Bohr’s Conception of the Quantum Mechanical State of a System and Its Role in the Framework of Complementarity

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Abstract

What Niels Bohr called the ‘epistemological lesson’ of ‘complementarity’ was the result of reasoning analogically from the classical conception of a mechanical state to a new quantum mechanical conception of an ‘object’ in a mechanical state. Bohr proposed to redefine the ‘objectivity’ essential for scientific description in terms of the epistemological demand for unambiguously communicable descriptions of observational results, a move which has profound consequences for how we can understand the concept of the quantum mechanical state and the nature of the ‘system’ which is ‘in’ this state. Here it is argued that the old notion of the ‘object’ which is in a classical mechanical state is drawn from a substance/property ontology derived from Aristotle’s analysis of categorical propositions. In moving to describing a system in a quantum mechanical state, the system that is ‘in’ such a state can no longer be so regarded as a substance possessing properties. Bohr argues that the concept refers to an interaction which has a feature of wholeness or ‘individuality’ that implies that the distinction between ‘object system’ and ‘observing system’ is relative to the context of the description. This conclusion, in turn, implies the need for a combination of complementary modes of description; however, because of his reticence in making ontological claims, he failed to develop this dimension of his new framework of complementarity.

1 The Conceptual Framework for the Description of Nature

The concept of the quantum mechanical state of a physical system around which so much controversy swirls was formulated by reasoning from an analogy to the classical mechanical state. Niels Bohr repeatedly appealed to this kind of reasoning in feeling his way from the ‘stationary states’ of his original quantized model of the atomic system
of 1913 to his mature understanding of the quantum formalisms of Heisenberg and Schrödinger. As a contribution to clarifying basic concepts, here I propose to offer an analysis of how this crucial concept of the ‘state’ of a ‘physical system’ was transformed from the ‘intuitive’ classical concept formulated in terms derived from ordinary human experience into the context of the ‘mysterious’ quantum theoretical representation of the atomic domain. This transformation, and the general epistemological lesson it teaches, is at the heart of Niels Bohr’s thinking in formulating his new framework of complementarity.

In reconstructing the thought of an influential scientist one must be careful not to impute to the historical actors a consciousness which itself is the product of their very own contribution to the scientific outlook, and hence how history often has come to perceive them. Thus Newton was no Newtonian—certainly not what that name would have meant even by the mid-eighteenth century. And Einstein had no conception of the Big Bang cosmology which is the boldest fruit of his contribution to the scientific conception of the universe. In Bohr’s case there are at least two ways which we can say the product of his labors has disoriented the philosopher’s attempt to reconstruct how he saw the scientists’ description of nature.

The first is the historical fact that Bohr came to play the role of captain of the philosophically quite diverse crew of Copenhagen. Whatever it was that this assortment of geniuses who professed loyalty to Bohr held in common was erected into something like a creed under the banner of ‘The Copenhagen Interpretation,’ the confession of which—in the opening paragraphs of a textbook—was held to expiate the author from demand for any further philosophical explication. ‘The Copenhagen Interpretation’ was a term Bohr never used and surely regretted. Given its essentially strategic function in the history of atomic physics, a sociological analysis of the party in the grip of the Copenhagenergeist, such as that offered recently by Beller, can provide an illuminating example of the dynamics of scientific belief formation, but inevitably only from the point of view of one who already knows where the story is going. Thus this cannot establish how the actors in these events saw what it was they were doing from their side of the revolutionary divide. Moreover even if we grant there is no single coherent account of nature in the so-called ‘orthodox view’—regarded as a strategic alliance among distinct thinkers—that does not establish that the individuals associated with it do not have a coherent view to call their own. But this does require that to make out some coherent reconstruction of Bohr’s thinking, we need to penetrate through the Copenhagener’s front lines, and look just at this individual physicist as he approached these issues.

A second way in which we lose the historical scent is that we ask questions that arise from how we currently understand the quantum formalism, which of course was not an available option in the midst of the quantum revolution. Clearly Bohr could not have thought in terms of mathematical representations such as the collapse of the wave packet or operations on vectors in Hilbert space—as we are wont to do today—for these came only later after his creative work was done. But even if we disregard its ahistoricity, such an approach which moves from the mathematical formalism to an account of nature, was the very opposite of Bohr’s philosophical modus operandi. His whole career was staked on the building of atomic models and a concern with what the physicist must do in order to make such models harmonize with the empirical evidence. The same approach has been proposed by Fuchs in a letter to David Mermin, where
he makes the following observation:

The issue in my mind is not to start with complex Hilbert space, unitary evolution, the tensor product rule for combining systems, the identification of measurements with Hermitian operators, etc., etc., and showing that Bohr’s point of view is consistent with that. Instead it is to start with Bohr’s point of view (or some variant thereof) and see that the precise mathematical structure of quantum theory must follow from it. Why complex instead of real? Why unitary, rather than simply linear? Indeed, why linear? Why tensor product instead of tensor sum? And, so on. When we can answer these questions, then we will really understand complementarity.\(^2\)

Although talk about the ‘quantum mechanical state’ is central to discussions which proceed from the current formalism, in fact that phrase was never used by Bohr. If we want to recapture how Bohr would have regarded this concept of a quantum mechanical state, we must approach it from his side of the revolutionary divide, not from that of the subsequent formalism.

By avoiding these disorienting ways of asking questions, we can reconstruct a plausible account of Bohr’s philosophy which is at least coherent, but frustratingly incomplete. To put things in philosophical jargon, I would maintain that many have misread Bohr as advocating an anti-realist interpretation of physics, whereas I maintain that if we look at him in the midst of the quantum revolution, we see a realist trying to reconstruct the classical conceptual scheme for the description of nature in order to deal with a brute shock to the physicists’ preconceptions about nature. The result was what he called ‘complementarity’ and what it purported to be was a ‘new framework for the description of nature.’ No matter what triumphs the Copenhagen Interpretation may have had, Bohr’s lifelong campaign to promote this new framework, which he often called the ‘epistemological lesson’ taught to us by atomic physics, was a failure. Perhaps one reason is that his ‘epistemological lesson’ needed an ontological lesson to go with it, yet Bohr failed to provide any clear indication of what such a revision would entail. Here I would like to pick up the trail and try to sketch out what I take to be the ontological revisions suggested by the framework of complementarity.

Bohr’s formation of his philosophy of science was more or less contemporary with the positivism of the Vienna Circle, and he does share much with the positivists, but his ‘big picture’ in building his philosophy of science really points at least as much towards later post-positivist images of science associated with so-called Weltanschauungen analyses. ‘Natural science’ for Bohr is that part of ‘human knowledge’ which is concerned with the ‘description of nature.’ A ‘conceptual framework’ is necessary for expressing the knowledge gained in this scientific description of nature in an ‘objective’ manner. The scientist attempts to fit the framework to agree with empirical evidence generated by the extension of the empirical basis into new domains, such as the interior of the atom. This requires revision of the framework which is constrained both by the demand for logical consistency and the need to accommodate the recalcitrant experience. Although contemporary philosophers have been made very much aware of these points by the works of Quine and Kuhn, it is worth pointing out that Bohr was writing well before these thinkers had made such themes familiar.\(^1\)

\(^1\)I suspect that this may be because all these thinkers shared a common debt to pragmatism generally, and William James in particular, but the evidence for the connection between James and Bohr, I have to
For Bohr the crux of the revision in our understanding of how this conceptual framework attaches to nature lies in the need to redefine the ‘objectivity’ of the description of nature. In particular, the epistemological lesson Bohr drew from this revolutionary transition taught that the ‘objectivity’ of a description cannot be based on the ontological claim that the description refers to the properties which define the mechanical state of a system isolated from interaction with observers. Hence he proposed to redefine the ‘objectivity’ necessary for scientific description in the epistemic demand for unambiguously communicable descriptions of observational results. This move has profound consequences for how we can understand the concept of the quantum mechanical state and the nature of the ‘system’ which is ‘in’ this state.

2 The Classical Mechanical State of the System

The thesis I want to explore is that the old notion of the ‘entity’ or the ‘object’ which is in a classical mechanical state is derived ultimately from a concept of ‘information’ based on the Aristotelian analysis of propositions and the substance/property ontology associated with it. Aristotle defined ‘primary substances,’ i.e., the ‘entities’ or ‘beings’ of which the physical world is composed, as that which is the ultimate subject of all predicative assertions but which themselves can never be predicated of anything else. While such primary substances are the ultimate individuals of the Aristotelian description of the physical universe, all such assertions, i.e., all statements of ‘information,’ predicate universals of the particular substance which is its subject. These are the substance’s ‘accidents’ or ‘properties.’

For Aristotle ‘scientific knowledge’ arises only when the active mind, nous, grasps the set of universals which are essential to that substance’s being what it is; but in doing so, knowledge can have as its object only the ‘whatness’ of that substance, never its individual ‘thisness,’ its particularity. The Aristotelian solution was to make the substance into a hylomorphic synthesis of form and matter with the universal form, the object of scientific knowledge, incorporated into the ‘matter’ which made a substance into an individual particular being. But while one can speak intelligibly of formed matter, the concept of pure ‘prime matter’ stripped of all form, becomes—on this analysis—ultimately unknowable, that of which no universal predicate can be affirmed. For this reason ultimately, in the Aristotelian system, knowledge of the individual of this particular, contingent world recedes from our grasp.

Ancient epistemology was not concerned with the distinction between the subject’s perception—of which we are immediately aware in consciousness—versus an ‘objective reality’ which in some way is imagined to lie ‘behind’ that conscious experience. For Aristotle we experience the world objectively as it is, and the world is as we objectively experience it. But in the modern philosophy of the Enlightenment, the mechanization of nature accompanying the Cartesian turn toward the certainty of what is present in subjective consciousness led to a conception of nature wholly unlike the world revealed in human experience. While the problem of accounting for knowledge of the particular individual ‘thisness’ of concrete beings confounded Aristotelian ontology, the new mechanistic world-view could easily deal with that problem by identifying the individual by its unique spatio-temporal locus. Thus the ‘objects’ of which the physical admit, is equivocal and it is not likely it will ever be established to everyone’s satisfaction.
universe is composed had to be things of which spatio-temporal locus, the property which makes a kinematic description possible, could be necessarily and universally predicated. Extension became the ‘essence’ of physical substance. This was significant for it meant that physical beings, the things that were ‘in’ classical mechanical states, must be the sorts of things that can be pictured; they are essentially, we might say, ‘visualizable in space and time’ even though (as Berkeley pointed out) no one has ever seen extended substance simpliciter.

With Newton’s achievement the mechanization of nature added to extended substances the dynamical properties necessary to account for the causes of change in kinematic properties over time. This then completed the list of properties objectively possessed by ‘mechanical systems,’ because together the kinematic and dynamic properties were all the predicates needed for a complete mechanical description of physical systems and their interactions. Therefore to construct a mechanistic ontology one needed only this small handful of properties which were solely those essential for a mechanical description of extended substances. Thus they came to replace the bounteous supply of Aristotelian natural essences, as the only universals which could be truly predicated of individual beings as they objectively exist in Nature. Aside from these true cases of objective predication, the rest of those universals we affirm of the objects of sensory experience have only subjective validity; these properties exist only in human sense perception of the world.

From the time of the scientific revolution initiating this classical mechanical worldview, the concept of an ‘objective’ description was understood in this ontological sense, as referring to a description which was limited to predicing only those properties actually possessed by the ‘object’ being described. These so-called ‘primary qualities’ of bodies are ‘real’ in the sense of existing apart from any observation of them; they are ‘out there’ in the ‘world.’ In contrast the far larger host of ‘secondary qualities’ which objects are perceived as having merely exist as the causal effects in a subject’s consciousness of the mechanical interaction between bodily sense organs and ‘external’ bodies which really possess only the primary qualities. The mechanician’s conception of the physical universe may seem an austere shadow of the luxuriant world of sensory experience, but it’s the real thing. It is what is required by an ‘objective’ description.

Of course this distinction between primary and secondary qualities arose in a Cartesian rationalist conception of the mechanical world view, and once imported into empiricism by Locke, it was exposed as an unfounded ‘philosophers’ distinction by Berkeley. No empiricist since Hume would countenance this rationalist hang up. In spite of that fact, up to the quantum revolution this seventeenth century understanding of the definition of the mechanical state of a physical system as essentially the representation of the primary qualities of a substance remained a standing rationalist bastion in a field otherwise conquered by empiricism. Yet in creating its concept of the ‘mechanical state’ of the ‘system’ from the older ontology of ‘substance’ and ‘accident,’ and making this the basis of ‘objectivity,’ classical mechanism naively moved from a concept of how we know the world to how the world must be with a distinctly pre-modern ease. Kant’s revolution was ‘Copernican’ in that it showed you cannot simply ‘read off’ the structure of Being from the structure of Knowing, as the older Enlightenment philosophers had naively presumed you could. But Kant’s revolution notwithstanding, the continued triumph of mechanism throughout the 18th and 19th centuries could easily be used to support the most materialistic of ontologies based on a univocal correlation of the
3 Bohr’s Rational Generalization of the Concept of the ‘Mechanical State of the System’

The central theme of Bohr’s career was the effort to fashion a successful theoretical model of the atomic system. From his experience with Rutherford at Manchester he entered the world of physics with the conviction that classical mechanics could not be successful at accounting for the stability of atoms by representing them as classical mechanical systems of charged particles. Although the notion of electron orbits often assumes center stage in presentations of Bohr’s model, in fact Bohr saw the heart of his ‘revolution’ to be the postulate that atomic systems exist in a quantized series of ‘stationary states’ which defy the laws of classical mechanics. Interactions between atomic systems and the electromagnetic field or other particles therefore imply discontinuous changes of state. “Taking the indivisibility of the quantum of action as a starting-point,” Bohr tells us, he was led to suggest “that every change in the state of an atom should be regarded as an individual process, incapable of more detailed description, by which the atom goes over from one so-called stationary state into another. According to this view, the spectra of the elements do not give us immediate information about the motions of the atomic parts, but each spectral line is associated with a transition process between two stationary states...the necessity of making an extensive use, nevertheless, of the classical concepts, upon which depends ultimately the interpretation of all experience, gave rise to the formulation of the so-called correspondence principle which expresses our endeavors to utilize all the classical concepts by giving them a suitable quantum-theoretical re-interpretation.” Thus ab initio Bohr’s work was predicated on an outlook which demanded in the atomic domain a new ‘quantum theoretical re-interpretation’ of a physical system being in a ‘mechanical state’ to replace the classical mechanical conception.

Bohr’s ground level argument appears in variations in many of his essays. He starts with the observation that widening experience often forces revisions of the conceptual scheme employed for the description of nature. He then turns to Planck’s ‘discovery’ (not ‘invention’) of the quantum of action as forcing such a revision. Bohr calls this surprising discovery the ‘quantum postulate’ and maintains that it has been forced upon us by the need to account for the known relations between matter and radiation. Thus the quantum revolution demands a revision of the conceptual framework for the description of nature because at the atomic level we must describe physical systems as changing their states discontinuously. Bohr expresses this point by saying that the quantum postulate requires that ‘interactions’ between ‘systems’ be accorded a feature of ‘wholeness’ or ‘individuality.’

Right from his 1913 model of the atom—long before the development of what we know as ‘quantum theory’—Bohr always emphasized two aspects of his atomic model: First, all information about the properties of atomic systems comes through interactions between atomic systems and the field or other material systems in which the atomic system changes from one ‘stationary state’ to another ‘stationary state’ discontinuously. Second, when no dynamical exchange is taking place between the atomic
system and electromagnetic radiation or other material particles, the atomic system exists in a ‘stationary state’ isolated from interaction. While one may construct familiar visualizable spatio-temporal models of this atomic system in its ‘stationary states’ isolated from any interaction, such constructions are purely theoretical abstractions because by definition of the ‘stationary state,’ the properties of the ‘orbits’ or otherwise visualizable trajectories used in these kinematic ‘pictures’ cannot be observed, because observation is interaction:

...any attempt to fix the space-time co-ordinates of the constituent particles of an atom would ultimately involve an essentially uncontrollable exchange of energy and momentum with the measuring rods and clocks which prevents an unambiguous correlation of the dynamical behaviour of the atomic particles before the observation with their later behaviour. Inversely, every application of conservation theorems, for instance to the energy balance in atomic reactions, involves an essential renunciation as regards the pursuance in space and time of the individual atomic particles. In other words, the use of the idea of stationary states stands in a mutually exclusive relationship to the applicability of space-time pictures.[4]

The visualizable ‘space-time pictures’ of the stationary states by means of orbits in space and time cannot be understood realistically because the energy exchanged between the atom and the field is a function not of the orbital characteristics but of the differences between the stationary states. Because they involve such discontinuous changes in state, interactions at the atomic level cannot be described as mechanical processes taking place in space and time.

Classical mechanics was able to get away with its conception of defining the state of an isolated system by observation only because the presumption of the continuity of interaction allowed one to make the dynamical effect of the interaction involved in the observation infinitesimally small. In much the same way that it was commonly held that relativistic mechanics is a ‘generalization’ of the ‘special case’ of classical mechanics in which the speed of light is imagined to be infinite, Bohr held that the quantum mechanical description is a rational generalization of the special case of the classical description, where it is imagined the parameter of action is defined for a continuous range of values.

Of course this view of progress which represents earlier theories as ‘special cases’ of later more general theories was common coin during the heyday of positivism when Bohr wrote, but today’s philosophers are keenly aware of a well known argument against it by Thomas Kuhn.[5] He argued that this alleged reduction of earlier theories to special cases of later theories is misleading to the extent that although the analogous theories are expressed in parallel vocabularies, in the transition from one framework to the next, crucial terms change meanings. Although Bohr no where advocates the radical semantic incommensurability which so preoccupied philosophers in the decades following Kuhn’s provocative work, far from taking the standard positivist line, Bohr actually anticipated Kuhn in cautioning that in this new quantum description of atomic systems one must recognize that the classical descriptive concepts employed attach to nature in a manner different from that of their use in the classical context. In particular, to pass the criterion of ‘science’ the revision of the ‘classical’ framework necessary to accommodate the quantum postulate must result in a description of nature which is ‘objective,’ but the ‘objectivity’ demanded of a description of the quantum state of a
system now has to be given a new meaning because of the semantic shift to the new framework.

Let us see how Bohr reached this conclusion: What we would like to determine by observation—based on our classically trained expectations—is a space-time ‘picture’ in which we ‘visualize’ the state of the system ‘objectively,’ i.e. how it is isolated from any perturbation in its state resulting from the observation. The system is imagined, along classical lines, as an entity which possesses essentially those properties which define its classical mechanical state. But observations require an interaction with the object system, which, because of the ‘indivisibility’ of interaction at the atomic level, alters its state in a non-determined way. For determining what state a system is in by means of observation, the dynamical conservation principles must be employed to trace the causal interaction between observed system and measuring instruments. Thus the classical description employed a conjunction of dynamical conservation principles for a causal analysis of the observational interaction with a spatio-temporal visualizable representation of the mechanical state of the system. But the indivisibility of interaction expressed by the quantum postulate now requires that this conjunction becomes transformed into a ‘complementary’ or ‘reciprocal’ relationship, as expressed in Heisenberg’s infamous relations. Complementarity is thus first proposed as a point of view to replace what Bohr called the ‘the frame of the ordinary causal description’ of the ‘ideal of causality’ employed by the classical framework. In a nice summary from 1937 he writes:

However, a still further revision of the problem of observation has since been made necessary by the discovery of the universal quantum of action, which has taught us that the whole mode of description of classical physics, including the theory of relativity, retains its adequacy only as long as all quantities of action entering into the description are large compared to Planck’s quantum. When this is not the case, as in the region of atomic physics, there appear new uniformities which cannot be fitted into the frame of the ordinary causal description ....Indeed this circumstance presents us with a situation concerning the analysis and synthesis of experience which is entirely new in physics and forces us to replace the ideal of causality by a more general viewpoint usually termed ‘complementarity.’ The apparently incompatible sorts of information about the behavior of the object under examination which we get by different experimental arrangements can clearly not be brought into connection with each other in the usual way, but may, as equally essential for an exhaustive account of all experience, be regarded as ‘complementary’ to each other.[6]

Note that Bohr presents this line of reasoning entirely from the quantum postulate and his general philosophical position regarding the need to revise conceptual frameworks with the expansion of experience into new domains. Nowhere does he appeal to the specific formalism of Heisenberg or Schrödinger or the properties of a mathematical representation or model. While Bohr’s formulation of this argument was coeval with Heisenberg’s derivation of the indeterminacy relations, it was the outcome of a path on which Bohr had been set long before 1927, rather than a move to explain or justify Heisenberg’s surprising mathematical derivation after the fact. Bohr saw in the indeterminacy relations confirmation of a point of view he had reached primarily from conceptual analysis.
Having established the need to revise the classical conceptual framework, Bohr then calls attention to the fact that an objective description of an observation requires an ‘object’ to be unambiguously distinguished from the physical systems employed as ‘measuring instruments’ in the observation.

This circumstance, at first sight paradoxical, finds its elucidation in the recognition that in this region it is no longer possible sharply to distinguish between the autonomous behavior of a physical object and its inevitable interaction with other bodies serving as measuring instruments, the direct consideration of which is excluded by the very nature of the concept of observation in itself....In particular, the frustration of every attempt to analyse more closely the ‘individuality’ of single atomic processes, symbolized by the quantum of action, by a subdivision of their course, is explained by the fact that each section in this course definable by a direct observation would demand a measuring arrangement which would be incompatible with the appearance of the uniformities considered.

By our free choice in designing a particular experiment we bring about the occurrence of a particular ‘phenomenon,’ as Bohr used that word after EPR in 1935. What Bohr calls the ‘interpretation’ of the phenomenon as an ‘observation’ or ‘measurement’ which yields a certain outcome requires describing the phenomenon as a dynamical interaction between the ‘object’ and the ‘measuring instruments.’ To make the distinction between object and observing instruments unambiguous in our description of the phenomenon, we must employ theoretical notions taken from classical physics, but the wholeness or ‘individuality’ of that interaction required by the quantum postulate implies that exactly where that distinction is drawn is a function of the particular description and whatever it is described as a measurement of. “Ultimately, every observation can, of course, be reduced to our sense perceptions,” he tells us, but the “circumstance... that in interpreting observations use has always to be made of theoretical notions entails that for every particular case it is a question of convenience at which point the concept of observation involving the quantum postulate with its inherent ‘irrationality’ is brought in.....After all, the concept of observation is in so far arbitrary as it depends upon which objects are included in the system to be observed.” It is this arbitrariness inherent in the description of an indivisible interaction as a measurement which later in response to EPR led Bohr to contend that in describing the interaction as an observation which determines the observed property of the object, our description will be ‘ambiguous’ unless the entire interaction—the whole ‘phenomenon’—is described. It is worth noting that the ‘ambiguity’ of which he speaks is not that it is ‘ambiguous’ whether the system is to be considered a ‘wave’ or a ‘particle,’ but rather that it is the ‘description’ of the state of the system which is ‘ambiguous’ because the experimental arrangements necessary to determine both canonical state parameters are mutually exclusive. He first introduces ‘complementarity’ in his ‘Como paper’ of 1927 with this remark:

This situation has far-reaching consequences. On one hand, the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case, according to the quantum postulate, any observation will be impossible, and, above all, the concepts of space and time lose their immediate sense. On the other hand, if in order to make observation possible we permit certain interactions with
suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word. The very nature of the quantum theory thus forces us to regard the space-time co-ordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively.

He observes, “This situation has far-reaching consequences” but aside from telling us that “space-time co-ordination and the claim of causality” are “complementary but exclusive features of the description” it is far from clear what these consequences are. Here I want to suggest that these consequences are ‘far-reaching’ because they imply that the ‘objectivity’ of the resulting description can no longer be grounded in the ontological supposition that the description of nature predicates properties of its ‘object’ which refer to properties actually possessed by the object system apart from any observational interaction with it. Thus to save the objectivity of the description, the ‘quantum mechanical state’ of a physical system must be understood in a different sense from the way the classical mechanical state description was understood.

In his new framework, Bohr moves ‘objectivity’ from the ontological context given to it by classical mechanism and reconstructs it on an epistemological basis. ‘Objective’ description now means description which is unambiguously expressed in terms of everyday human experience, of the ‘common framework adapted to human use and daily life’ such that everyone could agree on it. Again Bohr’s reasoning precipitates the subsequent development of positivism. In the 1920’s and 30’s when Bohr was writing, positivists hoped to reduce the superstructure of theoretical statements to foundational ‘incorruggible’ observation reports expressed in a purely observational vocabulary. This would have been the empiricists’ surrogate for the rationalist doctrine of primary properties. They would refer directly to properties of elements of pure experience, or sense data or whatever, unsullied by any subjective ‘interpretation’ put upon what is alleged to be ‘directly given.’ But the quest for such a foundational vocabulary was doomed. Eventually positivists—as well as the pragmatists and Popperian realists—had to retreat back to the conventionalist position that there is no one privileged language or conceptual scheme which attaches directly to empirical reality. Alternative possibilities exist, and the choice of the language that actually does get chosen is made for pragmatic, rather than foundational, reasons. This was Carnap’s move to ‘physicalism’: observation sentences are simply those on which all rational persons with normal sense organs will agree. In this sense Bohr’s new conception of ‘objectivity’—like the positivist recourse to physicalism—provides an empiricist foundational ‘observation’ statement, but it is only a relative foundation, relative to the particular framework used to express this particular description of nature. It is, I think, fair to say that Bohr’s proposed revision of the conception of objective knowledge is at least as much ‘pragmatic’ as ‘positivistic,’ but the point I want to make here is not its philosophical pedigree, but that once ‘objectivity’ is defined in this manner, its basis is epistemic, resting on what we are justified in accepting or believing, rather than ontological, seated in the properties independently possessed by an individual object, a body as described by classical mechanism.
4 The Ontological Lesson of Complementarity

Because Bohr redefines ‘objectivity’ in the manner he proposes, in moving from describing systems in classical mechanical states to describing them in quantum mechanical states the system which is in such a state can no longer be regarded as a ‘substance possessing properties’ precisely because what we predicate of the system in such a state is not, in general, regarded as the ‘properties’ possessed by a substance. Now in the quantum description, the ‘system’ which is in a quantum mechanical state must be reconceived as an interaction which has a feature of ‘wholeness’ or ‘individuality’ that implies that the distinction between ‘object system’ and ‘observing system’ necessary for making a description of that interaction ‘unambiguous’ is relative to the context of the description. He certainly recognized that this move would have ontological consequences, for in the passage immediately preceding his inaugural introduction of ‘complementary’ he tells us that “…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.” But aside from this merely negative declaration that they do not have “an independent reality in the ordinary physical sense,” Bohr leaves us in the dark ontologically, when it comes to the sort of non-ordinary ‘reality’ we are to ascribe to the objects of atomic physics. This reticence in making ontological claims left this dimension of complementarity undeveloped. So from here on we must extrapolate from—or perhaps reconstruct—what Bohr has told us about his ‘new viewpoint.’ Bohr developed an epistemological lesson because his argument terminated in a conclusion about how we gain scientific knowledge about physical systems at the atomic level. But epistemological claims about what kind of knowledge we can or cannot have about such systems have ontological implications about what such systems which are in quantum mechanical states must be. Until such implications are understood, the ‘foundations’ of the quantum theoretical description of matter will remain mysterious.

Traditional realists have aspired to construct ontological models on the basis of a pattern of reasoning long enshrined in the classical conception of an ‘objective’ description within a substance/property ontology. Following such reasoning, a ‘realist’ reading of complementarity seems to produce paradoxes such as a particle which traces a trajectory through the left slit, but ‘knows’ whether the right slit is opened or closed; or a cat in a superposition of alive and dead states. Such paradoxes do not arise because of any application of the formalism, which in each case is self consistent and in accord with the empirical data. However, the paradoxical character of the description lies in the disconnect between the concept of being the sort of ‘system’ which could be in a quantum mechanical state, and our ontological preconceptions about substances and their properties conditioned by classical mechanical expectations.

If we say that the ‘system’ which is described as ‘in a quantum mechanical state’ is not understood via the traditional Aristotelian conception of subject as substance, that of which our description truly predicates properties, but rather is an indivisible phenomenon described as an interaction of which we predicate possible outcomes, the paradoxical quality of the concept of the quantum mechanical state disappears. This is what Bohr called the unexpected feature of ‘atomicity’ in the quantum world. What are indivisible are not tiny ‘bodies,’ Cartesian rei extensae, but processes or events in which the prior state of one system has a causal effect on the subsequent state of another
system. Thus the ontological lesson which the need for recourse to complementary descriptions teaches us is that the physical properties to which the classical concepts refer now belong to the termini of an indivisible phenomenon; they define at one end its preparation state and at the other its outcome state. The quantum-mechanical ‘systems’ of which we predicate ‘quantum mechanical states’ are interactions with a ‘superposition’ of probabilistically weighted possible outcomes.

Much of our confusion, it would seem, arises from what amounts to an equivocation on what is an ‘object’ in the description of nature. Classically the ‘object of our description,’ a body possessing primary kinematic and dynamic properties, was the same object which is the ‘system’ that is ‘in a classical mechanical state.’ Whether that system was described as ‘interacting’ with another system or as ‘isolated’ from interaction classically was irrelevant. In the quantum theoretical description of nature at the microlevel we can no longer move directly from observed system to isolated system, but the tendency to do so is deeply entrenched because the objects in the world of our ordinary perceptual experience, which are the ultimate referents of any description of an empirical outcome, are objects which can be treated as ‘isolated’ from any dynamical effects of our perception of them. Consequently the predicative assertions we make about them can be treated as attributing properties to substances in the manner long ago analyzed by Aristotle. When we treat statements about the things described by quantum mechanics in the same way, because of the quantum postulate, we are led to paradoxical conclusions. Therefore, the object of our description, the ‘system’ which is ‘in a quantum mechanical state,’ cannot be a substance possessing properties, but must be regarded as a whole phenomenon which theory allows us to interpret as an interaction between measuring system and the object—the ‘atomic system’—of which a measurement outcome is predicated. But the quantum postulate, implying as it does the indivisibility of such interactions, forces us recognize that the ‘object’ in this sense of that of which we predicate a measurement outcome is not the same ‘object’ which is the system ‘in a quantum mechanical state.’

While I would contend that such an ontological lesson, once fully absorbed into the physicist’s conception of nature, would remove the paradoxical or mysterious quality of the microdomain, there remains—of course—something ‘surprising’ about this quantum description. It is that the objects of our description, these interactions, do not have determined outcomes. If Bohr and the Copenhageners are right, indeterminacy is a real aspect of Nature; and quantum theory is, after all, the consequence of a fundamental indeterminacy of nature at the microlevel. This is surprising against classical intuitions, but not ‘paradoxical’ in the same sense as a cat in a superposition of alive and dead states.

Of course we have had nearly a century to get used to the idea of indeterminacy at the atomic level. We’re not so classically obsessed anymore, and that’s not so terribly ‘surprising.’ But the ontological lesson—at least to a realist—that remains also still ‘surprising’ is that if the seeds of being are not substances possessing essentially spatial locus but are interactions which have a feature of ‘indivisibility’ or ‘atomicity,’ then a single whole interaction may very well have nonlocal outcomes. Bohr’s response to EPR explicitly warned that a description would be ‘ambiguous’—and so not ‘objective’ in his sense—if the entire phenomenon is not included as a single indivisible whole in the description. ‘Quantum systems’ are ‘non-separable’ precisely because on this view they are not spatio-temporally located substances; we must, in Bohr’s words, ‘renounce
space-time pictures.’ Thus in Bell type phenomena spatially separated measurements on ‘particles’ all form part of the outcome of a single interaction in a single ‘quantum mechanical state.’ Perhaps this remains surprising to us in a way which I suspect it didn’t seem to Bohr from his ‘new point of view of complementarity’ because we have not followed the same journey he did. After all, these violations of determinacy and locality had their birth in Bohr’s conception of the interaction between an atom and the field as a ‘discontinuous’ transition between non-visualizable stationary states: in the famous words attributed to Schrödinger: ‘those damned quantum jumps.’

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