Bohr's Answer to EPR

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You'll recall that the EPR argument is supposed to be a reductio ad absurdum of the idea that QM is complete. The key step in their argument is their "proof" that the reality condition implies that two conjugate quantities (in particular, position and momentum) can simultaneously have values. Let's call this part of the argument the **EPR lemma**:

> Given the reality criterion (and locality), it is possible for both *position* and *momentum* to have sharp values simultaneously.

Already by 1927, Niels Bohr had come to the conclusion that position and momentum cannot simultaneously have values. He calls this the **complementarity principle**. In this chapter, we'll look more closely at *why* Bohr is convinced of complementarity. As a preview, his reasons are *not* primarily mathematical. In particular, when asked to justify complementarity, Bohr doesn't typically invoke von Neumann's NHV theorem.

So, Bohr does not accept the conclusion of the EPR lemma. If the EPR lemma is a valid argument, then either Bohr rejects one of its premises, or (more radically) he rejects the framework in which the argument is formulated. In order to come to a fair assessment of what Bohr's objection amounts to, let's first gather two sets of data. The first set of data consists of some general remarks about Bohr's outlook. The second set of data consists of specific citations from the Bohr paper, to which I'll add some commentary.

Bohr's outlook

- Bohr thinks that there is no fixed boundary between "self" and "world", or between "subject" and "object." He illustrated that point with the

example of a walking stick. He says that the walking stick can be treated as an extension of a person's own body, or it can be treated as something *other*, i.e. an object of investigation.

Other examples Bohr might have availed himself of: prostheses, eyeglasses, smartphones.

Bohr thinks that this general point should be applied when talking about measuring devices. i.e. a measuring device can be considered as an extension of one's own self.

- Bohr thinks nothing can be the same after the discovery of the **quantum of action**, i.e. the discovery that the physical quantity "action" has a basic unit (Planck's constant) that cannot be further subdivided. In particular, Bohr claims that this fact implies a limit to the "analysis" of position and momentum relations between any two objects. In any interaction between two physical objects, if the second object serves a reference frame, then the law of conservation momentum no longer applies to it.

  See: "...the finite and uncontrollable interaction between the objects and the measuring instruments in the field of quantum theory." (p 700) I think Bohr means to say that a person/subject is also a measuring instrument, but the quantum of action implies that she cannot possible keep track of her own state/condition when she performs a measurement. e.g. if you perform a position measurement, then you can't keep track of how much your own momentum changed ("the transfer of momentum") in the process of the measurement.

  See: "...the renunciation ...of one or the other of two aspects of the description of physical phenomena ...depends essentially on the impossibility of accurately controlling the reaction of the object on the measuring instruments." (p 699)

- Bohr thinks that the complementarity between position and momentum is a relation between concepts, not between things out in the world. He thinks that when position can be defined, momentum cannot be defined. It's not that momentum is fuzzy (when position is sharp), it's that the momentum concept is inapplicable.

  Question: when is the momentum concept applicable?

Citations

- The reality criterion "contains an essential ambiguity when it is applied to quantum phenomena." (p 696, abstract)

  "... a criterion of reality like that proposed by the named authors contains ... an essential ambiguity." (p 697)

  "... essentially different experimental arrangements and procedures which are suited either for an unambiguous use of the idea of space location, or for a legitimate application of the conservation theorem of momentum." (p 699)

  "... the impossibility of defining these quantities in an unambiguous way." (p 699)

  These sentences refer to one of Bohr's favorite concepts: "ambiguity". He doesn't just mean that EPR have failed to express the reality criterion clearly. Instead, he intends to point to a deeper problem that an intented description of reality can fail to make sense if conditions aren't right ... or, more accurately, if one doesn't hold fixed certain presuppositions about one's own condition.

- "... lost our only basis for an unambiguous application of the idea of momentum ..." (p 700)

  Ambiguity again! Here's how I'm reading Bohr: imagine that you see a ship off in the distance, and you want to tell another person where it is. But imagine that you've become disoriented, so you don't know which direction is north, which is east, etc. Then you've lost your basis for an unambiguous application of the idea of direction. If you say that "the ship is at two o'clock" then your description is ambiguous.

  Similarly, imagine that you have no idea about how fast you're moving or in which direction. Then reporting to another person that something is moving at 10 mph is ambiguous, because they don't know which reference frame you are reporting from.

- "... such measurements of momentum require only an unambiguous application of the classical law of conservation of momentum." (p 698)

  For example, to describe something as having momentum, one needs to be in a condition where one can apply the law of conservation of

momentum unambiguously. (I'm not totally sure what those conditions are, but I suspect it has something to do with not supposing one's own spacetime location to be fixed.)

- "From our point of view we now see that the wording of the above-mentioned criterion of reality proposed by Einstein, Podolsky and Rosen contains an ambiguity as regards the meaning of the expression 'without in any way disturbing a system'." (p 700)

  Here I think Bohr is using "ambiguity" in a less technical sense. I think he just means that there are various things we can understand by "disturbing a system." He himself distinguishes between "mechanical disturbance" (which he says doesn't happen) and "an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system."

  This last sentence is a doozy. To be honest, I think Bohr is struggling here with what to say about the issue. By "very conditions which define the possible types of predictions" he might just be thinking of wavefunction collapse as an epistemic process, i.e. a sort of statistical updating (like Bayesian updating). But if we put emphasis on "types", then it's not about changing one's predictions, it's about changing the the types of predictions. That doesn't sound like simple updating.

  So, Bohr seems to accept that a measurement by Alice *can* disturb Bob's distant system in this second sense of "disturb."

- Looking at that last sentence again: "... an influence on the very conditions ..." and the subsequent sentence "Since these conditions constitute an inherent element of the description of any phenomenon to which the term 'physical reality' can be properly attached." (p 700)

  What do you think Bohr means here by "conditions"?

  If Bohr is equating "conditions" with "physical state of affairs", then it's not clear at all how his kind of disturbance would differ from mechanical disturbance. So, I think he isn't equating these two.

  Why would "conditions" make up part of any description to which the term 'physical reality' can be properly attached?

  There's also a clue here about what Bohr means by "conditions," because they make up a part of a "description." So, "conditions" isn't

a physical state of affairs, it's a kind of semantic thing. Compare, for example, with the notion of a "context" that is in use among linguists and philosophers of language.

- "Of course there is in a case like that just considered no question of a **mechanical disturbance** of the system under investigation." (p 700)