

Complementarity — Did Bohr miss the boat?

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“I have been unable to achieve a sharp formulation of Bohr’s principle of complementarity despite much effort I have expended on it”

[A. Einstein, 1949, p. 674]

“While imagining that I understand the position of Einstein, as regards the EPR correlations, I have very little understanding of his principal opponent, Bohr.”

[J.S. Bell, 1987, p. 155]

“Neils Bohr brain-washed a generation of physicists into believing that the problem had been solved fifty years ago.”

[Gell-Mann, 1979, p. 29]

“Every sentence I say must be understood not as an affirmation, but as a question.”

[Bohr in Jammer, 1966, p. 175]

“Bohr’s interpretation has never been fully clarified. It needs an interpretation itself, and only that will be its defense.”

[Von Weizacker, 1970, p. 25]

1.0 Introduction

Following through Weizacker’s suggestion, I shall offer a *constructive* reading of Bohr’s interpretation.

In part-1, I shall outline the principle details of Bohr’s interpretation. Bohr’s basic interpretive insight is ‘*quantum inseparability*’. Complementarity of phenomena and a “revision to our attitude towards physical explanation” then follow. *Together*, these can be said to constitute Bohr’s general viewpoint of ‘complementarity’. Bohr does not quite clearly spell out the content of these three ideas; I do.

In erecting the framework of complementarity, Bohr’s main goal is to avoid all direct contradictions between our everyday (or classical) space-time intuitions (which does form the basis of current realist, experimental praxis) and the non-classical quantum formalism. This effort has two distinct parts: (i) to show there is no ontological wave-particle duality; and (ii) to justify the current realist, experimental praxis. In part-2, I show that Bohr’s inseparability hypothesis is

sufficient to account for (i), but not for (ii). To account for (ii) requires revising our ordinary modes of thinking, which Bohr ruled out (rather unnecessarily) as impossible. In this sense, Bohr “missed the boat.”

In part-3, I in fact show that ordinary thinking does feature a non-classical and quantum conception of “position” as a *relation*, from which Bohr’s inseparability hypothesis is logically deducible, and furthermore the current quasi-classical experimental realism can also be recovered. The difficult notion of *epistemic* complementarity that Bohr struggled with, turns out to be after all not necessary at achieve Bohr’s goals.

2.0 Principal Elements of Bohr’s Interpretation

Let us consider what Feynman has called the only mystery in quantum mechanics, the self-interference of the single photon in the standard two-slit experiment. When detectors are placed close to the two slits, only one of them fires in any single observation; hence physicists talk of each individual photon as “going through” a slit (particle behavior); however, *where* in the far off photographic plate a photon would land depends on the situation at *both* slits, i.e. whether one or both slits are open (wave behavior).

This is a contradiction at the level of common sense. The text book wisdom moves to propose that the observed behavior *of the electron* is correlated, not to the (superposed) state of the electron prior to observation but to the state it enters *after* and due to the interaction with the specific experimental arrangement. In the orthodox interpretation, the projection postulate accounts for this transition of state. The EPR experiment shows that in the case of pairs of space-like separated particles, such a change of state at the point of, and *due to*, the measurement interaction entails a violation of locality condition. The orthodox interpretation readily embraces nonlocality as the essential consequence of quantum theory. This interpretation is called, strangely enough, the “Copenhagen interpretation” and is thought to be based on Bohr’s ideas. As we shall see, Bohr’s own interpretive moves are in an opposite direction.

Bohr moved to avoid the contradiction at the level of common sense *without* nonlocality by suggesting that the *observed outcome* is determined, *jointly* by the state of the electron and the details of the experimental arrangement. In this approach, one does *not* relate the experimental outcome to the behavior of the individual electron (or photon). To treat the electron (or photon) as the *observed system* and to consider its behavior to be entangled with the experimental arrangement

would be to understand Bohr's inseparability incorrectly. For Bohr, it is to the (epistemically) inseparable *joint* system that the quantum mechanical formalism must be applied.

“The main point is the distinction between the *objects* under investigation and the *measurement instruments* which serve to define, in classical terms, the conditions under which the phenomena appear...these bodies together with the particles would in such a case constitute the system to which the quantum mechanical formalism is to be applied [Bohr, 1949, 221, italics Bohr's; underlines mine]

Thus, upon Bohr's view, it is wrong to say that the *same* object is behaving differently in two different experiments. The totality of the observed system plus the experimental arrangement that “constitute the system to which the quantum formalism is to be applied” is simply *different* in the two experiments. The idea that the very observed system is different in the two experiments straight-forwardly accounts for the difference in the *outcomes* in the two experiments. This of course raises the question, how do physicists in praxis are able to relate the outcomes as giving knowledge of properties of an individual electron? I shall return to this point later.

We thus start by noting that Bohr's “inseparability hypothesis” is fundamentally different from the usual ‘quantum contextuality’ presented in text books as part of the “Copenhagen interpretation.” quantum contextuality is the idea that definite values for properties can be predicted to the individual electron only in the context of an actual (or possible) observation. Eigenstates and eigenvalues are created at and by measurement. Bohr explicitly cautions against this way of speaking.

“We are here dealing with a purely symbolic procedure, the unambiguous physical interpretation of which in the last resort requires a reference to a *complete experimental arrangement*. Disregard of this point has sometimes led to confusion, and in particular the use of phrases like “disturbance of phenomena by observation” or “creation of physical attributes of objects by measurements” which is hardly compatible with common language and practical definition.”

[Essays, p.5, italics mine]

Contextuality also runs into the question of why *one* of many possible values turns up in an individual observation. We have to either embrace quantum randomness or accord a causal role for measurement, neither of which is acceptable to Bohr. Bohr's inseparability is therefore *incompatible* with contextuality.

‘Inseparability’ constitutes the “epistemological lesson” that the finite quantum of action imparts. Due to inseparability, the observations cannot be interpreted as measuring properties of the individual atomic system.

“No result of an experiment ... can be interpreted as giving information about independent properties of the objects, but is inherently connected with a definite situation in the description of which the measuring instruments interacting with the objects also enter essentially.” [APHK, p. 25-26]

Indeed, because of the inseparability, the observations cannot even be related to the macroscopic observing instruments *within the formalism*.

“The quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena *nor to the agencies of observation*.” [ATDN, p. 54, emphasis mine]

“In atomic physics...it is no longer possible to sharply distinguish between the autonomous behavior of a physical object and its inevitable interaction with other bodies serving as measuring instruments...” [Bohr, 1937, p. 84]

Therefore, within the formalism, the laboratory events can only be treated as our *simple sense experiences*. Thus, post-1935 Bohr came to limit the use of the term ‘phenomenon’ to apply to individual observation experiences. Such phenomena are complementary because the ‘experimental wholes’ giving rise to complementary observations are different and mutually exclusive. The wave and particle complementarity thus applies, *not* to the ontological electron (or light) but to the phenomena, namely our *observations*. All ontological contradictions are avoided. This is the essence of Bohr’s complementarity viewpoint.

“In order to emphasize that we are not concerned here with real contradictions, the author suggested in an earlier article the term “complementarity”.” [ATDN, p.95]

The most mysterious aspect of the two-slit experiment, namely the correlation between the experimental configurations chosen and the behavior of the individual electron, as per Bohr, now stands dissolved. In choosing different experimental arrangements, we are *not* bringing about different behaviors of the individual electron, but are simply choosing between complementary phenomena to study.

“The question was whether, as to the occurrence of the individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on the part of “nature” or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the “observer” constructing the measuring instruments and reading their recording. *Any such terminology would however, appear dubious* since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand it is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged. To my mind, there is no other alternative than to admit that, in this field of experience,

we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us to only make a choice between different complementary types of phenomena we want to study.” [Bohr, 1949, p. 223, italics mine]

The signature of quantum theory then is not that it disallows definite trajectories for electrons. Rather, it just does not describe the individual electrons at all, much less their motions. Rather, QT accounts for the observations via a complementary mode of description in which the electron and the experimental arrangement forms a single whole and the observations are only our sense experiences.

“In contrast to ordinary mechanics, the new quantum mechanics does not deal with a space-time description of the motion of atomic particles.” [ATDN, p. 48]

“The physical content of quantum mechanics is exhausted by its power to formulate statistical laws governing observations obtained under conditions specified in plain language.” [Essays, p.12]

The net result is that quantum theory is *not an ontological theory*. The quantum formalism is not directly about light or material particles per se, it is only in the business of making statistical predictions about the observable laboratory outcomes qua our sense experiences, which are related to particles (or light) *plus* the experimental arrangement as a whole. As a result, there is nothing in quantum formalism that is contradictory to the particles having definite trajectories. Bohr is not shy to emphasize this consequence of his interpretation.

“The extraordinary development in the method of experimental physics has made known to us a large number of phenomena which in a direct way inform us of the motions of atoms and of their number. We are aware even of phenomena which with certainty may be assumed to arise from the action of a single atom, or even of a part of an atom. ... Recently, it has been possible even to obtain an interpretation of the radioactive transformations...we have here *a direct connection with the customary ideas of motion*, since, owing to the great energy of the fragments expelled by the atomic nuclei, the paths of these particles may be directly observed.” [ATDN, p. 102, 112, italics mine]

If electrons do have definite trajectories as per direct experimental evidence, then why do the electrons ‘going through’ the top slit (in the two slit experiment) arrive at two different locations depending on whether the ‘other’ slit is open or not? To ask this question is to miss the thrust of Bohr’s interpretation. As per Bohr, the two-slit experiment is not designed to observe the trajectories of the particles. It is a different experiment, and one should not analyze this experiment in terms of visualizations of the individual electron’s behavior. The observations are simply sensible events in the laboratory and quantum theory adequately predicts the statistics concerning

them by its new mode of description which treats the electron plus the totality of the experiment as a single, inseparable whole. From this viewpoint, even the trajectories observed in the bubble chamber are not described by quantum theory. These observations are also nothing but a succession of *sensible, individual* observation events (succession of condensed water drops) and it is their statistics that is predicted by quantum theory. That we interpret it as a trajectory in common-sense thinking is *independent* of the quantum formalism, and nothing in the formalism is directly in contradiction with it provided we embrace the notion of inseparability within quantum theory.

Because quantum theory is not about the behavior of individual electrons, the observations to be interpreted as measurements of physical magnitudes within the formalism.

“The numbers expressing the values of the quantum or spin in ordinary physical units do not concern direct measurements of classically defined actions or angular momenta, but are logically interpretable only by consistent use of the mathematical formalism of quantum theory.” [Essays, p.61]

Aage Peterson’s attribution to Bohr, that “there is no quantum world, but only quantum description” now makes sense. This statement pertains to the formal mode of description of the quantum *formalism*. This mode of description is compatible with the experimental evidence being interpreted as revealing directly the reality of atomic particles, independent of quantum formalism.

Philosophers have discussed at length whether Bohr is a scientific realist or not, but we would do well to recognize two kinds of scientific realism, theoretical and experimental. The former infers the existence of theoretical entities once a theory is observationally confirmed. But as often as not in science the experimentalist first ‘detects’ the existence of a thing, and only then does the theoretician develop a theory about how the observations pertaining to the behavior of these entities can be accounted for. This later form, which I call experimental realism, is true of quantum theory as it developed over many decades in the beginning. Thus, Bohr is scientific a realist in terms of this experimental realism. For him, electrons are classical particles.

Similarly, “as regards light, its propagation in space and time is adequately expressed by the electromagnetic theory.” Nothing in quantum theory need contradict this. Thus, “in the general problem of quantum theory, one is faced *not with a modification of the mechanical and electrodynamical theories* describable in terms of the usual physical concepts, but with an essential failure of the pictures in space and time on which the description of the natural phenomena has hitherto been based.” [ATDN, p. 34-5] This failure of pictures in space and time, we must note, occurs only at the level of the formalism which describes the electron plus the experimental arrangement as a single epistemic whole. As a result, the formalism cannot be realistically

interpreted, i.e. interpreted in relation to the independent states of the individual electrons. The space-times pictures, however, *can* be used to visualize the quantum phenomena, i.e. the observations independent of the formalism. However, such pictures will now be mutually exclusive since the phenomena themselves are mutually exclusive. All we have to learn from this is that no ontological theory of these phenomena is possible. All *apparent* difficulties arise only when we extend the common-sense pictures we invoke to interpret the observations to visualize an underlying quantum object. There is no such individual quantum object in quantum *theory*, due to the hypothesis of inseparability. Thus, the wide-spread attribution of the viewpoint that “the electron being a wave or particle depending on how we observe it” to Bohr, as Pais does in the following quote, is simply be incorrect.

In quantum mechanics, the question of whether an electron is a particle or a wave is meaningless, however. There one should rather ask: Does the electron (or any other object) *behave* like a particle or like a wave? That question is answerable, but only if one specifies the experimental arrangement by means of which ‘one looks’ at the electron. That is what Bohr meant in Como [lecture].” [Pais, 1993, p.314]

As Scheibe correctly and accurately points out, Bohr’s repeated references to apparent wave-particle duality serve only a *negative* purpose.

"Heisenberg [1955, p. 15] tells us that Bohr “intended to work the new simple pictures, obtained by wave mechanics, into the interpretation of the theory". Despite an initial approach of this kind, which may certainly be reckoned to Bohr's credit, the core of Bohr’s contribution to the interpretation of quantum mechanics must be sought elsewhere. In this respect, the reader will have to see for himself that the wave-particle duality [for light and matter] which Bohr indeed mentions over and over again, is only a part of the negative side of his arguments taken as a whole ; he uses it to illustrate the difficulty of the then existing position, but it does not itself contain any positive method of resolving the problems. The duality is always presented as a puzzle, a dilemma, a paradox or even a contradiction: always as something to be overcome and done away with." [Scheibe, 1973, 17-8]

The ontological paradoxes simply serve to show we ought not to link the observations to the electron (or light) *alone*. Pais further says “...Bohr stressed that only by insisting on the description of observations in classical terms can one avoid the logical paradoxes apparently posed by the duality of particles and waves.” From the viewpoint of this paper, the above would be wrong too. Bohr stressed that only by seeing that the observations cannot be linked to an individual quantum object alone, can we avoid the logical paradoxes. Once the quantum formalism cannot be linked to the individual quantum object, it follows that any realist interpretation of the observation can only be independent of the quantum formalism, and can only be classical.

Quantum theory does give an objective description, not of light or matter particles per se, but of light or matter *plus* the experimental arrangement. Hence Bohr's insistent claim his was "an objective interpretation."

Of course, in such an interpretation embracing inseparability, there is no causal account of the individual event in terms of the behavior of individual entities. But ontological contradictions are avoided.

"We cannot seek a physical explanation in the customary sense, but all we can demand in a new field of experience is the removal of any apparent contradiction."
[APHK, p. 90]

3.0 The Bohr-Einstein Debate

The lack of causal explanation, however, should not be seen as a lack in quantum theory and oblige us to search for another causal theory. What it entails is a "revision to our very attitude toward physical explanation". Bohr, however, provides no elaboration of what exactly is the nature of that revision to scientific explanation, beyond terming it as complementarity. I offer one below.

The task of communicating with another person is to get across the needed message, *not* to personally *see* the person. Although in the olden days we had to see a person personally to communicate, today we can communicate by phone or email without seeing the person but that does not make the communication any *less*. Nor does it mean the person does not exist. Similarly the task of science is to reduce the phenomena to order, *not* to describe the underlying world. of course in pre-quantum theories we first described the world *and thereby* ordered the phenomena, QT does *not* do that but that doesn't mean its explanatory framework is any *less*. Nor does it mean that atomic objects do not exist. They do. Otherwise, the very idea of "inseparability" is meaningless.

It is now easy to see why Einstein's "epistemological *credo* — "the *programmatic aim* of science is to describe the world as it exists independent of observation" and that if QT is incompatible with this undertaking, we must to look for another theory — was unacceptable for Bohr. For Bohr, the aim of science is *not* to describe the world, but to account for the observations. The world is of course involved in quantum account but only indirectly vide the talking/communication example. Bohr simply failed to present this aspect of his interpretation.

Furthermore, no a priori demand can be placed on the kind of explanation a physical theory must provide. "There could be no other way to deem a logically consistent mathematical formalism as

inadequate than by demonstrating the departure of its consequences from experiences or by providing that its predictions did not exhaust the possibilities of observation, and Einstein's argumentation could be directed to neither of these ends." [Bohr, 1949, 239]

4.0 Bohr's Response to the EPR Argument and the "cat paradox"

<to be rewritten>

5.0 Going Beyond Bohr

Nevertheless, Bohr's inseparability interpretation falls short. It treats the observations as simple sense experiences, whereas the current praxis which interprets the observations realistically. This short fall is supposed to be filled in by complementarity of phenomena, but complementary of phenomena makes no sense unless the observations in question are *themselves different*. But the basic observations in both wave and particle behaviors is the *same*, a localized event such as a spot on the photographic plate. This means, "complementarity of *phenomena*", a basic theme in Bohr's writings, fails to be convincing.

This is perhaps one reason why the standard interpretation invokes contextuality instead of inseparability and uses Bohr's term 'complementarity' as merely standing for mutual exclusivity. This allows for the observations to be related to the theoretical terms, but in the process it introduces a 'measurement problem' which I believe is in principle unsolvable.

Can Bohr's own interpretation be made realistic with respect to observations?

A person not knowing English, can treat the letters simply as shapes, and 'words' as a concatenation of such tokens and study English passages in terms of relative frequencies of occurrence of these symbol combinations. A sufficiently large sample base of English texts would indeed yield a statistics that *any* and all English passage must obey. Yet, within such a statistical view, it will be impossible to explain why a particular word appears at a particular location in any given text. Explaining *that* would require treating the individual letters, words and the whole passage semantically and invoking meta ideas such as grammar, meaning of the passage etc. Similarly, could there be two ways of interpreting our observation experiences realistically, as a localized position, and another as yet unknown manner that is perhaps more quantum-compatible? Are the statistical predictions simultaneously made possible and remain acausal because we adopt

the former interpretation? Indeed, Bohr repeatedly emphasizes the inadequacy of our usual forms of perception in quantum theory.

“As the goal of science is to augment and order our experience, every analysis of the conditions of human knowledge must rest on considerations of the character and scope of our means of communication. Our basis is, of course, the language developed for orientation in our surroundings and for the organization of human communities. However, the increase of experience has repeatedly raised questions as to the sufficiency of the concepts and ideas incorporated in daily language.

If it is the case that a causal (and an ontological) interpretation of quantum theory may need first a revision at the level of everyday thinking, Bohr is not going to find it since he also insists “all new experience makes its appearance within the frame of our customary points of view and forms of perception.” Bohr’s aim is thus to show “how, *without leaving common language*, it is possible to create a framework sufficiently wide for an exhaustive description of new experience.” [APHK, p. 88, italics mine]

In the process, Bohr ends up with a complementarity framework that is too narrow and insufficient to even account for the current realist praxis, as we have seen.

Ordinary language, however, does in fact contain resources for interpreting even a simple notion such as ‘position’ in a new manner. Recall that Bohr’s starting point is that the experimental setup contributes as much to the eventual outcome as the electron’s state. Heisenberg too, started his famous 1927 paper saying, “If one wants to be clear about the meaning of the words ‘position of an object’, for example an electron (in a given reference frame), one has to specify definite experiments with which one intends to measure the ‘position of the electron’; *otherwise these words have no meaning.*” [italics mine]

However, in current praxis, independent of the experimental arrangement, only the question of the *value* of position has no meaning. The concept “position” itself has meaning in an intrinsic or absolute sense.

Is there a possibility to interpret the ‘position’ concept in such a manner as to require a reference to the experimental arrangement in order to define its meaning?

One simple possibility is to treat the observation “electron is at the top slit” as revealing a *relational* position, like “moon inside the window”, instead of an absolute location like “cat on the mat.” It is the position of the particle at the two-slit screen, either at the top or bottom slit that we are defining (and aiming to measure) as ‘position’.

In other words, given an individual quantum particle, its properties are *not even defined* until we specify the experimental arrangement through which we observe it. This is in accord with Heisenberg's description of the essential feature of the quantum formalism. It is also in accord with the fact that quantum mechanical properties are specified by the observables, which are selected only when we select the full experimental situation under which it is observed.

If we place an N-slit screen (with a non-zero value other than 2) on the path of these microscopic quanta, then the electron can have N and only N possible positions. Classically, however, a particle should have only one absolute location, regardless of the value of N. The relational conception of position allows the electron or photon's possible locations to vary with N. If there are N windows, the same moon can *simultaneously* have N relational positions of being inside each window.

Furthermore, if 'position' (the x-observable) is just the classical position, then the electron would have to have contiguous positions in space, an idea that is not always compatible with quantum formalism. Whereas, by conceiving the 'position' as a *relation between the quantum and the two-slit screen*, we can easily accommodate how electrons can have discrete positions, and how such successive positions *do not imply a trajectory*. For, by placing the two-slit screen at different locations (along the x-axis), we shall observe different 'positions' of the quantum, but these relational positions can be no more combined to form a trajectory than two positions of the moon — one "inside the window" and another "on top of the tree" — can be combined to say that the moon moved from inside the window to the tree outside.

Similarly, other quantum mechanical observables can be regarded as representing relations at the *formal level*. Upon this view, 'position' and 'momentum' get *defined* when we choose the corresponding experimental arrangement. It is now easy to see Bohr could regard the uncertainty relations as placing limits to simultaneous *definability*, rather than simultaneous knowability.

“Quantum mechanics speaks neither of particles the positions and velocities of which exist but cannot be accurately observed, nor of particles with indefinite positions and velocities. Rather, it speaks of *experimental arrangements in the description of which* the expressions 'position of a particle' and 'velocity of a particle' can never be employed simultaneously.”

“The proper role of the indeterminacy relations consists in assuring quantitatively the logical compatibility of apparently contradictory laws which appear when we use two different experimental arrangements, of which only one permits the use of the concept of position, while only the other permits the application of the concept of momentum...” [Bohr, 1937]

In classical mechanics too, properties are relational, but in a weak epistemological sense. The properties belong to the object, but only their quantification requires expressing them in relation to standard rods and clocks. In our proposed way of conceptualizing the quantum mechanical kinematical concepts, the properties are relational in a much stronger sense. The very definition (or physical meaning) of the properties is in relation to the experimental conditions under which they are observed.

6.0 Toward an account of Current Statistical Quantum Mechanics

Why should quantum theory adopt this relational mode of description?

Our state-preparation and observation procedures in the laboratory, which necessarily have to be couched in ordinary language can ostensibly specify operations only on macroscopic objects, such as the source, even if our experiments are about microscopic objects. Thus, if these state preparation procedures are taken to result in the emission of an ensemble of microscopic objects, the resulting quantum state would be *common* to the entire ensemble. The ‘indistinguishability’ of microscopic objects described by a common ψ function, we regard then as due to failure of ostension of ordinary language at the level of state preparation.

However, at the point of an actual (or, potential) observation, we *can* refer ostensibly to an individual microscopic object even while using ordinary language. We can and do say, for example, that this spot is caused by this individual electron. It pragmatically works. If so, the *need* to use the relational mode of description at the formal level can be seen as the flip-side of the situation that we can refer to an individual microscopic object only with reference to an actual observation. At the level of state preparation, we can relate the quantum mechanical state ψ and the corresponding observables to the individual microscopic object only *in relation* to the experimental arrangement (which produces the observations). Hence, the interpretation of ‘position’ as a relation between the individual microscopic quantum and the macroscopic two-slit screen at the level of the formalism.

The fact that ordinary language regains its power of ostension with respect to microscopic objects at the point of an observation allows us to *reduce* the position-relation to being an ‘position’ in the intrinsic sense *at and only at the point of an actual observation*. Since ‘position’ is the most basic observation, once the notion of absolute position is recovered at the point of an observation, then we can recover the all other properties corresponding to quantum mechanical observables in the

usual intrinsic sense. This then allows the current range of physical thinking that underlies statistical quantum mechanics to proceed unhindered and achieve pragmatic success.

In a longer version of this paper, I try to more fully nuance Bohr's interpretation and the differences in the approaches to uncertainty relations between Heisenberg and Bohr. I also compare my reading of Bohr with those of other Bohr scholars.

7.0 CONCLUSION

If we start with the relational conception of 'position', Bohr's "epistemic inseparability" immediately follows as a logical consequence. The relational viewpoint also avoids ontological wave-particle duality. In addition, it permits deducing the realism of the experimental praxis. Furthermore, many of the un-intuitive aspects of quantum formalism, such as discrete locations, absence of trajectory etc., are rendered intuitively accessible. Feyerabend and Jammer have noted that the idea of relations is already implicit in Bohr's writings.

As I see it the most important element of Bohr's interpretation consists in the twin assertion that (a) the quantum theory will have to work with dynamical states which are only partly well defined and that (b) these dynamical states must be regarded as relations between the system and some appropriate measuring device. [Feyerabend, 1961, p. 372]

"The [quantum mechanical] description of the state of a system, rather than being restricted to the particle (or system of particles) under observation, expresses *a relation between the particle and all the measuring devices involved*. [Jammer, 1974, p. 197-198, italics mine]

The classical notion of position and the relational interpretation of position denote a fundamental complementarity at the level of *phenomena*. Bohr could not have formulated the relational notion of position, because he ruled out the possibility for interpreting the observations using new conceptual forms in ordinary language. In un-necessarily imposing this restriction, I see Bohr as having 'missed the boat'.

I do not offer the relational conception of position as a sufficient framework for an ontological interpretation of quantum theory. I present it merely to show that non-classical modes of thinking in ordinary language are available. This relational interpretation avoids the problems that Bohr sought to avoid (such as wave-particle duality and nonlocality) without the vagueness of his notion of inseparability. But it is also an epistemological interpretation and therefore needs to be transcended. Elsewhere [Gomatam, 1999] I have proposed that the notion of a relational *property* could provide

the basis for a truly quantum ontological interpretation. Such an interpretation would start from premises quite different from Bohr and will traverse a long route. Going into further details of ongoing work on this front is beyond the scope of this presentation.

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