingly, sharp wave "momentum" is not a property of underlying microscopic billiard balls. It is a local transient property of a propagating wavefront. In the described example with coherent waves, it can only be created in the focal plane of a lens. Likewise, the image from a slide in the source plane cannot be interpreted as "always there". It must be interpreted as physically lost in transit, and subsequently recreated by the projection in the image plane. This may sound surprising at first, but one can verify this possibility with Huygens-Fresnel analysis. There is nothing fundamentally strange about this assumption. Moreover, Fresnel integration leads to correct predictions about wave diffraction, and it obeys the ontological principles of classical mechanics (unlike the particle models, emerging from geometric analysis).

It bears repeating that waves are not propagating entities. In classical mechanics, they correspond to states of oscillation that belong to elastic media. It is a big mystery that such waves should exist at the quantum level, but the decisive argument in their favor is that quantum theory works with unquestionable accuracy. The relevant conclusion here is that

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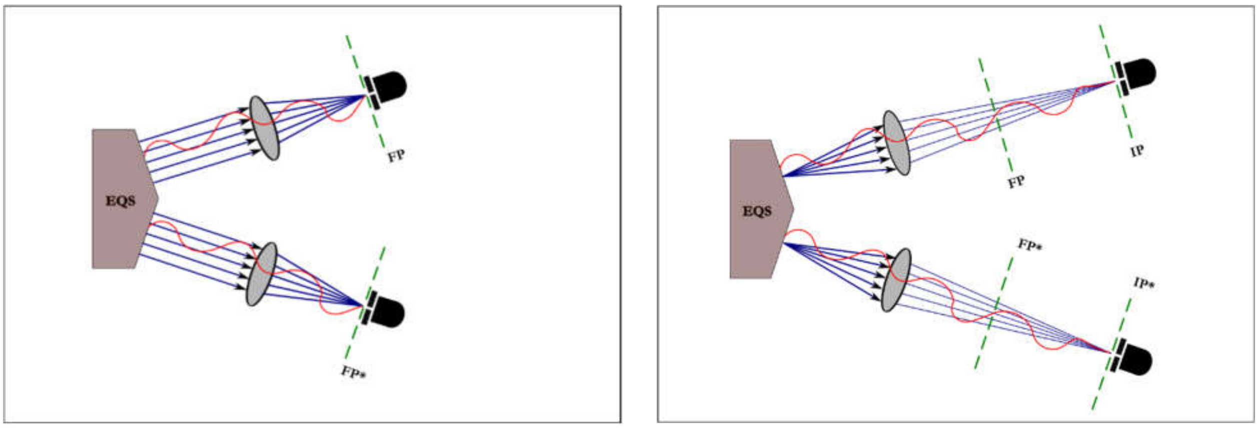
propagating quanta cannot be described as running "wave-packets", because this leads to models with permanent particle properties and their associated paradoxes. The evidence of wave-particle duality is best captured by the pilot-wave models, where hypothetical particles are assumed to surf hypothetical waves. As it is known from human experience, surfing is impossible when wave amplitudes tend to zero, but it can be successful when amplitudes are reasonably high. Accordingly, it is plausible to assume that quantum particles surf their pilot waves, and that the probability of finding them at any location is directly proportional to the relative amplitude of underlying waves. Indeed, one can speculate that such quanta have intrinsic "particle momentum" and "particle position", but such properties are outside the scope of quantum theory. The relevant aspect to keep in mind is that quantum experiments do not inspect particles directly for momentum and position. Instead, particles are counted at every point of interest. Their normalized distribution in the cross-section of a projection is what leads to information about corresponding wave amplitudes. Thus, in a truly classical ontology, "quantum momentum" and "quantum position" are wave properties that only exist when created in the corresponding planes of observation. Detectable quanta only serve as countable markers for such properties, as the context may be (Figure 4, below). Ergo, there is nothing strange about quantum non-commutativity. If the goal is to achieve a coherent description of the underlying physical reality, there is no reason to try to falsify it.



(**a**) (**b**)

Figure 4. EPR measurements without paradox. It is incorrect to describe quantum projections with discrete "wave-packets" that magically turn into extended "wavefronts". Instead, correct predictions follow if the wave-functions are described as wavefronts and particles as physical entities that surf them. (**a**) In the special case when entangled quanta are identical, two entities surf along identical Bohmian trajectories. They cross the focal point at identical coordinates and are counted as increments of "momentum" distributions. (**b**) Alternatively, the same quanta can be detected in the image plane, where they are counted as correlated increments of "position" distributions. It is enough to measure one quantum in order to obtain precise information about both of them. Yet, this knowledge is only applicable to the regions where such properties are physically possible. Note: red lines correspond to hypothetical quantum trajectories, while blue rays express the geometry of the wavefunction components associated with each coordinate of detection.

To sum up, it is possible to describe EPR-type quantum behavior with intuitive pilot-wave models, while including the correction described above. In particular, two discrete entities could have similar Bohmian trajectories when they propagate through correlated environments, as if they surf real identical waves. Accordingly, if two entangled quanta are both measured in the "momentum plane", their coordinates of detection should be highly correlated. If they are measured in the "position plane", their coordinates should be correlated again (see Figure 4 above). In contrast, if one is measured in the focal plane, while the other is allowed to propagate further into the image plane, they cannot be correlated. Both of these aspects (correlation in identical measurements, and non-correlation in different measurements) emerge as natural effects of the changing "vector sum" profile of their governing wave-function. In short, there is no need to speculate about "spooky action-at-a-distance", because contextual quantum properties do not materialize based on what we know. Rather, they emerge as transient qualities that exist objectively in predictable contexts, whether measured or not. Thus, quanta do not need to know what is going to happen to them. Instead, it is the observers who need to know where to look, in order to track quantum properties at the locations where such properties can exist. This conclusion seems natural in retrospect, but it is analytically inaccessible as long as wave interference is tackled with particle-based ontologies. Supporters and opponents of Einstein Realism were apparently drawn to similar ontological assumptions about particles, and this is why their debates lead to paradoxes. In the end, the solution to this problem is reducible to the mechanism behind quantum superposition, which was described above as the central problem of modern physics.

4. What is the essence of Bell violations?

Bell violations are often described as the most "bizarre" aspect of quantum mechanics. Therefore, it may be tempting to believe that such violations always defy understanding. In actuality, Bell's Theorem is derived for classical objects with jointly distributed properties. Their inability to violate the stated inequalities is natural and can be given a straightforward intuitive explanation. It is because of this obvious inability that "weird" ontologies are required, when the goal is to stretch them into "quantum" behavior. Yet, several concepts need to be reviewed and clarified here, in order to justify this claim. In particular, it is important to keep in mind the difference between physical and statistical contextuality. Sometimes, physical properties only exist when their preconditions for manifestation are satisfied. Yet, different variables from different physical contexts may still have stable features. In probability theory, measurement-independent properties that persist in time are expected to be jointly distributed. This means that repeated measurements sample the same distributions, and therefore their manifestation is statistically *non-contextual*. To clarify the reasons for this, recall that probability theory defines any combination of measurements as a context [46]. Thus, if different measurement combinations sample the same random variables, then the relevant variables are described as non-contextual. Changing the order of observation or changing the combination of joint measurements does not result in the detection of a different distribution (and therefore a different random variable) for the same physical property. In contrast, if changing the manner of joint observation requires new random variables for the same physical property of a given physical system, then such variables are described as *contextual*. As a result, statistically non-contextual variables are jointly distributed and fit together in a Kolmogorov probability space. Statistically contextual variables are usually not jointly distributed and do not fit in a Kolmogorov space. For the purpose of this discussion, the important distinction is that contextual variables can violate Bell inequalities, but non-contextual variables cannot.

The main features of contextual vs non-contextual variables can be captured intuitively with a simple example. If we imagine a warehouse full of shirts, three properties can be chosen for statistical analysis. For instance, we can define these qualities in binary ways by asking:

A. Are the shirts white (Y/N)?
B. Are the shirts made of cotton (Y/N)?
C. Are the shirts long-sleeved (Y/N)?

Shirt properties persist in time. Therefore, if we always sample the same warehouse, the resulting variables must be jointly distributed. This conclusion has a remarkable implication: pairwise coefficients of correlation for different combinations constrain each other's values. Suppose, for example, that two joint measurements produced the following results:

1. "All the white shirts are made from cotton." (**A**, **B**)
2. "All the cotton shirts are short-sleeved." (**B**, **C**)

It should become obvious that these two results automatically define the remaining third joint measurement. As long as we are dealing with the same random variables, the only possible observation is that:

3. "All the white shirts are short-sleeved". (**A**, **C**)

It would be a contradiction of the previous two results, even if just one shirt out of one million was white and long-sleeved. Because of this relationship, it is reasonable to expect that the sum of various coefficients of correlation should be limited for jointly distributed variables. This is the intuition that explains the validity of Bell's Theorem. In contrast, if every *joint* measurement is performed in a different warehouse, then we are dealing with different contextual variables for each joint measurement. In this case, it would be perfectly logical to have combinations of outcomes such that:

1. "All the white shirts are made from cotton."
2. "All the cotton shirts are short-sleeved."
3. "All the white shirts are long-sleeved."

Consequently, statistically contextual properties have no constraints on the possible combinations of their outcomes, and this difference is both mathematically predictable and experimentally verifiable. These basic details needed to be reviewed here, in order to make the point that Bell violations are not automatically "non-classical" or "nonlocal". However, it is very difficult to explain the emergence of statistical contextuality for joint quantum measurements with entangled systems, given the goal to describe relationships that span across physical contexts. For example, suppose that Alice has a choice between two measurements, while Bob is only measuring one property. In order to violate a Bell inequality, Bob's measurements have to be statistically contextual with any choice made by Alice. In other words, different measurements made by Alice result in different random variables for Bob, even though he is sampling the same property in the same physical context. At first sight, such a result may seem impossible without non-locality, but this is only true for particle models of wave-like behavior. As a reminder, single quanta are able to express many states of spin, one at a time, but their governing wavefunction contains all of those variables in superposition. Assuming component realism in this linear process, spin values for any variable must be visualized as "always there". Therefore, they are presumed to be jointly distributed and cannot violate a Bell inequality. In contrast, if vector-sum realism is assumed, then every component variable emerges as a local transient feature of a larger process of wave evolution. In this case, making a joint observation with entangled quanta is similar to measuring the same quantum non-invasively at two different stages of wave evolution. In propagating waves, any two sharp observables can be connected sequentially by local paths of wave-evolution. More importantly, different observables are connected by incompatible ensembles of paths. Accordingly, it is incorrect to visualize Alice and Bob as if they sample jointly distributed properties from a lottery bag. Instead, they sample consecutive wave profiles connected by transformations with known patterns of joint manifestation. (More on this in the next section). This is why quantum superposition is able to produce statistically contextual observations, leading to Bell violations without action-at-a-distance. Accordingly, Bell experiments are an essential tool for settling interpretive debates about the nature of wave superposition, rather than about speculative metaphysical concepts.

As it is well-known, quantum Bell violations were originally predicted for variables associated with electron spin, but were subsequently extended to photon polarization, given the formal similarity between the two types of observables. Let us dig deeper: what makes these properties statistically contextual? Why is it that electron spin and photon polarization can violate Bell-type inequalities? The answer is that we are dealing with sets of mutually dependent variables that are connected to each other by a non-linear rule, known as Malus' Law. (To clarify, each variable can have values that obey linear patterns, but the relationship between different variables is non-linear, as will be explained below). For the purpose of this discussion, the important aspect is that we are not dealing with a "non-classical" process. Malus' Law applies to high intensity optical projections, in the same manner as it applies to single quanta. As it is known, polarized waves can pass

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through filtering devices unobstructed, if their plane of oscillation is parallel to the structural axis of corresponding filtering channels. Furthermore, if there is a non-zero angle between the axis of a filter and the axis of wave oscillation, then a limited proportion of the wave energy can pass through, and the output axis of oscillation will be parallel to the filter axis. Malus' Law states that this proportion (in ideal conditions) is equal to the cosine squared of the angle between the input and output axes of oscillation. In essence, this is a process in which one virtual component of the input wave is transmitted, and the complementary virtual component is blocked (or reflected, if a two-channel polarizer is used). This is formally similar to any classical process of force redistribution, in terms of vector analysis. For example, if the vertical plane of oscillation is defined as 0°, then this state can be expressed as the sum of any two components with complementary angles: +10° and -80°, or +22.5° and -67.5°, or +45° and -45°, where the magnitude of each transmitted component is proportional to the cosine squared of the angle (and the magnitude of the reflected component is proportional to the sine squared of the corresponding angle). It is important to keep in mind that classical objects cannot move in two directions at the same time. Accordingly, it is always the vector sum of all the forces acting on an object that corresponds to the vector of displacement. Therefore, only the net state of a physical system can be interpreted as ontologically "real" in a correct classical model. In this case, the output state of polarization must be assumed to be physically real, in a way that it is was not prior to the act of filtration. However, there is a long-standing tradition in the field of classical wave mechanics to do the opposite. Namely, when a wave is decomposed into two components, it is usually suggested that the input wave is not transformed. Rather, the measured components are treated as if they were "always there" from the source and were only revealed by the act of observation. At first sight, there is no way to distinguish the two interpretive approaches, because they are mathematically equivalent. If $a+b=c$, how can one tell if the left side of this equality is "real", or the right side? As it turns out, there is an important physical difference between them. What we know today, but wasn't known before the development of quantum theory, is that the left side of $a+b=c$ ("component realism") cannot violate Bell's inequality, but the right side ("vector-sum realism") can do it naturally. The reason for this is straightforward: if a set of properties is presumed to propagate undisturbed from the source to the detector, then we are dealing with non-contextual variables. In contrast, if the net state is always real then we are dealing with transient properties that can display statistical contextuality [46].

One remarkable aspect of Malus's Law is that it leads to "impossible" predictions if component realism is assumed to be true. The reason for this is the non-linear progression of expectation values for different angles of filtration, given a fixed input state. In other words, if the angle of polarization analysis is doubled, then the proportion of blocked energy is not doubled. Instead, it keeps following the pattern of a squared cosine function. For example, if the output angle of polarization is at 22.5° relative to the input state, then 85% of the input projection is transmitted. In contrast, if the output angle is doubled to 45°, then the ratio of transmitted radiation is 50%. The interpretive challenges of this pattern can be revealed with a simple experiment, often used in introductory courses on Optics [23, 24]. Hence, a coherent projection from a laser beam (or even from a pencil of sunlight) can be passed through a single polarizing filter, with the observable effect that 50% of the input radiation is blocked. If a second polaroid is added to the path, with an orthogonal orientation to the first filter, then 100% of light is blocked (in ideal conditions). The curious thing is that a third polaroid can be added in-between the two filters (which, intuitively, should absorb even more light). Yet, if this intervening filter is diagonal to the other two, then suddenly 1/8th of the input radiation can pass through all the three filters (as opposed to 0% with just two filters). If we apply Malus' Law at every step of this process, then there is nothing mysterious. The first filter absorbs 50% of incident radiation because the input beam is depolarized. The second filter absorbs 50% of the transmitted radiation because it is diagonal to its own input. This remaining 1/4th of the input projection is linearly polarized at 45° to the final filter, and it is also reduced in half to 1/8th. However, if we assume that all the observable components are physically real in a

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permanent manner, all the way from the source, then we run into serious interpretive complications. For instance, we could say that the diagonal component, revealed by the second filter, always existed independently in the output of the first filter. However, if that is true, why did the horizontal filter block the full projection, when the diagonal filter was absent? A possible answer to this question is that the diagonal component was always real, but it was co-propagating with an anti-diagonal component. Accordingly, both of these components could have interacted with the horizontal filter, passing through with a reduced amplitude. Yet now we need to assume that the "always real" diagonal components were in fact composed of "real" vertical and horizontal components. These new horizontal components would have to pass through the horizontal filter. However, they would have to be out-of-phase and interfere destructively. Accordingly, this would imply that the dark projection is actually full of energy (even though such radiation is unobservable) [47]. The problem is that all this "transmitted" energy, supposedly present in the dark channel, can also be found in the reflected bright channel (if a polarizing beam-splitter is used instead of a polaroid filter), resulting in an implied contradiction with the principle of energy conservation. Furthermore, the incoming projection can be filtered at arbitrarily different angles, suggesting that it should contain an infinity of component states of polarization, all of which should be presumed to be real from the source. Taken together, this interpretation of classical wave behavior ends up with a fundamentally non-classical model, in which real objects move in many different directions at the same time (in a manner that is not observable) and violate the principle of energy conservation at every step (in a manner that is equally unobservable).

It is important to note that classical wave theory is interpretively agnostic with regards to the nature of wave superposition. The equations that describe vector summation (such as $\boldsymbol{a}+\boldsymbol{b}=\boldsymbol{c}$) cannot prescribe which side of an abstract equation is to be treated as real. This whole complication emerged as an accident, as far as we can tell today, because physicists may have become accustomed to geometrical methods, and never had to face the complications of their microscopic assumptions. In contrast, quantum theory is not agnostic in this way. First of all, quantum theory entails that wave energy is quantized. Therefore, it forbids any speculation about infinitely divisible energy, with infinite numbers of real components that may or may not exist at the same time. Secondly, quantum theory is explicit about treating the vector-sum effects of relevant wave-functions as ontologically real. While there is room for debate whether different wavefunction components exist and act all at once as distinct individuals, or whether only one vector equal to their sum is real, the point remains that individual quanta always reflect the local "vector-sum" of their context of measurement. Indeed, a distinguishing feature of quantum theory is that every single quantum is presumed to be "in all the component states at the same time". It is a big mistake to assume that some quanta express one component (such as one path in the double-slit experiment), while other quanta express another. Accordingly, quantum theory is incompatible with the so-called "classical" interpretation of wave polarization with persistently real components. When a quantum projection is depolarized, every single quantum is described as depolarized. After passing through a vertical filter, the wavefunction is updated and every single quantum is described as vertically polarized. All the other components are no longer assumed to be real. Next, after passing through a diagonal filter, the wavefunction is updated again and every transmitted quantum is described as diagonal. The same picture applies to the final filter, without any interpretive paradox. In short, quantum theory rejects the possibility of single quanta expressing non-contextual states of polarization. It is not possible to observe quantum properties in terms of qualities that are preserved unperturbed from the source. This means that quanta express physically contextual values for observable states of polarization, such that any two consecutive values are statistically contextual (if observed). Therefore, it is possible for them to violate Bell-type inequalities, if idealized consecutive measurements are replaced with parallel measurements in entangled systems. As seen in the EPR experiment, described in the previous section, non-identical quantum measurements with entangled quanta correspond to observations in consecutive planes of wavefront evolution (predictable with

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appropriate wavefunctions). This explanation is in reasonable agreement with the experimental data from numerous loophole-free Bell experiments [13-18]. In short, quantum Bell violations support a more intuitive picture of physical reality than previously expected, solving unsuspected problems in the classical understanding of linear wave superposition.

5. A toy model for Bell violations in quantum mechanics

In light of the preceding explanations, quantum physics is not fundamentally different from classical physics. It does not require "metaphysical" mechanisms. The same problems in the interpretation of wave behavior are present at both levels of analysis (macroscopic and microscopic). The difference is that classical mechanics does not have the tools to test microscopic implications, except with philosophical arguments, checking whether different assumptions lead to contradictions or not. Still, it might sound surprising that remote joint measurements of wave properties can lead to statistical contextuality. In what follows, this problem is going to be broken down into several explanatory steps, in order to develop an intuitive toy model for Bell violations in quantum mechanics. Unfortunately, meaningful explanations of quantum behavior are hindered by existing interpretive paradigms. Therefore, these obstacles need to be eliminated one by one. As shown above, the first obstacle is the established tradition to view superposed wave components as permanently real. In the case of optical polarization, the usual assumption is that complex projections contain numerous simple components that are "always there". At a superficial level of analysis, this assumption seems to make sense, but it runs into conceptual problems as soon as we put it to the test. Again, if a beam is passed through a sequence of two orthogonal polarizers, all the radiation is blocked. If a diagonal polarizer is inserted in-between, a significant proportion of the input radiation is transmitted. Even with classical high-intensity projections, the explanation of underlying mechanics becomes "weird" and "non-classical" if virtual components are presumed to be real. In contrast, we can apply the principle of quantum superposition and treat the net profile of the projection as real, at every stage of evolution. For example, when the beam passes through a vertical polarizer, we "update the wavefunction" and treat this new state of knowledge as a literal description of quantum reality. When this projection passes through a subsequent diagonal polarizer, the output wavefunction is updated again, and so on. Therefore, it is the quantum interpretation of wave-like behavior that makes the underlying ontology "classical", at any level of analysis. By implication, the reason for the special nature of quantum behavior is not that "particles" carry some sort of intrinsic spin qualities, but rather that the net amplitudes of their governing wavefunctions determine the transient properties that can be observed. After all, we are dealing with wave properties that are determined by counting particles.

An interesting feature of wave polarization is that consecutive measurements obey Malus' Law. This means that consecutive real states of polarization are statistically contextual by default. In other words, consecutive transformations from one state of polarization into another cannot be described with jointly distributed random variables. The first preparation always influences the second measurement in a contextual manner. In a series of multiple joint measurements, it is always a different measurement that serves as preparation for the next. Therefore, local measurements performed over one and the same beam in sequence are naturally expected to produce violations of Bell inequalities. Yet, nothing about this process can be described as "nonlocal". For example, a typical Bell experiment is conducted by pairing several observables in a closed chain. If four properties are chosen for observation, they must be combined as follows: **A** with **B, B** with **C**, **C** with **D**, and **D** back with **A**. In this case, the relevant Bell inequality is the Clauser-Horne-Shimony-Holt (CHSH) inequality [48]:

$$|E(\mathbf{A}, \mathbf{B}) + E(\mathbf{B}, \mathbf{C}) + E(\mathbf{C}, \mathbf{D}) - E(\mathbf{A}, \mathbf{D})| \leq 2.$$

Let us consider what happens if we measure the same variables with consecutive observations in classical beams. As seen in typical Bell experiments with entangled quanta, the relevant angles of measurement are 0° for **A**, 22.5°for **B**, 45° for **C**, and 67.5° for **D**. For a "joint" measurement of **A** and **B**, a laser beam can first be passed through a polarizing beam splitter (PBS) with its fast axis at 0°. Then each channel (transmitted and reflected) is passed through its own PBS at 22.5°. Given that such consecutive measurements obey Malus' Law, the expected coefficient of correlation between the two measurements can be rounded to 0.7. If the same principle is applied to all the other measurement combinations, then the CHSH equality becomes:

$$|E(\mathbf{A}, \mathbf{B}) + E(\mathbf{B}, \mathbf{C}) + E(\mathbf{C}, \mathbf{D}) - E(\mathbf{A}, \mathbf{D})| = |0.7 + 0.7 + 0.7 - (-0.7)| = 2.8.$$

This result is equivalent to the maximal possible quantum violation in a Bell experiment (2.8>2). Yet, there is nothing "nonclassical" or "nonlocal" about it. At least as a matter of principle, it is not true that any Bell violation is a result of quantum nonlocality.

Such conclusions notwithstanding, Bell experiments are conducted with two different beams, measured at different locations. In this case, observers do not make consecutive measurements over the same beam. Rather, every measurement is the first in its own beam. If we are to consider Alice's measurement as a preparation for Bob's measurement, doesn't that automatically require non-local influences? In order to answer this question, it is necessary to remove the second conceptual obstacle for the understanding of quantum behavior, this time created by Copenhagen-style interpretations. According to this tradition, wave-particle duality is simply a magical relationship. Unmeasured quanta spread out in the form of waves or clouds, and "collapse" instantaneously to discrete points at the moment of detection. If such a picture is taken for granted, then non-locality is inescapable in the analysis of entangled systems. Every time Alice makes a measurement, she is presumed to "collapse" a wave. The only way for this knowledge to be relevant about Bob's projection is if somehow Bob's wave also turns into a particle, for no physical reason. Yet, this interpretation is a flagrant distortion of quantum theory. It introduces magical elements, including nonlocality, by hand. The equations of quantum mechanics do not predict that a quantum is present *everywhere*. They only stipulate that it is observable *somewhere*. Yet, the probability of it being observed at any coordinate is determined by the local amplitude of the corresponding wavefunction. As shown above, this process is captured more intuitively by models with pilot-waves that have spatial extension and experience smooth evolution over time. Such a process can be accurately predicted by the calculus of Huygens wavelets experiencing Fresnel interference. The crucial feature that sets this model apart is that a particle is only able to express a microscopic "surfing" pathway in a wide field. It can be anywhere in the cross-section of a projection, but it can only express the net amplitude of the guiding wave at its own coordinates. If large numbers of particles are detected over time, all the possible trajectories are sampled. Still, one particle is only governed by a narrow slice of the wavefront, with important consequences for the analysis of entanglement. When two particles are correlated, they can be described as entities that propagate through correlated wave-like environments along correlated trajectories. For example, consider two entangled quanta propagating through identical Young interferometers. If Alice decides to make a detection in the interference volume, she can determine the fringe in which her quantum is present. Automatically, she can determine the fringe in which Bob's quantum is present in its own channel. Therefore, Bob does not need to make a detection. He can choose to make an observation later, for a non-commuting property. The near-future behavior of Bob's quantum will only be determined by the properties of the pilot-wave in its immediate vicinity (i.e., in its own fringe). Therefore, Alice and Bob can update their knowledge about this quantum and narrow down their analysis to the relevant slice from the input wavefunction. This works in the same way that would be observed if Alice were to make consecutive non-perturbative measurements over her quantum alone. Though, such local evolution can only be temporary. According to the Huygens-Fresnel model, wavelet effects from other regions of the wavefront will eventually become relevant, as they all converge and overlap at later stages of evolution. Yet, this is also a known feature of quantum behavior, sometimes described as "entanglement sudden death" [49] (or other similar names associated with quantum decoherence [50]). In short, the combination of quantum superposition and correlated

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dynamics is sufficient to explain quantum behavior in general, and entanglement in particular. Therefore, it is also possible to interpret Bell violations with local means, especially if no prior commitment is made to an ontology with instantaneous collapse.

The hard part of interpreting Bell violations consists in the requirement for statistical contextuality, over and above the existence of physical contextuality. It almost seems unquestionable that joint measurements without communication require joint distributions. For example, if Alice and Bob measure the same optical projection, one after the other, Alice will get a 50-50 distribution for a polarization measurement shifted by 45 °, and an 85-15 split for a relative angle of 22.5°. It is obvious that Alice samples two different random variables with one and the same measurement setting, depending on Bob's preceding choice of transformation. How is that possible in the case of correlated measurements in different beams, if Alice always makes the first measurement in her beam and the two beams are causally independent from each other? It seems reasonable to expect that Alice will always sample the same random variable, and the same considerations apply to Bob. Therefore, Bell violations seem impossible, and yet quantum theory entails the opposite. The solution is to consider the full problem, rather than a single measurement in isolation. A Bell test requires several joint measurements in a chain (usually four). It is not necessary for every measurement to be contextual in every instance, in order to get a violation. Rather, it is the opposite: Bell's inequality cannot be obeyed with necessity, unless *every* variable in the cycle of measurements is non-contextual. In the case of non-commuting wave properties, (such as polarization measurements that obey Malus' Law) this requirement is practically impossible to satisfy. The reasons for this are found by considering both the "single path" nature of individual quantum measurements and the requirement to sample multiple paths in the same experiment.

Quantum systems with undefined spin states are described by quantum theory as if they are in all the possible spectral components at the same time. Yet, well-defined measurements require the reduction of the wavefunction to a single spin vector. For example, in a recent Bell experiment, Rubidium atoms were trapped for analysis, while preserving their total spin state [18]. Then, experimenters fixed the outer electron orbitals to one of two possible planes with polarized lasers, in order to conduct individual spin measurements. How does an electron "collapse" from all the spin states at the same time to a single state? We do not need to speculate about all the details, since the goal here is merely to provide a plausible general mechanism. Accordingly, it is sufficient to allow that the *wavefunction* (extended in space) contains all the spin vectors at the same time, while a single *electron* follows just one Bohmian trajectory in such a field. For the purpose of this discussion, we can describe the electron as if it is in a constantly precessing orbital, conventionally expressed by an arrow on a clockface. We can further stipulate that every number on the clock corresponds to a spin-like dichotomous variable. A measurement can only be made when the arrow points at the corresponding coordinate. The relationship between any two consecutive measurements can be predicted with a Malus-like law, by considering the known orientation of the arrow. In particular, imagine that Alice and Bob each have such a "clockface", knowing that the two arrows always rotate in parallel in the same angular direction, because they are "entangled". To restate, the process of wavefunction evolution contains all the possible transformations in superposition. This implies that some individual paths will unfold as if the arrows follow clockwise patterns of rotation, while others will be counterclockwise. In a perfectly balanced system, the two alternatives are distributed 50-50.

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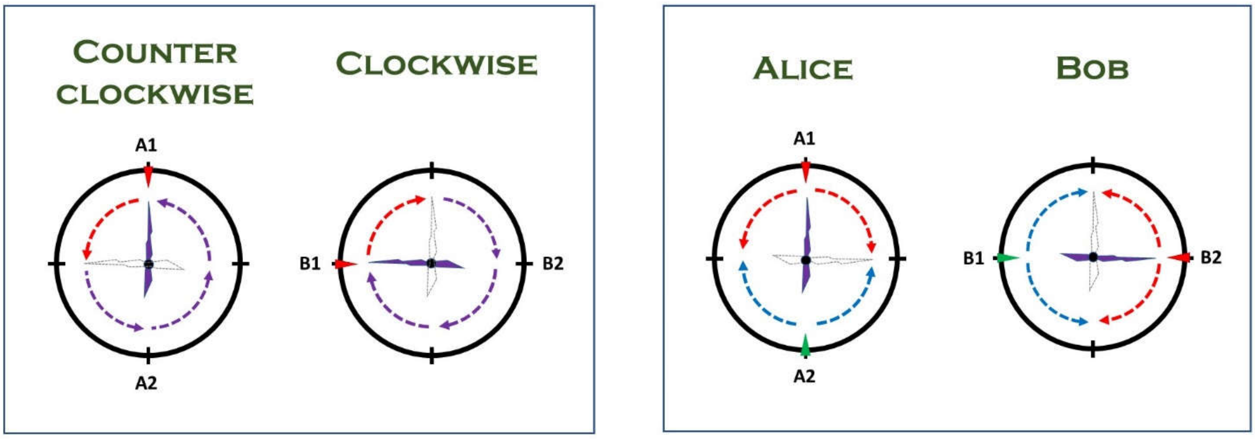

a) (b)

Figure 5. Toy model for correlated spin measurements. This is an imaginary scenario, in which a spin-like dichotomous property obeys a Malus-like Law (cosine squared of ¼ the angle between measurements) for visual clarity. The goal is to explain how such a manifestation is possible, given that Alice and Bob are ignorant about each other's choices. (**a**) Alice and Bob measure observables triggered by identical rotating entities. For each observation, there is a delay until the arrow reaches the designated pointer. In some events, the rotation is clockwise (right circle). This means that Bob's event at B1 happens first and serves as an anchor for the wave transformation that determines the probability of Alice's observation at A1. In others, the rotation is reversed (left circle), and Alice's event is the anchor. In both cases, the Malus-like law predicts the same correlations, as if these were consecutive measurements in a single beam. (**b**) With half of all the possible events, the two types of rotation can be combined such that Alice samples one random variable for both joint measurements at each location (left circle). In this case, Bob is forced to sample two distributions for the same measurement choice. His events are always the result of wave transformations that begin at Alice's coordinates. The other half of the events can be grouped such that Bob samples a single distribution for two joint measurements (right circle). Yet, in this case Alice is forced to sample two distributions for each setting. It is not possible for all the twin measurements to be jointly distributed in such an experiment. This is why Bell violations emerge, as predicted by quantum theory.

Let us consider the clockwise subset of observables (as shown in Figure 5a, on the right). Alice decides to make an observation at the 12 o'clock position (A1), while Bob has a choice between making a detection in the 9 o'clock (B1) or the 3 o'clock (B2) orientations. The crucial detail is that Bob can only make one measurement. In the case of B1, his arrow will reach the detector first. Therefore, Bob acquires exact knowledge about the simultaneous orientation of Alice's arrow. The subsequent evolution of Alice's quantum (till it reaches A1) is governed by a process of wave evolution, equivalent to a formal transformation. The probability of Alice's outcome is determined by the Malus-like law that is postulated for this example. (Again, this is similar to the case of consecutive measurements on a single projection). However, if Bob chooses to measure B2 instead, the two arrows will cross A1 first, determining the probability of *Bob's* observation through a similar wave transformation. Accordingly, we get two incompatible measurements with incompatible bases for transformation. It is never possible to reduce these joint measurements to a single Bohmian path of evolution. Schematically, there are two consecutive joint measurements (**B1**, **A1**) and (**A1**, **B2**), but they always occur on different individual trajectories. Therefore, they do not influence each other's statistics of correlation, and the manifestation of the stipulated Malus-like law is possible without interpretive contradictions. The same reasoning applies to the counterclockwise set of trajectories, presented in Figure 5a on the left, except in reverse. To sum up, sharp quantum measurements truncate the space of probable outcomes and only isolate the local effects of one transformation. Different "phases" of this probabilistic system are sampled incoherently. When different

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parts of a single system are transformed in different ways, at different stages of evolution, it is no longer required to expect joint distributions. Therefore, the normalized sum of all the joint event probabilities no longer adds up to 100%, as one might expect in a fairly sampled Kolmogorov probability space. If it is physically possible for Malus' Law to be in force, then Bell violations become natural and even unavoidable.

An interesting problem to consider is whether it is possible to rearrange the list of events in this experiment by hand, such as to avoid a Bell violation. For instance, it was shown above that some trajectories are clockwise, and others are counterclockwise in this model. This means that half of the events can be grouped in manner that create joint distributions for any two double measurements performed by Alice (Figure 5b, left). If Alice's events are defined as anchors for both (**A1**, **B1**) and (**A1**, **B2**), then she can sample one and the same random variable for both combinations. The same pattern can be obtained for the joint measurements with A2. Therefore, Alice's measurements are non-contextual. However, this arrangement necessarily implies that Bob's measurements are contextual. All the events for (**A2**, **B1**) are anchored in A2, and all the events for (**A1**, **B1**) are anchored in A1. Bob's events emerge as transformations from different wave profiles, beginning with Alice's reference points. In short, Bob is unavoidably sampling two random variables with the same measurement setting, and the same reasoning applies for measurements at orientation B2. Conversely, the other 50% of the events can be grouped such that Bob samples a single distribution for any measurement choice on Alice's end (Figure 5b, right circle). Yet, this time it is Alice who necessarily samples two distributions for each measurement choice on Bob's end. In short, it is not possible to arrange the events such as to have joint distributions for all the measurements in a Bell experiment. We started by asking how it was possible for Bell violations to occur, only to discover we cannot avoid them.

It is important to emphasize that such behavior is not due to "particle" behavior. The two evolving quantum orbitals are represented by arrows, but the observed values are caused by the wave properties that can be sampled when the particles are in the adequate orientation to be counted. The reason for contextuality is found in the emergence of transient properties at every stage of wave evolution, as a direct consequence of quantum superposition. As a corollary, Alice and Bob do not need to "cheat", or even to know what the other party is doing, in order to obtain Bell violations. The nature of quantum spin measurements is such that contextuality emerges by default. Instead, Alice and Bob would have to coordinate efforts and "cheat" in order to obtain coincidences that *do not* violate Bell inequalities, given the same experimental design. In conclusion, quantum wavefunctions describe hypothetical fields with spatial extension. While quantum superposition applies to every possible observation, it does not follow that every component from everywhere in this field should act on every individual quantum. Instead, individual quanta can be assumed to reflect the *local* vector-sums of relevant component amplitudes along unobservable trajectories. Therefore, it is possible to acquire more precise knowledge about the coordinates of a quantum (by measuring its entangled partners) and to update the knowledge about its wavefunction slice for the purpose of near-future predictions. This model entails that spin-like properties cannot exist at the same time, as elements of reality. They can only emerge in sequence, connected by an underlying process of wave-like evolution. As a result, pairs of measurements with entangled quanta express the same behavior that would be seen if similar properties were measured in series, in one and the same projection. The difference is that sequential measurements produce direct and complete transformations at every measurement, while correlated measurements sample different combinations of potential transformations. In the end, the reason for Bell violations is the same in both cases. It is determined by the type of correlations that are encoded in the wave transformations that connect any two consecutive properties. Thus, if we treat quantum variables as wave properties (as indeed they are expressed by quantum theory), and if we interpret wave properties as transient (as suggested by the principle of quantum superposition), then it is possible to explain entanglement as a local process. This means that Bell's inequality is not a tool for establishing the reality of metaphysical interactions.

Instead, it helps to confirm the validity of quantum superposition as a source of observable quantum behavior.

6. Discussion and final conclusions

Einstein, Podolsky and Rosen showed, in 1935, that quantum properties cannot be produced by the mere act of observation. In the case of entangled quanta, such a mechanism would require impossible physical interactions, including action at a distance. This appeared to imply that quantum properties are jointly well-defined from the source, even when they do not commute. Yet, Bell's theorem showed the opposite. Jointly defined variables cannot reproduce the predictions of quantum theory unless they are also allowed to exhibit mysterious interactions. Accordingly, it seems that there are only two ways to interpret quantum behavior and both of them entail nonlocality. Therefore, one should conclude that quantum behavior is nonlocal. As it turns out, this perception is incorrect, because the two listed alternative define a false dichotomy. Physical properties can either be permanent (and non-contextual) or transient (and contextual). In the second case they can emerge objectively, whether observed or not. This distinction is a central notion for the understanding of wave propagation, but it was rarely recognized as such. The relevant concept here is the centuries-old question about the nature of running waves. Do they propagate like particles with rectilinear trajectories (as suggested by geometric models), or do they propagate like energetic oscillations without transport of matter (as seen during Fresnel propagation)? More importantly, what happens when waves intersect? Is wave interference a macroscopic illusion, or does it take pace with real energy redistribution? Classical physics adopted a particle model of wave interaction, deciding that wave components go through each other unperturbed. Unfortunately, this assumption entailed a nonclassical and nonlocal ontology. Furthermore, classical mechanics had a good solution for the problem of interference, known as the Huygens-Fresnel formalism. Yet, this approach was apparently underestimated and practically ignored as "non-physical". When quantum mechanics was discovered, classical interpretations were falsified. Quantum theory supported a different approach to linear superposition: when waves overlap, energy redistribution must be treated as ontologically real. Wave vectors may capture the geometrical structure of this process, but they do not correspond to "wave-packets" going through each other unperturbed. In short, the interpretation of classical waves was now possible with a truly classical ontology. Instead, the weakness of the traditional ontology was not acknowledged, and scientists found it easier to accept the Copenhagen interpretation. Namely, they accepted the principle that interference did not happen, unless someone was looking at the quanta in the interference volume. As shown above, this is the true source of quantum weirdness: wave-like phenomena are interpreted with strange particle models, with no regard for interpretive consistency.

How do Bell violations happen in quantum mechanics? If wave interference is assumed to be ontologically true, then spectral components cease to exist in complex waves. Only the vector sum of all components describes the true profile of a wave. This means that spin-like wave properties do not propagate unchanged from the source. They are not "always there". Instead, they are created by a process of energy redistribution, as captured by the Huygens-Fresnel model. If the output of any operation of spin measurement is treated as contextual, then classical wave mechanics leads to Bell violations. However, electron spin and photon polarization are often described as permanent indestructible components, and this is why Bell violations are perceived as non-classical. Again, quantum weirdness is a matter of perception, and boils down to the interpretation of linear wave superposition. If measurement outcomes are treated as contextual, any two consecutive measurements of photon polarization are expected to obey Malus' Law, without interpretive complications. Accordingly, different joint measurements belong to different statistical contexts. It is impossible to reconcile a chain of double measurements in a single Kolmogorov space, and Bell violations emerge as a natural outcome. As a corollary, Bell experiments reproduce with entangled projections what is possible to observe with consecutive measurements over single projections. The nuance is that pilot-wave models describe quantum particles as individual entities surfing extended waves. One can either measure the same entity twice along one "surfing trajectory", or measure two correlated entities once along identical (or otherwise correlated) "surfing trajectories". In contrast, mainstream approaches favor the principle of wave-particle complementarity. They assume that large waves collapse into point-like particles at random. This makes it challenging to visualize quantum correlations other than strange nonlocal interactions. Again, quantum behavior seems weird because of the interpretive assumptions that are imposed on its analysis. This is not justified by the features of the formalism, or by the known details of actual quantum experiments. In conclusion, quantum mechanics does not have a "nonlocality" problem. It has an "interpretation" problem.

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