Mysteries without Mysticism and Correlations without Correlata: On Quantum Knowledge and Knowledge in General

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Following Niels Bohr's interpretation of quantum mechanics as complementarity, this article argues that quantum mechanics may be seen as a theory of, in N. David Mermin's words, "correlations without correlata," understood here as the correlations between certain physical events in the classical macro world that at the same time disallow us to ascertain their quantum-level correlata.

1. QUANTUM MYSTERIES AND QUANTUM CORRELATIONS: AN EPISTEMOLOGICAL OUTLINE

Quantum mechanics and its extensions to quantum electrodynamics and other quantum field theories, or the ultimate constitution of nature according to these theories, are often viewed as deeply strange and mysterious by their friends and foes alike.[2] One could cite numerous statements that testify to this widely held perception and display a broad spectrum of valuations of this mysteriousness itself. One of the most eloquent expressions of it is found in N. David Mermin's article "Spooky Action at a Distance: Mysteries of the Quantum Theory," an invaluable guide to quantum mysteries for both specialists and lay readers, included in his *Boojums All the Way Through: Communicating Science in a Prosaic Age*. The title

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[2] Throughout this article, by quantum mechanics I refer to the standard version of it, covered by Heisenberg's or Schrödinger's formalism (or their usual modifications, such those of Paul Dirac's or John von Neumann's formalisms), rather than to, say, Bohmian mechanics or other alternative accounts of the experimental data in question.

a position (or complementarily, momentum) measurement in quantum mechanics "measures" a correlation whose quantum-level correlata are rigorously unascertainable and indefinable or even inconceivable by any means available to us.

The EPR-type experiments and correlations involve the same type of measurement. Assuming that we perform the first measurement on the first particle of the EPR pair and use it to make a *prediction* concerning the second, a position *measurement* on the second particle of the EPR pair will supply *classical* correlata to the EPR correlations. These correlata, however, could only be classical but never quantum-level ones, and the correlation itself in question would be manifest and numerically ascertainable only through them. Indeed, in any given measurement, the quantum object and the measuring instrument involved, via a quantum part that interacted with this object, become entangled in the EPR way, as Bohr observed (*PWNB* 2, pp. 57, 60). In this sense, every quantum measurement involves an EPR-type entanglement. This is perhaps why Bohr did not see anything essentially new in the EPR argument. As Mermin suggests, Bohr could have told us about correlations without correlata and perhaps missed his chance to do so in this post-Bell way.[13]

An important qualification is in order here. In referring to the EPR (or Bell) correlations, one should properly speak of certain *sets* of correlations between outcomes of measurements and the relationships between the elements of these sets. These sets and the relationships between their elements appear to defy classical explanation, as opposed to any particular correlation, assuming that we can speak of a single correlation, especially given the irreducibly probabilistic character of quantum mechanics. Given this character, however, Bohr's statement that "in fact to measure the position of... [a particle] can mean nothing else than to establish a *correlation* between its behavior and some part of a measuring instrument," too, could apply only statistically in quantum (as opposed to classical) mechanics. Bohr might well have had this qualification in mind and perhaps should have clarified his statement accordingly.[14] A single "measurement" cannot guarantee that a

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[13] See N. David Mermin, "What Is Quantum Mechanics Trying to Tell Us?" (Ref. 4, p. 765, No. 3).

[14] Analogous statistical considerations were crucial to Bohr's work on measurement in quantum electrodynamics in his collaboration with Léon Rosenfeld, "On the Question of the Measurability of Electromagnetic Field Quantities" (reprinted in *QTM*, pp. 479–522), in response to Lev Landau and Rudolf Peierls's argument. This article was written in 1933, only two years prior to Bohr's exchange with EPR, where the statement just cited is found. These considerations also affect our understanding of uncertainty relations (including those found in quantum electrodynamics, one of the concerns of the exchange just cited), which can, accordingly, be seen in terms of statistical deviations in the outcomes of corresponding measurements. We recall that, in Bohr's interpretation, uncertainty relations rigorously apply only to certain parts of measuring instruments involved and not to quantum objects.

relation between a quantum object and the apparatus that has registered an event has in fact been established or even that an interaction with a proper quantum object has in fact taken place. In other words, a single event cannot guarantee that a measurement has in fact taken place (hence my quotation marks). Thus, an occurrence of a single spot on the screen in the double-slit experiment cannot guarantee that an emission from the source has in fact taken place. The occurrence of all such "events" could only be ascertained on the basis of statistical considerations involving a sufficiently large number of experiments, whereby a certain particular type of correlations, absent in classical physics, is found. The same considerations would apply to the "entanglement" between measuring instruments and quantum objects, referred to above.

The two concepts of my title, "mysteries without mysticism" and "correlations without correlata," are, thus, themselves correlative. The impossibility of, in Bohr's language, *unambiguously* specifying or even conceiving of the quantum-level correlata of any possible quantum-mechanical correlations is correlative to quantum mystery (without mysticism) in the sense of Bohr's appeal to the recognition that beyond certain limits an analysis of quantum phenomena "is *in principle* excluded." Just as are the "properties" of quantum objects and of their behavior (if one can speak here in terms of "properties," "behavior," "quantum," or "objects"), the correlata of the quantum-mechanical correlations are irreducibly beyond the limits of physical description and of our knowledge in general. In other words, the "properties" and "correlata" in question are one and the same. We can only have knowledge concerning the effects of the interactions between quantum objects and the measuring instruments upon certain classically describable parts of those instruments. It is through these effects that we establish certain correlations in question in quantum physics. Hence, following Mermin, we can rigorously speak of "correlations and only correlations," without ever being able to speak about the *quantum-level correlata* of those correlations. These correlations give us, in John Bell's words, what is "speakable" in quantum mechanics. Their quantum correlata are, in the present view, un-speakable, unthinkable, and inconceivable, including as "quantum" in any given sense of the term even at the level of theoretical idealization. The ultimate constitution of nature itself may be at an even further remove from our grasp than this idealization, if inexorably affecting our interaction with nature. It may be unspeakable even as unspeakable, unthinkable even as unthinkable, inconceivable even as inconceivable. Admittedly, this is not a situation that Bell himself saw as desirable any more than did Einstein, although both appear to have accepted it as logically possible.[15] To give this situation logic, as Bohr did, is no small feat, however.

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[15] For Bell's comment on this possibility see John Bell, *Speakable and Unspeakable in Quantum Mechanics* (Ref. 6, p. 155).

2. THE QUANTUM POSTULATE AND BOHR'S CONCEPT OF PHENOMENON

The argument just outlined extends primarily from the post-EPR version of complementarity. This version departs from the version offered in the Como lecture of 1927, published as "The Quantum Postulate and the Recent Development of the Atomic Theory" (*PWNB* 1, pp. 2–91). Bohr returns to Heisenberg's initial ideas used in developing his matrix quantum mechanics. The Como version is substantially indebted to Louis de Broglie's and Erwin Schrödinger's "wave" theories (although not their interpretations of those theories), far less significant for Bohr's later works. Bohr's 1935 reply to EPR was arguably the most decisive work in reshaping complementarity, although there is earlier evidence of this shift, around 1930, under the impact of his previous exchanges with Einstein. In any event, Bohr eventually arrived at an argument, to which, in hindsight, Heisenberg's early work leads more directly. Bohr's comments on Heisenberg's discovery in his 1925 survey "Atomic Theory and Mechanics" already contain a statement that essentially defines his ultimate epistemology of quantum theory (most key epistemological propositions of the later works may be seen as developing this insight). The statement precedes Bohr's introduction of complementarity in Como and, notably, before Schrödinger's wave mechanics, but immediately follows Heisenberg's paper introducing his matrix mechanics, a "*rational* quantum mechanics," as Bohr characterized it. This was a "step," Bohr rightly surmised, "probably of fundamental importance" (*PWNB* 1, p. 48).

Heisenberg argued that quantum mechanics required, first, a "new kinematics," fundamentally different from that of classical mechanics. "Kinematics" may not be an altogether appropriate term to use in these circumstances. As the etymology of the term indicates, traditionally it refers to a representation of the attributes of motion, such as positions (coordinates) or time, or velocities of a body. In classical mechanics this representation is usually done by means of continuous (actually differential) functions. By contrast, Heisenberg's "new kinematics" referred its mathematical elements to what (in this case atomic spectra) is observable in measuring instruments under the impact of quantum objects, rather than represented the attributes of these objects themselves. In addition, these "new" kinematical elements were no longer functions or any form of representation of the properties of quantum objects or their behavior. Instead they were conceived as infinite-dimensional matrices of complex variables with no classical-like or ultimately any relation to these properties, but related only to the impact of the interaction between quantum objects and measuring instruments. (Heisenberg appears to have been

unfamiliar with matrix algebra, by then a well-developed branch of mathematics, and reinvented parts of it in working on his paper.) In his commentary, Bohr observed that the "fundamental importance" [of Heisenberg's step] was in "formulating the problems of the quantum theory in a novel way by which the difficulties [that besieged quantum theory since Planck's discovery] attached to the use of mechanical pictures [to describe quantum entities] may, it is hoped, be avoided" (*PWNB* 1, p. 48). (Eventually Bohr was compelled to abandon such a use altogether.) Remarkably, however, the formalism enabled excellent statistical predictions concerning the outcome of experiments and allowed for a proper application of the key physical laws, such as conservation laws (*PWNB* 1, p. 48). Bohr explained:

> In [Heisenberg's] theory the attempt is made to transcribe every use of mechanical concepts in a way suited to the nature of the quantum theory, and such that in every stage of the computation only directly observable quantities enter. In contrast to ordinary mechanics, the new mechanics does not deal with a space-time description of the motion of atomic particles. It operates with manifolds of quantities which replace the harmonic oscillating components of the motion and symbolize the possibilities of transitions between stationary states in conformity with the correspondence principle. These quantities satisfy certain relations which take the place of the mechanical equations of motion and the quantization rules [used by the "old quantum theory," preceding quantum mechanics and developed primarily in the works of Planck, Einstein, Sommerfeld, and Bohr himself]. (*PWNB* 1, p. 48)

The classical (Hamiltonian) equations of motion are formally retained in this scheme, but are now applied to abstract matrix variables and no longer to anything describing the motion of physical objects (in this case electrons in atoms). Bohr's appeal to the "symbolic," rather than descriptive, nature of Heisenberg's new kinematics is noteworthy. It indicates that, rigorously, one should speak of the probabilities of transition between certain measurements, with which such states were associated at the time. Moreover, the elements involved are complex variables and, hence, are also symbolic rather than physically descriptive in the way real variables are in classical physics. One, thus, needs to establish proper procedures of relating these elements to the actual probabilities of the transitions in question, which are real numbers (between zero and one). This was done more rigorously later by Max Born in terms of Schrödinger's wave function, although the concept is implicit in Heisenberg's paper. At least in Bohr's interpretation, this or equivalent procedures cannot be given a physical justification (say, of the kind one finds in classical statistical physics). In the Como lecture Bohr reiterated his view of the situation as follows: "The new development [of quantum theory] was commenced in a fundamental paper by Heisenberg, where he succeeded in emancipating himself

completely from the classical concept of motion by replacing from the very start the ordinary kinematical and mechanical quantities by symbols which refer directly to the individual processes demanded by [Planck's] quantum postulate" (*PWNB* 1, pp. 70–71). The phrase "individual processes" must be seen as referring to what is actually observed in measuring instruments rather than to quantum processes, since otherwise the statement is manifestly incorrect. The view expressed here still shapes Bohr's argument in the Como lecture, even though Schrödinger's wave mechanics now becomes equally germane to this argument. The wave mechanics qua mechanics, however, is in turn seen as symbolic rather than as offering a physical description of the kind found in classical wave theory, which Schrödinger's mechanics, thus, also resembles only formally but not in the substance of its physical reference. In this respect, it is no different from Heisenberg's matrix mechanics or from Planck's quantum postulate, to begin with.

Bohr's work on complementarity may be seen as his life-long effort to give the proper meaning to "the quantum postulate," his interpretation of Max Planck's discovery of 1900, which inaugurated quantum physics. Viewed from the perspective adopted at the time, Planck's discovery revealed that radiation, previously believed to be a continuous (wave-like) phenomenon in all circumstances, could, under certain conditions, have a discontinuous, quantum character. The limit at which this discontinuity appears is defined by the frequency of the radiation and a universal constant of a very small magnitude, h, Planck's constant. Planck termed it "the quantum of action," and it turned out to be one of the most fundamental constants of all physics. The indivisible (energy) quantum of radiation in each case is the product of h and the frequency v, $E = hv$. Rather than tracing the history of Bohr's interpretation of Planck's discovery, I shall offer here a rendition of the quantum postulate, first in general terms and then in terms of Bohr's special concept of phenomenon, developed by him in the wake of the EPR argument:

Any observable phenomenon of quantum physics is either an individual discrete (discontinuous) phenomenon or event or is a discrete sum, indeed a finite (if usually very large) sum, of such individual phenomena or events.

The summing-up ultimately pertains to records of such events occurring over certain periods of time, as in the case of collisions between quantum objects and the screen in the double-slit experiment. It follows that there are no continuous, such as wave-like, quantum phenomena, even if one uses, as I do for the moment, the term phenomenon in its general rather than Bohr's sense, which only pertains to individual phenomena in

question. There are certain composite phenomena that are wave-like insofar as one can invoke such wave-like features as "diffraction" or "interference" in order to describe the effects defining these phenomena. Such wave-like effects appear under certain, rigorously specifiable, experimental conditions, once a sufficiently large number of events are accumulated. The individual phenomena comprising them are particle-*like* in the sense of being analogous to the effects of the interactions between particle-like classical objects and measuring instruments. One cannot, however, speak of "particles" any more than of "waves" at the quantum level, as Bohr noted already in the Como lecture (*PWNB* 1, p. 57).

The apparent inadequacy of applying such concepts as "particles" and "waves," or conceivably any physical concepts, to quantum objects themselves became especially vexing in the wake of the EPR argument. These new complexities made Bohr reassess and redefine the concept of physical phenomenon as applicable in quantum mechanics. Bohr's redefinition does not change the formal statement of the quantum postulate given above (except insofar as the term phenomenon in Bohr's sense only applies to individual phenomena), but the change in epistemology is essential. All phenomena available to quantum-mechanical treatment are now constituted by certain, sometimes correlated, recorded effects of the interaction between quantum objects and measuring instruments upon those instruments, or, in Bohr's words, "practically irreversible amplification effects," such as a click of a photo-detector or a blackening of a grain of a photographic emulsion (*PWNB* 2, p. 51). The very language of effects becomes persistent in Bohr's post-EPR writings and gives further support to my argument. As I have indicated, such effects are physically described in terms of classical physics, but can be predicted only by means of quantum mechanics. Thus, quantum-mechanical phenomena are no longer conceived in terms of the properties of quantum objects and their behavior, now placed beyond any knowledge and conception. The assignment of such properties is rigorously prohibited in view of "the *impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear*" (*PWNB* 2, pp. 39–40).

By the same token, the term "phenomenon" now refers to *registered* observations. It refers only to what has already happened and not to what may happen, even if the latter possibility corresponds to a rigorous prediction enabled by quantum mechanics. In other words, phenomena in Bohr's sense *enable* predictions but do not involve them in their definition and constitution as phenomena. (Such predictions could, again, only be statistical and hence never fully guarantee a given outcome.) This centrality of

the *actual* in Bohr's concept of phenomenon is a crucial point, often missed by commentators, specifically, as will be seen, in the context of the EPR argument. In Bohr's own words:

> I advocated the application of the word *phenomenon* exclusively to refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement. In such terminology, the observational problem is free of any special intricacy since, in actual experiments, all observations are expressed by unambiguous statements referring, for instance, to the registration of the point at which an electron arrives at a photographic plate. Moreover, speaking in such a way is just suited to emphasize that the appropriate physical interpretation of the symbolic quantum-mechanical formalism amounts only to predictions, of determinate or statistical character, pertaining to individual phenomena appearing under conditions [of measuring instruments] defined by classical physical concepts. (*PWNB* 2, p. 64)

One might prefer to speak, along the lines of the argument given earlier, of *an* (rather than *the*) appropriate interpretation. On the other hand, it is important to stress that Bohr's insistence on the indispensability of classical physical concepts only involves the description of certain parts of measuring instruments. As concerns quantum objects themselves or their quantum interaction with other (quantum) parts of measuring instruments, classical concepts are not only dispensable but are rigorously inapplicable. For all quantum entities are now seen as physically indescribable either by means of classical or any other concepts, if indeed we may have concepts other than classical.[16] The quantum interactions between quantum and measuring instruments are, however, capable of producing classically describable effects upon the measuring arrangements involved. More accurately, these interactions are capable of initiating the process that ultimately leads to these changes, whereby these interactions are "amplified" to the classical level, compelling Bohr to speak of "practically

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[16] One might define as *classical* whatever we can in principle conceive, and one can see the conceptuality of classical physics as a particular, suitably refined, form of what is in principle conceivable. Conversely, the type of objects that are beyond all of our means of conception, representation, knowledge, access, and so forth, and the theories that treat them may be called *nonclassical*. (As earlier, I speak of such objects as objects of those theories that deal with them as theoretically idealized entities, rather than something in nature that these theories may relate to.) As both Bohr and Heisenberg emphasized, classical physics may be seen as a refinement of our common perception and thinking. This refinement, however, and conceivably anything our mental capacities allow us to do may not reach the objects in question in quantum mechanics. Complementarity of course expressly places these objects beyond this reach.

irreversible amplification effects."[17] This double character of the physics of measuring instruments, classical at the level of manifest effects and quantum at the level of their interactions with quantum objects, is often missed by commentators on Bohr and his argument concerning the classical description of the measuring instruments in quantum physics. In this interpretation, however, it is only this double, classical *and* quantum, character of the physics of measuring instruments that allows one to speak of "correlations without correlata," correlations without the *ultimate* quantum-level correlata. These correlations only manifest themselves as correlations between registered classical physical events, while disallowing us to establish the quantum-level correlata of such events. Otherwise, these "correlations" are correlations not only without establishable ultimate correlata but even without actually manifest or ascertainable, numerically or otherwise, correlations. Every quantum-mechanical prediction, *when verified by a measurement*, is of the first kind, correlating an initial set-up measurement ("preparation") and the registered outcome (again, keeping in mind that such outcomes are ultimately meaningful only in statistical terms). Any given measurement is of the second kind vis-à-vis the quantum object and the quantum part of the apparatus involved. A measurement would be a correlation of the first, manifest kind, if it is linked to a preparation.

While, however, *each* effect of that type could, once registered in our measuring instruments, be described as a physical object in terms of classical physics, the totality of these effects is explainable classically. In addition, as I have stressed here, neither this totality nor each of the individual effects is predictable by means of the classical theories, but only by means of the quantum theory, ultimately in statistical terms. On this view, quantum objects or, in view of the argument given earlier, something in nature that they relate to as an idealization may and indeed must be seen as *existing* independently (in a way that is inaccessible or inconceivable to us). They cannot, however, be meaningfully *considered* independently, apart from these interactions. Hence, these interactions cannot be neglected or compensated for in the way it could be done, at least in principle, in classical physics. Any attempt to circumvent their role would, on this view, only result in another phenomenon or set of phenomena in Bohr's sense, possibly different in the observational outcome but the same in their character,

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[17] On this point I permit myself to refer to "Reading Bohr: Complementarity, Epistemology, Entanglement, and Decoherence" (Ref. 7). See also Ole Ulfbeck and Aage Bohr, "Genuine Fortuitousness: Where Did That Click Come From?" (Ref. 8).

defined by the irreducible role of the measuring instruments involved in their physical constitution as phenomena.

This situation defines the wholeness or indivisibility of quantum-mechanical phenomena in Bohr's sense. Ultimately, all quantum characteristics—discreteness, discontinuity, individuality, atomicity (indivisibility), and so forth—are transferred by Bohr to the level of phenomena in his sense. This transfer enables Bohr to introduce a new concept of atomicity (in the original Greek sense of the indivisibility of certain entities, "atoms"). It derives from "Planck's discovery of the universal quantum of action," which Bohr sees as "reveal[ing] a [new] feature of atomicity in the laws of nature going far beyond the old doctrine of the limited divisibility of matter" (*PWNB* 2, p. 33; also *PWNB* 3, p. 2). Bohr's concept requires a terminological adjustment, insofar as the application of such terms becomes conceptual rather than physical. "Atomicity" now refers to physically complex and hence *physically* further sub-divisible entities, defined by certain effects of the processes taking place by virtue of particular experimental arrangements. It no longer refers to single physical entities, whether quantum objects themselves ("particles") or even point-like traces of physical events.[18] To quantum objects themselves one cannot ascribe atomic, any more than other physical properties, or perhaps any other properties.

Bohr's "atoms" are thus conceived of as individual phenomena in his sense, rather than as indivisible atomic quantum objects. As I said, any attempt to "open" or "cut through" a phenomenon can only produce yet another closed individual phenomenon, a different "Bohr's atom" or set of such "atoms," leaving quantum objects themselves both (and correlatively) irreducibly inaccessible and inside phenomena (*PWNB* 2, pp. 39–40, 51). Bohr also speaks of "closed" phenomena in this context (*PWNB* 2, p. 73). By the same token, phenomena become *individual*, each of them—every (knowable) effect conjoined with every (unknowable) process of its emergence—unique and unrepeatable. Some of them can be clustered insofar as they refer to the "same" quantum entities, "individual," such as elementary particles, or collective, for example, such more or less stabilized composites of quarks and gluons, such as protons or neutrons. Reciprocally, however, this is the only way to define and identify such entities, individually or collectively. Thus, along with the quantum atomicity as

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[18] A collision of a "particle" with a silver bromide screen is discrete (a "dot") only in a low resolution, since physically such a trace or the process that led to it is immensely complex. Cf. Ulfbeck and Bohr's argument in "Genuine Fortuitousness" (Ref. 8).

indivisibility, the quantum atomicity as *individuality* is now also understood as the individuality and, ultimately, uniqueness of each phenomenon. Finally, quantum *discontinuity*, another general characteristic of "atomicity," is now also something different from discontinuity at the level of quantum objects. It is redefined as the irreducible inaccessibility of quantum objects themselves, the impossibility of applying either of these concepts, continuity or discontinuity, or any conceivable concept, to their "relation" (another inapplicable concept) to the manifest effects of their (quantum) interaction with measuring instruments, which is responsible for these effects. The "discontinuity" part of Bohr's concept phenomenon is not always properly taken into account, which often leads to a misunderstanding of Bohr's atomicity, specifically as only referring to the wholeness (indivisibility) of phenomena in his sense.[19]

It is worthwhile to illustrate the preceding argument by discussing, *from the perspective of this argument*, the double-slit experiment, sometimes argued to contain all of the key features of quantum mechanics and the questions it poses. The main reason for revisiting this familiar terrain is that the present interpretation introduces certain nuances often missed in the discussion of the experiment. These nuances are, however, crucial, sometimes the more crucial the more minute and subtler they are. The well-known arrangement consists of a source; a diaphragm with a slit (A); at a sufficient distance from it a second diaphragm with two slits (B and C), widely separated; and finally, at a sufficient distance from the second diaphragm a screen, say, a silver bromide photographic plate. A sufficient number (say, a million) of quantum objects, such as electrons or photons, emitted from a source, are allowed to pass through both diaphragms and leave their traces on the screen. Provisionally, I speak for the moment in terms of quantum objects themselves or "particles." According to the present view, we can only observe certain effects on the screen or other physically equivalent macro-phenomena. What we have in any given event is a trace of a "collision" on the screen. As I have explained, such a trace could be seen as correlated with an emission from the source only in statistical terms on the basis of other observations and measurements that one can perform in similar circumstances, since in itself it does not guarantee that an emission corresponding to it has taken place. No emission from a quantum source is ever assured, regardless of preparation. Two set-ups are considered, in the first, with both slits open, we cannot know through

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[19] I have considered Bohr's atomicity in detail in "Quantum Atomicity and Quantum Information: Bohr, Heisenberg, and Quantum Mechanics as an Information Theory" (Ref. 9).

phrase, "spooky action at a distance," is Albert Einstein's. It sums up his view
of the famous thought experiment proposed by him, together with Boris
Podolsky and Nathan Rosen, and known as the EPR experiment, and of the
"mysterious" correlations between distant events found in it. Many, the
present author among them, would not find any *physical* "action at a dis-
tance" (in the sense of any physical nonlocality incompatible with relativity)
in this case or elsewhere in quantum mechanics.[3] Most, however, would see
the EPR situation as "spooky," strange, albeit not surprising by the standard
of quantum mechanics or the world according to it. For, Mermin tells us, the
EPR experiment and quantum mechanics show that, confounding our prosaic
age, "the world behaves in a manner that is exceedingly strange, deeply
mysterious, and profoundly puzzling" (Ref. 1, p. 126).

There are exceptions to this view or to this dramatic way of expressing
the situation, notably Niels Bohr, as Mermin himself observes in the same
article and in his perceptive review of Bohr's philosophical works (*Boojums
All the Way Through*, Ref. 1, pp. 114, 136–39). Throughout his writings,
Bohr aimed, in his words, to "clear up... misunderstandings" concerning
any "underlying mysticism foreign to the spirit of science" that could be
associated with quantum mechanics. Instead, beginning with his initial
response to Heisenberg's introduction of quantum mechanics, he appeals
to the *rational* character of quantum mechanics and even defines it as a
rational theory (Ref. 2, Vol. 1, p. 48).[4] Accordingly, while, as I shall argue

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[3] The particular meaning of locality as compatibility with relativity will be applied throughout
this article. One encounters a number of conceptions of locality or nonlocality in the discussions
of the EPR-type situations. Other terms, such as nonseparability, are also used and are in turn
given various meanings. Some of these conceptions are compatible with my argument here,
while others would require further qualifications. These qualifications are, however, not essen-
tial for my argument as such, since the latter only involves locality in the sense just defined.

[4] Most of Bohr's works to be cited here are found in Ref. 2, Niels Bohr, *The Philosophical
Writings of Niels Bohr*, 3 vols., (hereafter *PWNB*) and in Ref. 3, John Archibald Wheeler
and Wojciech Hubert Zurek, eds., *Quantum Theory and Measurement* (hereafter *QTM*). It is
true that Bohr invokes the "irrationality" (Bohr's quotation marks) of *the quantum postulate*
in his early writings (*PWNB* 1, p. 54). (I shall explain "the quantum postulate" below.) This
"irrationality" is, however, *not* an "irrationality" of *quantum mechanics* itself, which Bohr,
again, sees as a rational theory, a *rational* theory of something *irrational*. Bohr's point is
often misunderstood, in part by virtue of overlooking (beginning with Bohr's quotation
marks) the difference between the rationality of a theory and the irrationality of what it
(rationally) deals with. Bohr's invocation of "irrationality" appears to be based on an
analogy with irrational numbers. The Greeks, who discovered the irrationals, could not find
an arithmetical, as opposed to geometrical, form of representing them. (The Greek terms
were "alogon" and "arreton," which may be rendered as "incommensurable" and "in-
comprehensible.") The problem was only resolved in the nineteenth century, after over two
thousands years of effort. It remains to be seen whether the quantum-mechanical "irratio-
nality" will ever be resolved, assuming (not everyone does) it exists now.

which slit each particle passes, in the second we can, either in practice or, importantly, in principle.

In the case of the first set-up, a "wave-like" interference pattern will emerge on the screen, in principle (there could be practical limitations), regardless of the distance between slits or the time interval between the emissions of the particles. The traces, once a sufficiently large number of them are accumulated, will "arrange" themselves in a pattern, even though the next emission occurs after the preceding particle is destroyed after colliding with the screen. This pattern is the actual manifestation and, according to Bohr's and most standard interpretations, is the only possible physical manifestation of quantum-mechanical "waves." As I said, in this type of interpretation at least, it is only by convention that one can speak of "wave-propagation" or of any attributes of the classical-like phenomenon of wave-propagation. The same, however, is also true as regards the attributes of classical particle motion, in particular trajectories. In considering individual marks on the screen we may rigorously speak of them only as *particle-like effects*, and not as traces left by collisions with classical-like particle objects. In sum, we see on the screen only classically manifest effects of the interactions between quantum objects and measuring instruments upon the latter. In accordance with the quantum postulate, each of these effects or marks is a discrete, particle-like, entity and an individual phenomenon in Bohr's sense. Certain (discrete) collectivities of such effects may, given proper arrangements, be wave-like in the ("interference") pattern of their arrangement. Quantum objects themselves are destroyed in the process of this "irreversible amplification" of their interaction with measuring instruments to the classical level (*PWNB* 2, p. 51; *PWNB* 3, p. 3).

If, however, in the second set-up, we install counters or other devices that would allow us to check through which slit particles pass, the interference pattern inevitably disappears. Merely setting up the apparatus in a way that such knowledge would in principle be possible would suffice. The fact that even the possibility in principle of knowing through which slit the particles pass would inevitably destroy the interference pattern may be shown to be equivalent to uncertainty relations. It can also be given a proper statistical interpretation further indicating that the statistical nature of quantum mechanics may be and, in the present view, is irreducible (*PWNB* 2, p. 34; *PWNB* 2, pp. 43–47; *QTM*, pp. 146–47).

If one speaks in terms of quantum objects themselves, in the interference picture the behavior of each appears to be "influenced" by the location of the slits. Individually or (which is hardly less troubling) collectively, quantum objects appear somehow to "know" whether both slits are or are not open, or whether counting devices are or are not installed. The situation is all the more remarkable given the fact that the interval

between emissions could be made large enough for the preceding quantum object to be destroyed before the next one is emitted, without affecting the appearance or, conversely, disappearance of the interference pattern depending upon a given set-up. Attempts to conceive of this behavior in terms of physical attributes of quantum objects themselves appears to lead to unacceptable or at least highly problematic consequences. Among such consequences are logical contradictions; incompatibility with one aspect of experimental evidence or the other; a strange or mysterious behavior of quantum objects; difficult assumptions, such as attributing volition or personification to nature in allowing particles individual or collective "choices"; or nonlocality of the situation, making it incompatible with relativity. The latter alternative was first proposed by Einstein in the context of the EPR and analogous arguments and is legitimate once such an attribution is made.[20] Such locutions as strange, mysterious, incomprehensible, or paradoxical are hardly surprising in these circumstances.

Bohr, by contrast, sees the situation as indicating the "essential ambiguity" of ascribing physical attributes to quantum objects themselves or to their independent behavior. He writes: "To my mind, there is no other alternative than to admit that, in this field of experience, we are [rather than with properties of quantum objects] dealing with individual phenomena [in Bohr's sense] and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary phenomena we want to study" (*PWNB* 2, p. 51). In other words, we are dealing with two different and mutually exclusive types of effects of the interaction between quantum objects and measuring instruments upon those instruments under very particular physical conditions, as just explained. Once, however, this type of interpretation is in place and any reference to the properties of quantum objects themselves is suspended, the undesirable features mentioned above are removed without affecting the integrity of the data or the formalism of quantum theory. At the very least, and I make no stronger claim here, this interpretation is both consistent with the quantum-mechanical predictions and is local (in the sense of its compatibility with relativity).

It is, as I said, crucial that in this interpretation an unambiguous reference to quantum objects and processes would remain impossible even when one speaks of single such attributes, rather than in the case of a

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[20] Yet another alternative would be a retroaction in time, which is hardly less problematic, albeit not inconceivable and entertained by some. See Henry P. Stapp, "Nonlocal Character of Quantum Theory" (Ref. 10), and, for an effective counterargument, N. David Mermin, "Nonlocal Character of Quantum Theory?" (Ref. 11).

simultaneous attribution of joint properties involved in uncertainty relations, and even at the time when the measurement takes place. It is clear that Bohr has in mind this more radical view. In speaking of the ambiguity of all such references he never qualifies it by a reference to either joint properties or to the uncertainty relations, as, for instance, throughout "Discussion with Einstein" (e.g., *PWNB* 2, pp. 40, 51, and 61). In other words, *neither one nor the other* complementary variable could be assigned or even defined for quantum objects themselves, rather than only one or the other, say, a position or momentum. The latter ("either one or the other") situation and, hence, uncertainty relations themselves now apply to the corresponding (classical) variables of suitably prepared measuring arrangements, impacted by their interactions with quantum objects. We can either prepare our instruments so as to measure a change of momentum of certain parts of those instruments or arrange them so as to be able to locate a spot impacted by a quantum object, but never do both together. The mutual exclusivity of such arrangements and yet the necessity of both for a comprehensive account of the situation is the proper meaning of their *complementary* character. As Bohr says:

> This point is of great logical consequence, since it is only the circumstance that we are presented with a choice of *either* tracing the path of a particle *or* observing interference *effects*, which allows us to escape from the paradoxical necessity of concluding that the behavior of an electron or a photon should depend on the presence of a slit in a diaphragm through which it could be proved not to pass. We have here to do with a typical example of how the complementary phenomena appear under mutually exclusive experimental arrangements... and are just faced with the impossibility, in the analysis of quantum *effects*, of drawing any sharp separation between an independent behavior of atomic objects and their interaction with the measuring instruments which serve to define the conditions under which the phenomena occur. (*PWNB* 2, pp. 46–47; emphasis on "effects" added)

While the language of effects is right (that of particles is obviously provisional), in order to observe interference effects we would need many particles, although the probabilistic prediction for any single particle would be affected accordingly as well. Thus, all quantum measurements may indeed be seen in terms of correlations that have no specifiable quantum correlata (at either end, that of the object and that of the quantum constitution of the instrument). They do, however, have specifiable classical correlata, defined as the outcomes of measurements performed and pertaining to the classically describable aspects of measuring instruments under the impact of their interaction with quantum objects. (The statistical nature of these correlations must, again, be kept in mind.)

We now see why Bohr needs his concept of phenomena as defined by the appearance of the particular individual effects recorded in certain parts

of measuring instruments *under rigorously specifiable experimental conditions* and why *this specification must itself be seen as part of the phenomena*. In Bohr's interpretation, the constitutive role of these conditions can never be eliminated in considering the outcomes of quantum-mechanical experiments in the way it can, at least in principle, be done in classical physics. This is impossible even when, as in the EPR experiment, our predictions concern objects that are physically unaffected by measurements enabling such predictions. Thus, if seen independently of the quantum-mechanical context of its appearance, each mark on the screen in the double-slit experiment would be perceived in the same way or as the same phenomena in the sense of the philosophical phenomenology, from Kant to Husserl. (There are further complexities to their views as well.) Such a mark would appear the same regardless of the difference in the physical conditions and, hence, outcome ("interference" or "no interference") of the double-slit experiment. According to Bohr's understanding, however, each mark is, or is part of, a *different individual* phenomenon depending on these conditions, which are always mutually exclusive in the case of complementary phenomena, and are unique in any circumstances. Thus, in the double-slit experiment, rather than dealing with two phenomena, each defined by a different multiplicity of spots on the screen, we deal with two distinct multiplicities of individual phenomena, each defined by a spot on the screen. Each is an individual phenomenon in Bohr's sense and depends on a different set of conditions of the experiment. One of these sets will lead to the emergence of the interference pattern, "built up by the accumulation of a large number of *individual* processes, each giving rise to a small spot on the photographic plate, and the distribution of these spots follows a simple law derivable from the wave analysis" (*PWNB* 2, pp. 45–46; emphasis added). The other will not. In short, in accordance with the quantum postulate, each spot must be seen as a different individual phenomenon defined by the conditions in which the event occurs, while two different patterns, "interference" and "no-interference," pertain to two sets of different individual phenomena. Any given quantum-mechanical situation of measurement is always unique and unrepeatable, singular, and as such is incompatible with any other actual situation of measurement. These measurements are, of course, not all necessary for a comprehensive account in the same way as are properly complementary, mutually exclusive, measurements, such as the position and the momentum measurements, leading to the uncertainty relations. This necessity gives such measurements a special and crucial role in quantum mechanics and complementarity.

Far from being a matter of convenience, this distinction between two multiple-spot phenomena and two multiplicities of different individual spot-like phenomena is essential for Bohr's meaning and for the consistency of his argumentation. The statistical qualifications given above (e.g., that a

single trace on the screen may in fact be meaningless vis-à-vis any arrangement) do not diminish Bohr's argument but would reinforce it. Given this type of view, first, no paradoxical properties, such as simultaneous possession of contradictory wave-like and particle-like attributes on the part of quantum objects themselves, are involved. Secondly, we can never mix considerations that belong to complementary experimental set-ups in analyzing a given experimental outcome even when dealing with a single spot on the screen, as we could, in principle, do in classical physics. This is not an uncommon problem, including in some of Einstein's arguments, which could, again, lead to the appearance of physical and epistemological difficulties.[21] These difficulties are avoided once the rule of complementary mutual exclusivity of such considerations is followed.

Following upon these considerations, Bohr stresses that in the situations invoked in Einstein's key arguments, including those of the EPR type, in ascribing and predicting the values of the complementary variables involved, "we are not dealing with a *single* specified experimental arrangement, but are referring to *two* different, mutually exclusive arrangements" (*PWNB* 2, p. 57). This particular point reflects the actual physical situation rather than only Bohr's interpretation of it, although, as will be seen, the fact that it could be interpreted in this way is crucial in turn. The point becomes especially significant in the EPR context. In this case the term phenomenon in Bohr's sense could only refer to a single measurement actually performed on one and only one of the two quantum objects of the EPR pair. It does not refer, as is argued sometimes, to physical considerations involving both (spatially separated) objects at the same time, specifically by including into a phenomenon what is predicted concerning the second object on the basis of a measurement performed on the first. In the latter case nonlocality (again, in the sense of compatibility with the requirements of relativity theory) could emerge in Bohr's scheme, as some argue, in my view, by displacing Bohr's concept.[22] By contrast, the individuality of Bohr's phenomena as actual, registered phenomena allows one to avoid nonlocality and is conceivably the only way to do so.

Accordingly, Bohr argues that, at least from the perspective of his interpretation, "this necessity of discriminating in each experimental arrangement between those parts of the physical system considered which are to be treated as measuring instruments and those which constitute the

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[21] Cf. Bohr's discussion in "Discussion with Einstein" (*PWNB* 2, pp. 41–47).
[22] See, for example, Henry Folse, "Niels Bohr's Concept of Reality" (Ref. 12).

objects under investigation may indeed be said to form a *principal distinction between classical and quantum-mechanical description of physical phenomena"* (*QTM*, p. 150; also *PWNB* 2, p. 50). While "in classical physics the distinction between object and measuring agencies does not entail any difference in the character of the description of the phenomena concerned," in quantum physics it does (*QTM*, p. 150; also *PWNB* 2, p. 50; *PWNB* 3, p. 3). This statement may suggest that while parts of measuring instruments are described by means of classical physics, the behavior (in space and time) of quantum objects is described by means of quantum-mechanical formalism, a relatively common view, but not Bohr's. Bohr obviously says the former, but he clearly does not say and does not mean the latter here (or elsewhere). In his interpretation the behavior of quantum objects cannot be seen in terms of quantum-mechanical or any other formalism.

Now, as Bohr points out, "it is true that the place within each measuring procedure where this discrimination is made is in both cases largely a matter of convenience" (*QTM*, p. 150). At this point, Bohr brings into consideration the transformation theorems of quantum mechanics. The latter mathematically ground the EPR argument and, according to Bohr, "perhaps more than any other feature of formalism contribute to secure its mathematical completeness and its correspondence with classical mechanics" (*QTM*, p. 145, Note).[23] For, "by securing its proper correspondence with the classical theory the theorems exclude in particular any imaginable inconsistency in the quantum-mechanical description, connected with a change of the place where the discrimination is made between object and measuring agencies. In fact it is an obvious consequence of [Bohr's] argumentation that in each experimental arrangement and measuring procedure we have only a free choice of this place within a region where the quantum-mechanical description of the process concerned is effectively equivalent with the classical description" (*QTM*, p. 150).[24]

First, this last point conveys the deeper epistemological aspects of Bohr's correspondence principle, at least, again, as used in his later works. What makes it especially important, however, is that quantum objects are now always on the other side of the "cut" and may even be rigorously defined accordingly—that is, as something on the other side of any possible "cut." At one end, by virtue of their classical nature, the individual effects

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[23] What Bohr refers to by "the transformation theorems" is a set of transformations of Hilbert-space operators (corresponding to conjugate variables) that enables the EPR predictions.

[24] The phrase "the quantum-mechanical description" must be seen as referring to the overall scheme of quantum mechanics and not to a description of what physically happens at the quantum level, which is impossible in Bohr's interpretation.

in question can be isolated materially and phenomenologically—we can perceive and analyze them as such—once an experiment is performed. They cannot of course be separated from the process of their physical emergence by even conceiving of, let alone analyzing, this process. The indivisible wholeness, the irreducible "atomicity," of Bohr's phenomena makes this separation impossible. By contrast, at the other end, quantum objects and processes can never be isolated, either materially (from the measurement process and measuring instruments) or mentally, since we cannot in principle conceive of what actually happens at that level or how, even in terms of idealized models. In short, complementarity entails the impossibility of idealized *descriptive* models at the quantum level as part of its own idealized *predictive* model of quantum mechanics.

It follows that in this interpretation the mathematical formalism of quantum mechanics refers to the effects of the interaction between quantum objects and measuring instruments upon those instruments, and only to these effects. It does so in terms of predictions, statistical in character, concerning outcomes of future possible experiments on the basis of the classical information obtained from the experiments already performed. This formalism does not describe or otherwise account for the physical properties of quantum objects and processes (at least partly quantum in character) that are responsible for these effects in the way classical physics does or is customarily interpreted to be doing. It does not do so either before the measurement interference takes place, or between instances of such interference, or even during measurement. As we have seen, beginning with the immediate aftermath of Heisenberg's discovery of quantum mechanics, Bohr rejects the view that the quantum-mechanical formalism can unambiguously refer to quantum objects and processes in terms of space-time concepts. This formalism could be related to observations, always recorded in real (actually rational) numbers, by means of artificial schemes, such as Born's "square moduli" rule for deriving probabilities from quantum amplitudes, John von Neumann's projection postulate, and so forth. Ultimately this formalism defies all "unambiguous use of space-time concepts," which is "confined to the recording of observations which refer to marks on a photographic plate or similar practically irreversible amplification effects" (*PWNB* 2, p. 51). Bohr saw the formalism of quantum mechanics as correlative to this situation, including as applied to the EPR experiment (*QTM*, p. 145). He also stressed, however, that "such argumentation does of course not imply that in atomic [quantum] physics, we have no more to learn as regards experimental evidence and the mathematical tools appropriate for its comprehension. In fact, it seems likely that the introduction of still further abstractions into the formalism will be required to account for the novel features revealed by the

exploration of atomic processes of very high energy" (*PWNB* 3, p. 6; also *PWNB* 2, p. 63).[25] He hasn't been proven wrong so far.

3. THE EPR CORRELATIONS AND COMPLEMENTARITY

The current stage of the debate concerning quantum mechanics is dominated by the arguments addressing the EPR type experiments and "quantum entanglement"—the existence of a particular type of correlations, the EPR correlations, between certain spatially separated quantum-mechanical events. These correlations are inherently quantum-mechanical and are extraordinary in their character and implications, and by now possible applications, such as quantum cryptography and computing. On the other hand, they are only one among other manifestations of quantum mystery or indeed correlations. Some see the EPR situation as implying the nonlocality either of quantum mechanics or of the quantum data itself (one does not need quantum mechanics to ascertain the EPR correlations). Either view can, I argue, be avoided, given a Bohr-type interpretation, which is local. I, again, use the term "local" in the sense of the compatibility with the requirements of relativity, stressed by Bohr in the case of quantum mechanics and complementarity throughout his writings. I shall not consider EPR's and Einstein's related arguments and Bohr's replies to them in proper detail, which, to do them justice, would require a discussion beyond my scope, and shall restrict myself to a few key points more or less immediately following from the preceding argument.

According to Bohr, it is the singular position of measuring instruments in the account of quantum phenomena, "together with the relativistic invariance of the uncertainty relations... that ensures the compatibility between [his] argument and all exigencies of relativity theory," and, hence, the locality of complementarity in its post-EPR version (*QTM*, p. 150; *QTM*, p. 150, note). Quantum mechanics correctly predicts the data in question, correlations included, without requiring one to make claims concerning the properties of quantum objects. Complementarity, again,

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[25] The epistemology of quantum electrodynamics and quantum field theory, and the significance of these theories for the history of quantum mechanics are important subjects. Bohr's thought was clearly influenced by these developments, especially by Dirac's work, some of which was done while Dirac was in Bohr's institute in Copenhagen. Bohr addressed the question of measurement in quantum electrodynamics in his collaborations with Léon Rosenfeld, "On the Question of Measurability of Electromagnetic Field Quantities" and "Field and Charge Measurement in Quantum Electrodynamics" (*QTM*, pp. 479–522 and pp. 523–34). The topic cannot, however, be addressed here.

expressly prohibits such claims. On the other hand, any classical-like theory (i.e., based on the attribution of properties to quantum objects themselves) that would predict these data appears to be nonlocal in view of Bell's theorem and related results. The situation would be similar to Bohmian, hidden variables, mechanics, where, however, nonlocality is an explicit consequence of the mathematical formalism (in any version of it available so far). Bell's theorem tells us that any classical-like (hidden variables) theory would be nonlocal, a finding further amplified by related theorems, such as the Kochen–Specker theorem, all of which, in the present view, appear to support Bohr's argument.[26] While not going as far as rigorously proving the impossibility of local classical-like theories compatible with the data of quantum mechanics, Bohr found that it is possible to interpret quantum mechanics (cum the data it considers) locally through the epistemology discussed in this article. In other words, the question of locality (or of course completeness) of quantum mechanics rests or, at least, significantly depends on whether one can or cannot interpret it in a nonrealist manner. Bohr's complementarity answers this question in the affirmative, since it prohibits any attribution of any properties to quantum objects, even a single classical-like conjugate variable (which appears to be necessary for locality), and even when the measurement is performed. Thus, complementarity offers a local and nonrealist interpretation of quantum mechanics as a complete theory. The argument, accordingly, avoids the alternative, argued for by Einstein (under the epistemologically realist conditions of completeness), between quantum mechanics as a local but incomplete theory and a nonlocal but complete theory.

EPR base their argument on the following criterion of physical reality, retained (with relatively minor nuances) throughout Einstein's arguments: "*If, without in any way disturbing a system, we can predict with certainty (i.e., with the probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity*" (*QTM*, p. 138). It may appear that this criterion applies in quantum mechanics. The reasons for this apparent applicability are as follows. In view of uncertainty relations, it is only a joint simultaneous

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[26] I must bypass the debates concerning Bell's theorems and related findings, specifically as regards how tight these arguments are ultimately. The subject has generated an immense body of literature, reflecting a virtually uncontainable multitude of views. The view just expressed may be argued to be consistent with that of a significant majority of commentators. See, for example, Mermin's "Spooky Action at a Distance" and other essays on the subject collected in *Boojums All the Way Through* (Ref. 1), or, with a different valuation, most of Bell's articles on the subject in *Speakable and Unspeakable in Quantum Mechanics* (Ref. 6).

measurement, determination, and prediction (these, as will be seen, must be carefully distinguished in turn) of two variables involved in the quantum-mechanical physical description that is impossible. Accordingly, a measurement, a determination, or a prediction of the value of a single variable is possible, with any degree of precision (within the capacity of our measuring instruments, while uncertainty relations are not affected by this capacity). This claim covers the EPR experiment as well, even though it deals with the measurements, determinations, and predictions concerning physical variables *associated with* two spatially separated quantum objects that have previously been in interaction.[27] The nature of this association is, however, a different matter, as must be apparent from the preceding discussion. Specifically the question is whether these variables pertain to quantum objects themselves or to the measuring instruments impacted by quantum objects, which alternatives define the views of Einstein and of Bohr

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[27] As I have explained, there is always a nonzero probability that our attempts to verify such predictions (or indeed our attempts to make the measurements necessary to make these predictions) will not encounter the objects in question, for example, the second object of an EPR pair (or the first after the initial preparation of the pair). It is not that the formulas for the wave function used by EPR do not give us the probability equal to unity for the predictions in question. They evidently do, as Bohr stresses from the outset of his reply. It is, however, the specific features of EPR's thought experiment, including the wave function that they consider and a possible realization of it as an actual experiment, that involve a certain set of idealizations that must be carefully considered and taken into account in this and other respects. These features and idealizations have been subjects of much discussion and debate, and they were not missed by Bohr, as his discussion of EPR's wave function indicates (*QTM*, p. 149, Note). Cf. also Mermin's argument concerning the statistical aspects of the EPR correlations and the actual vs. idealized experimental data involved in "Can You Help Your Team Tonight by Watching on TV?" (*Boojums All the Way Through*, Ref. 1). I shall by and large bypass these statistical complications here. I would argue, however, that they help Bohr more than Einstein, especially given that in Bohr's view the mathematical formalism of quantum mechanics does not describe the physical behavior of either quantum objects or measuring instruments, but only provides an "algorithm" (the term sometimes used by Bohr) for statistical predictions concerning certain experimental events. Einstein admitted that the statistical considerations affect his argumentation, including as concerns the possible nonlocality (rather than only completeness) of quantum mechanics. What he did not appear to accept or possibly even consider is Bohr's argument that, in spite and even because of its statistical nature, quantum mechanics could be seen as a complete physical theory of individual phenomena rather than of statistical ensembles of phenomena (unless of course one needs do deal specifically such ensembles, as in quantum statistics). According to this argument, any analysis of each individual phenomenon reaching beyond its statistical nature by providing a causal and realist explanation of it is "*in principle* excluded" (*PWNB* 2, p. 62). These considerations do not of course imply that one could easily dispense with Einstein's arguments, which, as Bohr clearly saw, require a thorough response. Indeed these considerations are necessary for such a response. The question could only be whether they are indeed sufficient for it.

here, Bohr's interpretation of quantum mechanics as complementarity (or, at least, the present interpretation of Bohr's interpretation) allows one to associate with it a certain mystery, this mystery is a mystery without mysticism. I shall now outline my reasons for this argument.

If there could be a single statement that defines Bohr's argument concerning the epistemology of complementarity, it is the one made by Bohr in his "Discussion with Einstein on Epistemological Problems in Atomic Physics." This statement also captures the essence of the Bohr–Einstein debate, including in their exchanges concerning the EPR experiment. Einstein ultimately rejected Bohr's argumentation as "contrary to [his] scientific instinct," even though he saw it as "logically possible without contradiction" (*PWNB* 2, p. 61). Bohr's statement defines his argument as "aiming to show that, in quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded" (*PWNB* 2, pp. 61–62; Bohr's emphasis). The statement requires further explication, especially, first, as concerns Bohr's concept of physical phenomenon as applicable in quantum theory and, second, as concerns the actual limits beyond which such an analysis is *"in principle* excluded." I shall offer this explication below, stating for the moment the essential points that enable Bohr to address both concerns. Bohr's concept of phenomenon is defined by the irreducible role of measuring instruments in quantum mechanics. This irreducibility entails the impossibility of meaningfully considering quantum objects apart from the effects of these interactions upon measuring instruments. An analysis of anything beyond these effects becomes *"in principle* excluded." Bohr further argues that the limit in question is rigorously specifiable by virtue of the fact that, at least in this interpretation, any physical analysis of quantum phenomena is restricted to the area where classical and quantum mechanics give the same predictions (*QTM*, p. 150). This argument may also be seen as giving the proper meaning to Bohr's correspondence principle, at least as the latter is understood in his later works.

Thus, quantum mechanics as complementarity may indeed be seen as containing an essential mystery. This mystery is defined by the fact that complementarity places beyond the limits of quantum mechanics something essentially responsible for all observable phenomena in question in it. In particular, it places beyond these limits quantum objects and processes or what we infer or, as I shall explain presently, theorize or "idealize" as such on the basis of the data in question. In other words, complementarity leaves the ultimate objects it considers beyond any explanation, specifically in terms of an underlying space-time physical description of the kind we use in classical physics. Ultimately, it leaves these objects beyond any

respectively. Although Bohr, using EPR's language, does speak of "particles" in his reply, he also indicates that it is more appropriate to speak of "variables involved in the quantum-mechanical physical description" (*QTM*, pp. 144 and 145), which is to say, variables describing, in terms of classical physics, the behavior of certain parts of measuring instruments.[28] In any event, in the EPR case predictions concerning the variables involved do indeed take place without "disturbing" a quantum system by performing a measurement upon it. Bohr speaks more cautiously of not "interfering" with this system, since in his interpretation there is no classical-like or otherwise specifiable undisturbed configuration or properties that are then disturbed in the process. Such predictions are indeed possible for (this remains crucial) *a single variable* involved in certain quantum-mechanical situations, such as those of the EPR type. These predictions can be obtained by means of performing measurements on other systems that have previously been in an interaction with the system under investigation but are spatially separated from the latter at the time of measurement.

The fact of this previous interaction diminishes the difference between the EPR case and other quantum-mechanical predictions. As Bohr observes, the EPR conditions in effect apply to all quantum-mechanical predictions. In any quantum measurement, we can *predict* either the position or the momentum of a "particle," which is, crucially, not the same as *ascertain*, as against EPR's criterion of reality. That is, we can predict the value

[28] EPR's language of particles and, hence, of quantum objects themselves is essential to their argumentation. It does not always help Bohr, however, and sometimes leads him to statements that are, technically, inconsistent with his argument, specifically in potentially suggesting that physical properties, such as position and momentum, could apply to quantum objects themselves. The first part of his discussion of the EPR experiment in terms of the double-slit experiment, in general a weaker part of Bohr's reply, especially suffers in this respect (*QTM*, p. 149). It is possible that at this juncture (and other points in question) he is presenting the situation from EPR's viewpoint rather than his own. Even if such is the case, however, these statements require more precision, whether as concerns this difference or in general, and need to be modified in accordance Bohr's epistemology as here considered. These problems make Bohr's reply more vulnerable to criticism, sometimes justified, although rarely sufficiently attentive to Bohr's overall argument. Bohr was never altogether satisfied with his reply himself, although, as will be seen, he thought (rightly, I think) that the complexities of his epistemology were also responsible for the difficulties he faced in writing it. Most of these problems were straightened out in Bohr's subsequent writings, beginning with the Warsaw lecture of 1938, where he rigorously defines his concept of phenomenon, which is especially crucial in this context. These writings refine the argument of his reply to EPR and complementarity itself, which is why I use them throughout this article. Complementarity was a lifetime's work, as Bohr said on many occasions, and it would be difficult to expect otherwise, given what is at stake in it. That said, however, my aim here is not a defense of Bohr's reply to EPR or even his argument for complementarity, but instead an attempt to assess what they have to offer to our understanding of quantum mechanics and of the nature of scientific knowledge and knowledge in general.

of a corresponding variable pertaining to a certain part of the measuring instruments involved, *after* a preceding measurement took place and on the basis of this measurement. Hence we can do so without interfering with the quantum object under investigation and without assuming that we can define either quantity independently of measurement (*PWNB* 2, p. 57). The object and those (quantum) parts of the measuring instruments that interacted with it become entangled in the EPR way (*PWNB* 2, p. 60), analogously to the way the EPR objects are. In the EPR situation, which involves two particles, rather than a particle and a measuring apparatus, we have a slightly more complicated, but not fundamentally different, case, as Bohr points out (*QTM*, pp. 149–48; in this order).

Mermin elegantly relates the EPR experiment to his argument (based on the Hilbert space formalism of quantum mechanics and the mathematical notion of state vector there) that *"the quantum state of a complex system is nothing more that a concise encapsulation of the correlations among its subsystems"* ("What Is Quantum Mechanics Trying to Tell Us?" Ref. 4, p. 756). Mermin's argument, however, also draws our attention to the double difficulty of the situation. The first is the difficulty and, in Bohr's interpretation, the impossibility, of unambiguously referring to physical attributes of quantum objects, considered apart from their interaction with measuring instruments. This, accordingly, includes the very notion of (physical) "state" or ascertaining whether the two entangled objects of the EPR pair should be considered (if viewed independently) to be in the same or two separate *physical states*. On Bohr's view, the two objects in question must be seen as spatially separated. That is, we must consider as spatially separated the two situations of measurement in question, to which and only to which space-time considerations could now be properly applied, but apart from which quantum objects cannot be unambiguously considered. Or, in the language adopted here, they cannot be unambiguously considered apart from the effects of the interaction between quantum objects and the measuring instruments upon those instruments. By contrast, the *independent existence* of quantum objects as *inconceivable objects* could be ascertained, including when they are considered as spatially separated from each other. Rigorously, it may, again, be necessary to speak of two independent, spatially separate physical "objects" in nature, idealized as inconceivable by complementarity. The fact that they may be idealized otherwise does not affect the present argument, which only depends on the fact that an interpretation of this type and the idealization it uses are possible. It is this delicate conceptual handling that assures the locality of quantum mechanics (or the data in question), including in the EPR situation, in Bohr's interpretation. The second difficulty that I am referring to is, then, that of this conceptual delicacy, including the adjustments

pertaining to the statistical aspects of the situation, which are also necessary for establishing the rigorous physical meaning of Mermin's statement just cited. In commenting on this difficulty, as manifest in his reply to EPR, Bohr said in "Discussion with Einstein": "Rereading these passages, I am deeply aware of the inefficiency of expression which must have made it very difficult to appreciate the trend of the argumentation aiming to bring out the essential ambiguity involved in a reference to physical attributes of objects when dealing with phenomena where no sharp distinction can be made between the behavior of the objects themselves and their interaction with the measuring instruments" (*PWNB* 2, p. 61).

Once one follows this trend, however, the EPR situation appears in a different light. In Bohr's view, predictions (limited by uncertainty relations) concerning a given quantum object and the measuring instruments involved are possible on the basis of measurements performed on another quantum object that has previously been in an interaction with the first object, but, at the time of measurement, is in a region spatially separated from the latter. Hence, at the time of determination in question, there is no physical interaction either between the two quantum objects in question or between any measuring apparatus and the second object. This fact may suggest that the situation involves some nonlocal connections, a "spooky action at a distance." But, Bohr argues, such connections (of a physical nature) are not in fact inherent in the circumstances of measurement just described. He saw the argument to the contrary as correlative to EPR's criterion of reality, which he did not view as necessarily applicable in quantum mechanics and which EPR, by contrast, appear to have seen either as applicable to quantum mechanics or, else, as necessary for the completeness of a given physical theory. Accordingly, if EPR's criterion were applicable, quantum mechanics could indeed be argued to be either incomplete or nonlocal. I shall now sketch why such is the case.

The physical situation, regardless of interpretation or at least as agreed upon by EPR and Bohr, is as follows (again, leaving aside certain statistical qualifications indicated earlier). After the EPR pair is properly prepared, a measurement of the value of one of the two complementary variables, say, position, *associated* with the first object of the pair and the mathematical formalism of quantum mechanics allow one to *predict* the exact value of the position variable *associated* with the second (spatially separated) object without physically interfering with it. The main question that defines the debate is, I argue, that of the nature of this association of physical variables with quantum objects in quantum mechanics, specifically whether one can, as EPR appear to do, or cannot ascribe physical variables to quantum objects or, conforming to EPR's terms, relate them to "elements of reality" at the quantum level. Bohr argues that one does not need and

might not be able to do so, primarily in view of locality considerations. This question, accordingly, inevitably involves interpretation.

Given the possibility of the EPR predictions, EPR's criterion of physical reality and an interpretation or a set of interpretations of the situation this criterion implies (specifically, again, by virtue of attributing, as elements of reality, physical properties to quantum objects) would allow one to *determine* the position value in question without a measurement performed on the second object. They would, thus, also allow one, in the first place, to properly *define* the position variable itself for this object (a qualification that is, as we have seen, important for Bohr). Then, a measurement of the value of the other complementary variable, momentum, which is possible to perform since we are *not* measuring the position at this point, would allow us to *determine* its value and, again, to properly *define* the variable itself for the same object. Hence, one would indeed be able to determine the simultaneous values of both complementary variables for a quantum object. Since such a determination is in conflict with uncertainty relations (which are a rigorous consequence of quantum mechanical formalism), quantum mechanics could be argued to be either incomplete or, if complete, nonlocal.

Given this argument, one can indeed appreciate the significance of the difference, suspended by EPR's criterion of reality, between *determining* (unambiguously ascertaining) a value of any physical variable in question and *predicting* such a value for Bohr's interpretation of quantum mechanics as complementarity and for his understanding of the EPR experiment based on this interpretation.[29] As explained earlier, according to this interpretation, only an actual measurement or a *registered* phenomenon allows one to *determine* a value of and, in the first place, unambiguously *define* any physical variable considered in quantum mechanics. As *physical* variables (the way they are linked to the mathematical formalism of quantum mechanics is a different matter), all such variables now pertain strictly to the physics of the measuring instruments involved impacted by

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[29] Bohr's discussion of the EPR situation in terms of "a rigid diaphragm with two parallel slits," cited above, may cause confusion concerning the difference between a prediction of the value of a given variable, which does not require an actual measuring of this variable, and its determination as a variable, which does require an actual measurement (*QTM*, p. 149). In this particular arrangement, however, this difference is indeed less essential, since it allows one to see all predicted as well as measured values of the positions in question as determined by the positions of the slits. As I said, however, this discussion is a weaker part of Bohr's argument.

their interaction with quantum objects and, as such, are the standard variables of classical mechanics. The determination of the value of and the definition of the complementary variables, such as position and momentum, at any given point requires two incompatible, mutually exclusive experimental arrangements, which situation, as we have seen, also gives the physical meaning of uncertainty relations in Bohr's interpretation. This circumstance makes EPR predictions concerning the outcome of a position or, conversely, momentum measurement associated with the second object of the EPR pair mutually exclusive in turn. Such is the case because each of these predictions is uniquely defined by a corresponding position or, conversely, momentum measurement associated with the first object of the pair, and these two measurements are mutually exclusive by virtue of involving two complementary variables. Now, suppose that we have made a position measurement associated with the first object, which enabled a corresponding prediction for the second object. In order to verify this prediction we must perform a position measurement associated with the second object. Doing this, however, would automatically preclude us from simultaneously determining the value of the complementary variable, momentum, and, again, defining it as a variable that could be associated with that object, since this determination would require a measuring arrangement mutually exclusive with the one used in the position measurement. Importantly, however, we can make such an alternative arrangement and perform the corresponding measurement instead of making an arrangement for and performing the position measurement. If we do, we will properly determine the value of momentum and define it as a variable, but only, unavoidably, at the cost of precluding the possibility of *determining* the value of the position variable or of defining it as a variable, even though such a value was properly *predicted* by the initial measurement upon the first object of the EPR pair. It follows that in quantum mechanics the fact that "without in any way disturbing a system, we can predict with certainty (i.e., with the probability equal to unity) the value of a physical quantity" does not automatically imply, as EPR's criterion would require, that "there exists an element of physical reality corresponding to this physical quantity." At least it does not do so if one follows Bohr's interpretation of the situation based on his concept of phenomenon.

One can now see why in Bohr's view EPR's criterion acquires an "essential ambiguity when it is applied to the actual problems" of quantum mechanics, those of the EPR experiment included, and is, it follows from the preceding discussion in fact inapplicable to quantum mechanics in Bohr's interpretation (*QTM*, p. 146). For, once this interpretation is in place, one can no longer argue, in the way EPR do, that, on the basis of one EPR type prediction and one actual measurement, one could determine

the values of and properly define both complementary variables pertaining to the corresponding parts of the measuring arrangement associated with the second object of the EPR pair. Such a determination would of course still be in conflict with uncertainty relations (which now apply to the physical variables pertaining to measuring instruments) and, thus, would still allow one to argue for the incompleteness of quantum mechanics. It is the EPR type of reasoning itself, as outlined above, that becomes no longer possible. There is no single arrangement and thus no single situation of measurement to which one could apply uncertainty relations in this way, since they now relate to two mutually exclusive measuring arrangements and situations of measurement. Nor, accordingly, can one combine, as EPR want, a *prediction* concerning, say, the possible position of a trace left by a collision between the second quantum object of the EPR pair and a photographic plate with an actual momentum *measurement*, say, a change in momentum of a certain part of the measuring arrangement considered under the impact of this object. As explained above, EPR could appeal to this type of combination only because the prediction and measurement they consider concerned the respective complementary variables ascribed to the *same* (quantum) object or, again, the corresponding elements of reality pertaining to the same object. The analogous (but, it follows, not identical) *prediction* and *measurement* involved in Bohr's understanding of the situation, cannot, even in principle, relate to the same phenomena in Bohr's sense and, thus, to a single physical object, classical or quantum. Instead they relate to two mutually exclusive phenomena and the two mutually exclusive classical physical objects corresponding to them. The prediction and the measurement in question become mutually exclusive in turn, along with, and correlatively to, the position and momentum measurements on the first object of the EPR pair and the two corresponding predictions concerning the second object, or two subsequent measurements that relate to the second object and verify such predictions.

To properly consider (and in the process indeed inevitably to correlate) the measurements and predictions involved would require a reenactment of the whole experiment using another EPR pair, since, once any measurement on the first object of the initial pair is performed, this object is no longer available for further EPR measurements. This fact has momentous implications (including as concerns the irreducibly statistical nature of quantum-mechanical predictions) extending well beyond Bohr. Their proper context is that of Bell's theorem and related findings, extending to Mermin's "correlations without correlata." For the moment, the preceding argument makes clear why, in his discussions with Einstein, Bohr repeatedly stressed that "we must realize that in the problem[s] in question we are not dealing with a *single* specified experimental arrangement, but are

referring to two mutually exclusive arrangements (*PWNB* 2, p. 57). To some degree, EPR realize the complications just sketched when they say, in closing their article, that "one would not arrive to our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality *only when they can be simultaneously measured or predicted*" (*QTM*, p. 141; EPR's emphasis). They, however, see this possibility as implying nonlocality, a view carried over in and, again, central to Einstein's subsequent arguments. The implication, it follows from the preceding analysis, is logical, given the epistemology of their argument. Bohr's interpretation avoids nonlocality through a fundamentally different epistemology, namely, by virtue of suspending the possibility of considering physical attributes of quantum objects as "elements of reality" and thus by epistemologically recasting the EPR situation and, as I have explained, complementarity itself in terms of phenomena in his new sense.

With the preceding discussion in mind, one can summarize this recasting as follows. As I have stressed from the outset, in Bohr's interpretation one cannot unambiguously ascribe, as Einstein wanted to do, even a *single* physical attribute to a quantum object considered independently of measurement and hence of our interaction with it by means of observational devices. Any independent consideration of quantum objects apart from measuring instruments, breaking the wholeness of Bohr's phenomena, is impossible. He makes this point at length in his reply, and he states it at least three times in "Discussion with Einstein" (*PWNB* 2, pp. 39–40, 52, and 61). This separation is impossible even though we can predict the outcome of such measurements on the basis of earlier measurements performed on a given object or on other objects that have previously been in interaction with it. Hence, such measurements would not directly relate to this object as such at the time of determination of the variables concerned, which is crucial to Einstein's argument. Accordingly, Bohr argues that "under these circumstances an essential element of ambiguity is involved in ascribing [any] conventional physical attributes to quantum objects [themselves]," even a single independent property to quantum objects, let alone both complementary ones (*PWNB* 2, p. 40). Nor, as we have seen, can we ever unambiguously define both such variables for any among the measuring instruments involved. Combining these two prohibitions enables Bohr to recast the EPR experiment, along the lines of the preceding discussion, and to argue that "a criterion like that proposed by [EPR and inherent in all of Einstein's argument] contains... an essential ambiguity when it is applied to the actual problems with which we are here concerned" (*QTM*, p. 146). This is the same ambiguity.

The crucial role of interpretation in assessing Bohr's argument concerning the EPR experiment and quantum mechanics now becomes

apparent. EPR's argument does demonstrate that we can (again, with qualifications concerning the statistical considerations involved) predict either one or the other of the two complementary variables (but, as EPR also agree, never both simultaneously) for the measurement pertaining to the second quantum object of the EPR pair, or in any quantum mechanical prediction. However, there exists an interpretation in which we cannot ascribe any such variables to this object or to any quantum object itself or to anything in nature that quantum objects theoretically idealize. All variables or "elements of reality" considered are now associated strictly with certain classically described parts of measuring instruments. The possibility of this interpretation was not considered in EPR's initial argument (concerning the incompleteness of quantum mechanics). The existence of this interpretation, however, means that this impossibility of ascription of physical properties to quantum objects or to anything in nature at that level at least *may be* a fact of nature. That such *may be* the case (rather than a stronger claim that such *is* the case) is, however, sufficient to properly respond to the EPR argument and the related argument by Einstein, even as concerns locality, let alone completeness, of quantum mechanics, unless one requires a given theory to conform to EPR's and Einstein's conception in order to be complete. EPR do claim an incompleteness of quantum mechanics, or either incompleteness or nonlocality, a view, again, adopted in most of Einstein's related arguments.

As concerns completeness, if one cannot definitively prove that we actually can ascribe both complementary variables (or "elements of reality" corresponding to them) to quantum objects or even to the measuring instruments involved, one cannot argue for the incompleteness of quantum theory within its proper limits (as a nonrelativistic quantum theory). Neither EPR nor Einstein elsewhere prove this, and, as I argue here, they do not even prove that one could ascribe even a single such variable to a given quantum object (*PWNB* 2, p. 57). Accordingly, one could at most say that quantum mechanics, as a theory accounting for the data in question, may be as complete as such a theory can be, given the character of these data (Bohr's view), or that it may eventually prove to be incomplete.

As concerns locality, Bohr agrees that quantum mechanics allows for and enables certain ("at-a-distance") predictions and by so doing rigorously accounts for quantum correlations, quantum entanglement included. At the same time, his particular interpretation avoids nonlocality, even though the correlation part of the EPR-type argument can be adjusted so as to refer only to the outcomes of measurements rather than to quantum objects. In other words, while entangled quantum-mechanical events do exist, it only means (a) that particular forms of experimental detection (phenomena or effects) are possible, and (b) that the quantum-mechanical

formalism allows us to predict such effects.[30] Accordingly, nonlocality, which is entailed neither by (a) nor by (b), need not follow, unless it is independently derived from either the formalism or the data itself, which does not appear to be the case thus far, although there are claims to that effect.[31] One can of course continue to search for an alternative and, on Einstein's (realist) view, "more complete," conception. That is, one might seek either another interpretation of quantum mechanics or another theory accounting for the data in question and also retaining locality, something that, for example, Bohmian theories (which are, on other respects, such alternative accounts) expressly fail to do.

Obviously, there remains the fact that we make predictions concerning certain future measurements pertaining to the second quantum object of the EPR pair. That is, we do, in such situations, make predictions concerning spatially separated events by interfering, substantially (by physically engaging with measuring devices) and unsubstantially (by making meaningful statements or predictions), with the local measuring system associated with the first quantum object. This interference enables us to unambiguously define either one or another complementary variable (but never both simultaneously) associated, via a corresponding measurement or phenomenon, with the second quantum object. A measuring system of the same type may be introduced for the second object and then correlated with the measurement system associated with the first object, once this second system is being in turn interfered with, for example, in order to measure the value of a given variable pertaining to it. The same type of correlations is also involved in Bell's theorem and its refinements, and in the discussions surrounding these findings, more recently around Greenberger–Horne–Zeilinger and Lucien Hardy types of experiments, which are particularly striking versions of the EPR type of experiments. One can, however, accommodate them to the argument, given here, that entanglement and locality can be both maintained and understood within the epistemology under discussion. But then entanglement is only part of what we cannot conceive of in quantum theory, beginning with the double-slit experiment. How do electrons "know," individually or collectively, that

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[30] The statistical character of both propositions, (a) and (b), remains irreducible. This, to reiterate, need not mean that quantum mechanics is not a viable theory of individual events or phenomena, as Einstein thought, but only that we may have encountered certain limits upon how far our analysis of individual events or phenomena could possibly reach (*PWNB* 2, pp. 61–62). In this case, these limits include the fact that in quantum mechanics (at least as complementarity) individual events are not subject to law in the way they are in classical mechanics, thus indeed making quantum mechanics the probabilistic theory of individual rather than only collective events.

[31] Cf. again, the Stapp–Mermin exchange cited earlier in Note 19 (Ref. 10 and Ref. 11).

both slits are open to arrange themselves in the interference-like pattern? Bohr, accordingly, saw Einstein's arguments not as proving the incompleteness or nonlocality of quantum mechanics but instead as revealing, with great subtlety and power, how far quantum physics may depart from classical physical and philosophical ideas, and from the possibility of pictorial visualization of physical processes (*PWNB* 2, p. 59).

The type of *interpretation* of quantum mechanics considered here prohibits doing or knowing in principle what *quantum mechanics itself*, as a physical theory, cannot, it appears, do or know in practice. But it delivers plenty of what can be known and different ways in which knowledge can be obtained and processed, for example, through quantum entanglement, which, among other things, enables the whole field of quantum cryptography and computing. That it entails the impossibility of any knowledge or conception concerning the ultimate constitution of nature has a positive role to play, since this impossibility enables knowledge that would not be possible otherwise.

4. CONCLUSION: THE UN-UNWEAVABLE RAINBOW

As I am also an English professor, I would like to close with poetry, which, it appears, most physicists prefer to philosophy, in this case the poetry of John Keats, who famously wrote in Lamia:

> ...Do not all charms fly
> At the mere touch of cold philosophy?
> There was an awful rainbow once in heaven:
> We know her woof, her texture; she is given
> In the dull catalogue of common things.
> Philosophy will clip an Angel's wings,
> Conquer all mysteries by rule and line,
> Empty the haunted air, and gnomed mine—
> Unweave a rainbow...

(Lamia, Part II, ll. 229–238.)

Here, as Keats has both Newton and Descartes in mind, philosophy is also natural philosophy or what we now call science, specifically physics. Keats may be right about fleeing charms. The remainder of the passage, however, has proven to be, at least for now, among the least prophetic of Keats's insights. Keats, were he alive, might have delighted in this failure, even though he might not want "cold philosophy" to ever arrive, however slowly, where poetry gets so quickly and with so much charm on its wings. The ultimate unweaving of the rainbow does not appear to be possible. The rainbow is ultimately un-unweavable. This is what physics and its cold

possible conception, including that of "object" or "quantum." Accordingly, the quotation marks around these terms or any other terms referring to "quantum objects" are presupposed throughout this article. While, thus, forming physically an irreducible part of and enabling each phenomenon in question, quantum objects and processes never physically manifest themselves as such. All knowledge and predictions are now restricted to the (manifest) effects of the interaction between them and measuring instruments upon those instruments. Each such effect is a classical physical object or is idealized as such: it is experimentally observed in the way we observe physical objects in classical physics and is describable (and, in this interpretation, is always described) by means of classical physics.[5] It is properly predictable, however, only by means of quantum mechanics.

Indeed, it is an obvious consequence of this epistemology that we can only relate to quantum objects in an irreducibly indirect way through the effects of their interaction with measuring instruments upon these instruments and, via this interaction, upon the classical world. How could we possibly do it otherwise, given that they are theorized or, again, idealized as something whose nature, properties, and behavior are beyond any possible knowledge or conception? Reciprocally, such objects are conceived of, conceived of as inconceivable, on the basis of such effects so as to enable the logical and conceptual consistency (and, as will be seen, locality) of the overall scheme. It is especially the existence of certain particular, mutually exclusive or, in Bohr's terms, complementary, configurations of these effects that makes this type of epistemology possible. Bohr introduced the term complementarity in order to define such effects: mutually exclusive and, hence, never applicable simultaneously, and yet all necessary for a comprehensive theoretical framework accounting for the situation in question. Eventually complementarity came to designate Bohr's overall interpretation of quantum mechanics.

It follows that in Bohr's interpretation or, again, at least in the present interpretation of Bohr's interpretation, the mathematical formalism of quantum mechanics does not describe quantum objects and processes. These, importantly, include those quantum processes that are involved in the interaction between quantum objects and measuring instruments, which interaction is responsible for the emergence of the observable effects considered in quantum mechanics. Nor does quantum mechanics physically

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[5] It is true that observation is involved in the constitution of physical phenomena in classical physics as well. In this case, however, this constitution allows us to speak, at least in principle and by way of idealization, of physical objects as independent of observation and assign to them physical properties accordingly, which is no longer possible in quantum mechanics as complementarity.

philosophy appear to have revealed to us as they arrived to relativity and quantum physics, the ultimate theory (at least for now) of light. Light cannot ultimately be catalogued in terms of common or any other things, that is, reduced to the known, simple constituents, for example, of the kind that the Democritean atomism (or classical optics, linear or wave) would envision. According to the view presented here, the ultimate nature of light cannot even be envisioned. Its ultimate mystery, here seen as mystery without mysticism, cannot be conquered by rule or line, which, however, does not prevent but instead enhances knowledge and makes it possible. It is the responsibility of "cold philosophy," part of its commitment to the maximal possible rigor, to *confront*, as both Einstein and Bohr did, this unknowable as, at least, a *possible* aspect of nature, even if one is reluctant, as Einstein was, to accept it as part of one's vision of the ultimate constitution of nature.

Quantum mechanics teaches us a tremendous lesson concerning the role of the unknowable in knowledge, which may be the ultimate meaning of the phrase "the epistemological lesson of quantum mechanics," often invoked by Bohr. In the twentieth and by now the twenty-first century we have moved into extraordinarily complex territories of both knowledge and the unknown or, ultimately, the unknowable, in mathematics and science or indeed in most human endeavors. The unknowable, however, especially once its mystery is, as in quantum mechanics, stripped of mysticism, still appears to us as a ghostly stranger, and we are reluctant to heed Hamlet's advice to Horatio upon the appearance of his father's ghost: "This is wondrous strange!/ And therefore as a stranger give it welcome./ There are more things in heaven and earth, Horatio/ Than are dreamt of in your philosophy." We are even more reluctant (Hamlet was too) to talk of such ghosts to others, even those in our own field, be it quantum mechanics, philosophy or literature, and perhaps especially when we talk to those whose knowledge and whose unknowable are elsewhere. If, however, to have an *expertise* is to reach the limits of both what is knowable and what is unknowable in one's field, to share our expertise is to offer others a sense of both of these limits. Perhaps, then, the epistemological lesson of quantum mechanics is also a lesson for the interconnections and interactions between the proverbial "two cultures," the sciences and the humanities, which are always more than two cultures, or more than two and less than one. Bohr must have thought so when he spoke of his "dream of great interconnections," perhaps only a dream, yet another dream of philosophy. In the same poem, also a poem about dreams, Keats says, "Real are the dreams of Gods" (*Lamia*, Part I, l. 126). Our dreams are rarely so lucky.

It is a very special pleasure to dedicate this article to David Mermin, one of the most penetrating, lucid, and eloquent commentators on quantum

mechanics and its mysteries and correlations. The article is a tribute both to his science and to his culture, his more than two cultures (never less than one). With unwavering generosity, he would always tell me and, to my knowledge, all his audiences, even in his sharpest criticism (a form of generosity, too) more about what he does not know than about what he does know, which is a lot. This is why one can learn so much from him. I certainly did, and I don't think I can ever repay him, for one thing, because I both know and don't know so much less. But I am always curious as to what else he does not know.

REFERENCES

1. N. David Mermin, *Boojums All The Way Through: Communicating Science in a Prosaic Age* (Cambridge University Press, Cambridge, 1990).
2. Niels Bohr, *The Philosophical Writings of Niels Bohr*, 3 vols. (Ox Bow Press, Woodbridge, CT, 1987).
3. John Archibald Wheeler and Wojciech Hubert Zurek, eds., *Quantum Theory and Measurement* (Princeton University Press, Princeton, 1983).
4. N. David Mermin, "What Is Quantum Mechanics Trying to Tell Us?" *Am. J. Phys.* **66**, 9, 753–67 (1998).
5. Carlo Rovelli, "'Incerto Tempore, Incertisque Loci': Can we compute the exact time at which a quantum measurement happens," *Found. Phys.* **28**, 7, 1031–43 (1998).
6. John Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, Cambridge, 1987).
7. Arkady Plotnitsky, "Reading Bohr: Complementarity, epistemology, entanglement, and decoherence," in *Decoherence and its Implications in Quantum Computation and Information Transfer*, Tony Gonis and Patrice E. A. Turchi, eds. (IOS Press, Amsterdam, 2001).
8. Ole Ulfbeck and Aage Bohr, "Genuine fortuitousness: Where did that click come from?" *Found. Phys.* **31**, 5, 575–774 (2001).
9. Arkady Plotnitsky, "Quantum atomicity and quantum information: Bohr, Heisenberg, and quantum mechanics as an information theory," in *Quantum Theory: Reconsideration of Foundations (Proceedings of the Conference, Växjö (Smaland), Sweden, 17–21 June, 2001)*, Andrei Khrennikov, ed. (Växjö University Press, Växjö, 2002).
10. Henry P. Stapp, "Nonlocal character of quantum theory," *Am. J. Phys.* **65**, 300–04 (1997).
11. N. David Mermin, "Nonlocal character of quantum theory?," *Am. J. Phys.* **66**, 920–24 (1998).
12. Henry Folse, "Niels Bohr's concept of reality," in *Symposium on the Foundations of Modern Physics 1987: The Copenhagen Interpretation 60 Years after the Como Lecture*, Pekka Lahti and Peter Mittelstaedt, eds. (World Scientific, Singapore, 1987), pp. 161–80.

describe these effects, which are described instead by means of classical physics, even though their totality is not accountable by classical means. The formalism of quantum mechanics does, however, enable excellent statistical predictions of these effects and, correlatively, of the observable complementary configurations. In short, in this view, quantum mechanics only *predicts* but does not *describe*. Classical physics, by contrast, does both within its proper scope. At least it does so according to most interpretations of it, including that used by Bohr in complementarity in order to *describe*, but, again, *not to predict*, observable effects in question in quantum mechanics. The latter, by contrast, predicts the appearance of these effects and of certain configurations of them but, at least as complementarity, does not describe the ultimate dynamics of their emergence. Quantum objects are part of and are fundamentally responsible for this indescribable, inconceivable dynamics. As I shall explain, however, in order to ensure the locality of the overall scheme, quantum objects must also be seen as existing independently, but in a manner that is inconceivable to us. Or, more accurately, something in nature that we idealize in this way must be seen as existing independently of our interaction with it.

As this last qualification indicates, the epistemological situation just outlined has a certain additional complexity, or may be given a further interpretation. This interpretation depends on or may be seen as correlative to how one views the status of complementarity itself as an interpretation of quantum mechanics. Specifically, the question is whether one sees it as *an* interpretation, one among other possible interpretations, or, conversely, as *the* interpretation of quantum mechanics and thus, assuming quantum mechanics itself is correct, also as a statement concerning the ultimate constitution of nature, even if only within the proper (nonrelativistic) scope of the theory. I shall in this article adopt the former, more cautious view. Bohr's position on this issue appears to be more ambivalent, although there are indications that he was at least inclined to a similar view.[6] In this type of view, as an interpretation of quantum mechanics, complementarity constructs a particular type of theoretical idealization, in which the ultimate objects of quantum mechanics are conceived of or idealized as ultimately inconceivable. This idealization does allow one to infer the existence of something in nature that is manifest in and is responsible for certain phenomena in the classical macro word but that is irreducibly beyond anything

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[6] Bohr's customary caution would in itself suggest that he would likely be so inclined. Consider, for example, the following formulation found in the abstract of his reply to EPR: "*a viewpoint* termed "complementarity" is explained from which quantum mechanical description of physical phenomena [in Bohr's sense] *would seem to fulfill*, within its scope, all rational demands for completeness" (*QTM*, p. 145; emphasis added).

we can experience or beyond anything we can possibly conceive of. By the same token, however, such inconceivable entities are seen as the ultimate objects of complementarity as a particular interpretation of quantum mechanics and *not* as objects of nature. Hence, I speak of idealization.[7] Whatever exists in nature that is responsible for the experimental data in question might, in this view, remain beyond even this idealization and may, accordingly, prove to be something else, either something nonclassical-like or something classical-like in character, or something altogether beyond this type of scheme. As such, it may be subject to alternative interpretations, either involving quantum mechanics or based on alternative accounts.

Complementarity of course makes no claim upon the ultimate constitution of nature (at least within the scope of quantum mechanics) already by virtue of the fact that this constitution is placed beyond any possible knowledge and conception. As *an* (rather than *the*) interpretation of quantum mechanics, however, it also allows for a different view of nature, different theories of the data in question, or different interpretations of quantum mechanics itself. Complementarity is, thus, defined by an epistemological double rupture, first, between itself and its ultimate objects, placed beyond the reach of the theory itself or any possible conception, and, second, between this scheme and a possible constitution of nature. As will be seen, the first rupture is the proper meaning of quantum discontinuity according to Bohr, in contrast to a classical particle-like, punctual discontinuity, with which quantum phenomena were associated in the wake of Planck's discovery and still often are. The second rupture defines the first rupture as a theoretical idealization and complementarity itself as *an* interpretation of quantum mechanics, thus conceivably leaving nature itself to an even greater mystery. This is not altogether surprising given what higher-level quantum theories appear to tell us. But, as we haven't heard their last or perhaps even the last word of quantum mechanics (there may not ever be such a last word), one cannot be sure. Nature might show itself less mysterious, more classical (if classical physics is indeed any less mysterious than quantum) at the next stage of our, it appears, interminably inconclusive encounter with it.

Quantum mechanics as complementarity is, thus, mysterious insofar as it enables excellent predictions (in general, of statistical nature) of the phenomena in question in it without explaining the ultimate underlying

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[7] As I have indicated, the *classical* description of measuring instruments and of the effects of the interactions between them and quantum objects must in turn be seen as an idealization. This idealization is, however, very different from that found in complementarity, since classical physics provides an idealized *description* of its objects, as opposed to idealizing them as indescribable in the way complementarity does.

mechanism of their emergence or without assuming the possibility of conceiving of such a mechanism. Hence, it functions, and does so very effectively, without an underlying mechanics of the kind used in classical physics.

It is by virtue of this character of quantum mechanics as a positive and effective science of nature, the character supported by complementarity, that its mystery is a mystery without mysticism. Quantum mechanics as complementarity suspends any possible description and, thus, both realism and causality at the level of the ultimate objects that it considers. Nevertheless, it is a rational physical theory, free from any "underlying mysticism foreign to the spirit of science," in the same sense that classical physics or relativity are, and certainly without presupposing some inaccessible mystical agency (for example, on one or another theological model), responsible for the situation in question in quantum mechanics. It conforms to all the standard disciplinary requirements defining modern mathematical sciences of nature, from Galileo on. It provides as rigorous theoretical and experimental knowledge as does classical physics, and it rigorously relates (for example, by means of uncertainty relations) what can and what cannot be known. It involves experimental verification, logical arguments, the mathematical character of the theory, and so forth. In short, it fulfills all the major requirements of modern physics and modern scientific inquiry in general, not the least insofar as it provides the pathway to the discovery of new physical laws, the primary business of all physics.

Indeed, according to Bohr, beyond being merely consistent with this possibility, complementarity enables quantum mechanics to do so. In other words, it does so not *in spite of* the fact that it suspends realism and causality at the ultimate level, but *because* it suspends them. The reason for this claim is that, as Bohr explains in his reply to EPR, "it is only the mutual exclusion of any two experimental procedures, permitting the unambiguous definition of complementary physical quantities" (which entails this suspension) that "*provides room* for new physical laws," the laws that quantum mechanics rigorously incorporates in its theoretical framework (*QTM*, p. 148; emphasis added). That is, complementarity and the suspension of reality and causality that it entails allow for the proper place of these laws and of quantum mechanics itself as a physical theory in physics as a modern mathematical science of nature. It is true, as Bohr notes on the same occasion, that "the coexistence of [these laws] with the basic principles of science [might at first sight appear irreconcilable]" (*QTM*, p. 148).[8] But in fact such is not the case. Complementarity makes this coexistence possible, even if at the cost, to some (Einstein and Schrödinger, among them) unacceptable, of reconceiving the nature of physical phenomena and of our way

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[8] I slightly modify Bohr's (somewhat tortured) syntax. I do so with some trepidation but, I believe, without a loss to Bohr's meaning.

of rigorously treating them. "It is," Bohr concludes, "just this entirely new situation as regards the description of physical phenomena, that the notion of *complementarity* aims at characterizing" (*QTM*, p. 148).

The expression "correlations without correlata" of my title is due to Mermin and his argument, extending primarily from the EPR experiment, for what he calls "the Ithaca Interpretation of Quantum Mechanics." My concept of these correlations might be seen as correlative (with correlata) to Mermin's, even though it derives from Bohr's argument for the irreducible role of measuring instruments in quantum physics, from which Mermin wants to free his own interpretation (Ref. 4). In Bohr's view, all phenomena in question in quantum mechanics arise only in and are, thus, irreducibly determined by the interactions between quantum objects and measuring instruments. As I indicated earlier, Bohr defines the concept of phenomenon as applicable in quantum mechanics on the basis of these interactions, specifically in terms of their effects upon certain classically describable parts of measuring instruments. Bohr's definition of phenomenon also includes the specification of each arrangement, as defined by the particular character of a given measurement or prediction. According to Bohr, "in fact to measure the position of... [a particle] can mean nothing else than to establish a *correlation* between its behavior and some part of a measuring instrument rigidly fixed to the support which defines the space frame of reference" (*QTM*, pp. 149–48; in that order; emphasis added).

This statement as such applies in both classical and quantum physics. In classical physics, however, such a correlation allows one to ascertain, again, at least in principle and by way of idealization, the actual position of the measured objects as well as that of the measuring instrument involved. Thus one can also ascertain the two (classical) correlata of this correlation. In fact, in classical mechanics it is always possible, at least in principle, to ascertain simultaneously the values of all four variables or four correlata, both the position and the momentum of the object considered, and both the position and the momentum of the corresponding part of the measuring apparatus involved. That the determinate values of both conjugate variables can, first, be assumed and, second, be in principle determined by measurement makes classical mechanics both ontologically causal and epistemologically deterministic. It is ontologically causal insofar as the state of a classical system at a given point determines its state at all other points, and it is epistemologically deterministic insofar as we can, in principle, make definitive predictions concerning the behavior of the system.[9] By the same token, it can also be and usually is interpreted as realist.

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[9] The terms causality and determinism will be understood in this article in accordance with this definition. They may be and have been defined otherwise.

By contrast, in quantum mechanics (as complementarity), such a correlation would only allow one to ascertain the position of the classically describable part of the measuring arrangement, say, that defined by a slit in the double-slit experiment, or, in the case of a momentum measurement, a change in momentum of another such part. It does not, however, allow one to ascertain the position of the particle itself, which is why Bohr speaks of the particle's *behavior* and *not position*. It is of course impossible to ascertain the values of or even define both complementary variables for the relevant parts of the apparatus in the same arrangement, by virtue of uncertainty relations. The latter, in this view, only apply to the classical variables of certain parts of measuring instruments impacted by their interactions with quantum objects. Nor, rigorously, can one speak of "particles" either, any more than one could speak of "waves." Bohr's usage of both terms is provisional, since, on his view, rigorously these terms must be seen as altogether *abstracted* from any physical behavior at the quantum level.[10] Nor could one ascertain or even attribute the position or any other physical properties to those parts of the measuring instruments involved that have interacted with the quantum object considered, the quantum tip of the quantum-classical (quantum at one end, classical at the other) iceberg, forming the slit through which the "particle" passed.[11] It is also impossible to ascertain or assign the time of this quantum interaction, or ultimately to attribute temporality to it any more than spatiality.[12] It is worth stressing that, while this epistemology is part of Bohr's interpretation of uncertainty relations, the impossibility of, at any point, ascertaining the position or momentum of a given quantum object is general, rather than applicable only in the context of uncertainty relations. Thus, if one can speak of "measurement" at all, rather than correlation, in these circumstances,

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[10] The character of this abstraction is different in the case of waves vs. particles. Waves are seen, along the lines of Max Born's interpretation, as *mathematical* abstractions allowing one to map the probability distributions governing quantum-mechanical predictions. By contrast, particle-like phenomena, such as dots left on the screen in the double-slit experiment, are defined by the *physical* effects of the interactions between quantum objects and measuring instruments. These effects are similar to those produced by particle-like objects upon measuring instruments in classical physics. As I shall explain below, in this view, all wave-like *physical* phenomena in question in quantum mechanics are discrete collectivities of particle-like individual phenomena. Bohr's term phenomenon rigorously applies only to such individual phenomena. It is worth adding that "particle" and "wave" are the concepts of classical physics and, thus, of a particular idealization of the space-time behavior of physical objects.

[11] The situation is equivalent to that of Heisenberg's "microscope" thought experiment (in Bohr's understanding of it).

[12] Cf. Carlo Rovelli, "'Incerto Tempore, Incertisque Loci': Can We Compute the Exact Time at Which a Quantum Measurement Happens," Ref. 5. Rovelli, however, attributes temporality to the processes occurring at the quantum level.