The ontological status of quantum probabilities

or

Quantum probabilities: What the hell are they?

May 26, 2014

Ronnie Hermens

university of groningen

Common wisdom? Some snapshots

"An experimentally tested theorem by the Northern Irish physicist John Bell says there is no true state of the particle; **the probabilities are the only reality** *that can be ascribed to it."*

–

wired.com

"**The quantum world is probabilistic** *in nature not because quantum mechanics as a theory is incomplete or approximate, but rather because the atom itself does not 'know' when this random event will take place. This is an example of what is called 'indeterminism'."*

–

Al-Khalili

"**There is no quantum world.** *There is only an abstract physical description."*

–

Bohr

Outline

Historical part:

- Probability in the old quantum theory
    - When and why were probabilities introduced, and how were they received?

Formal part:

- The untenability of determinism
    - Conway & Kochen's 'Free Will' Theorem
    - $\Rightarrow$ Quantum Probabilities do not express ignorance about 'hidden variables'
- The untenability of objective chance
    - Bell's Theorem
    - $\Rightarrow$ Quantum Probabilities are not chances

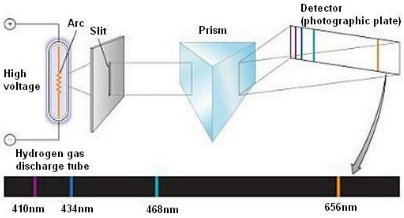
Conclusion:

- Indeterminism without chances
    - $\Rightarrow$ Quantum Probabilities are epistemic judgments about undetermined measurement outcomes

Probability in the old quantum theory

Putting the quantum in quantum theory

19th century: Development of spectroscopy



The spectrum of light emitted is discrete.

1885: Balmer finds empirical formula

1888: Rydberg generalizes

$$\frac{1}{\lambda} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right), \; n_1 < n_2$$

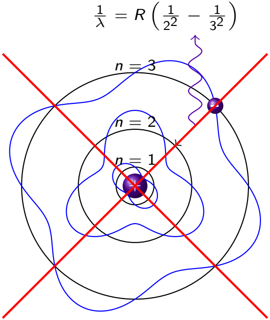
These results are phenomenological, the development of a theoretical underpinning is tied up with the development of quantum mechanics.

Probability in the old quantum theory 2

1913: Bohr's model: Possible classical orbits of electrons are also discrete.

1923: De Broglie: particles are constrained by waves.

1925: Heisenberg introduced **matrix mechanics**. No pictorial representation. Incomplete: $[x, p] \neq 0$.



1926: Schrödinger introduced **wave mechanics**. Waves as ontological objects. Empirical 'equivalence' with matrix mechanics. Heisenberg and Schrödinger don't have opposing theories, but opposing **interpretations** of the same theory: **quantum mechanics**.

1926: Born introduces probability as a 3rd interpretation of the quantum state, opposing both Heisenberg's and Schrödinger's interpretation.

Probability in the old quantum theory 3

1926: Heisenberg didn't like Schrödinger's view:
"The more I think about the physical portion of Schrödinger's theory, the more repulsive I find it... What Schrödinger writes about the visualizability of his theory 'is probably not quite right,' in other words it's crap."

1927: but embraced Born's probabilities to motivate his own **Copenhagen interpretation**.
Derived uncertainty relation $\Delta x \Delta p \geq \hbar/2$ that defends 'incompleteness' of his theory.

1927: De Broglie suggests 4th interpretation. **Pilot-wave theory**: waves are not the primitive ontological objects but are guiding the particles. Probabilities only play a secondary role.
Nobody seemed to like it and it was believed that von Neumann proved in 1932 that it was inconsistent.

Born's probabilities are useful, but what about their interpretation?

Einstein's view on quantum probabilities

Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one'. **I, at any rate, am convinced that He is not playing at dice.** *Waves in 3n-dimensional space, whose velocity is regulated by potential energy... – 1926 (letter to Born)*

The attempt to conceive the quantum-theoretical description as the complete description of the individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that **the description refers to ensembles of systems and not to individual systems***...quantum theory would, within the framework of future physics, take an approximately* **analogous position to the statistical mechanics** *within the framework of classical mechanics. – 1949*

Probability in the Copenhagen view

From the fact that in quantum theory a particular state only yields a probability function, one may say, with Born and Jordan, that a characteristic statistical move is made away from the classical theory. However, one can also say, with Dirac, that **the statistics are brought forward by our experiments.**

Heisenberg 1927

The entire formalism is to be considered as a tool for deriving predictions of definite or statistical character [...]These symbols themselves [...] are **not susceptible to pictorial interpretation***; and even derived real functions like* **densities and currents are only to be regarded as expressing the probabilities** *for the occurrence of individual events observable* **under well-defined experimental conditions.**

Bohr 1949

Intermediate evaluation (or Conclusion?)

Three views:

1. Orthodox view: QM is complete, quantum states and associated probabilities pertain to (intrinsic) properties of systems.
2. Hidden variables: QM is incomplete, quantum probabilities express an ignorance concerning hidden parameters.
3. Epistemic view: QM is complete, quantum states and associated probabilities are epistemic descriptions of systems.

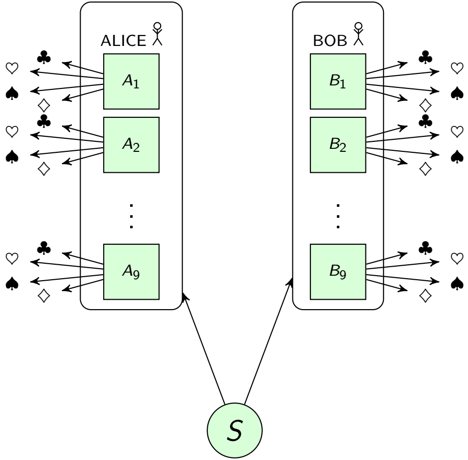
Questions:

- Is indeterminism in the sense of value indefiniteness of observables necessary?
  - Answer: no, but there are 'good' reasons to accept this form of indeterminism.
  - This question can be investigated without going into the role of probabilities!
- Accepting value indefiniteness, does this imply the existence of objective chances?
  - Answer: no, and the same reasons to accept indeterminism also motivate an epistemic stance on quantum probability.

Constraints on determinisn: the free will theorem

⇒ Based on the paper by Cator & Landsman arXiv:1402:1972.

$$\text{Determinism} \wedge \text{Parameter Independence} \wedge \text{Freedom} \wedge \text{Nature} \rightarrow \bot$$



Possible outcomes

$$\mathcal{O} = \{\clubsuit, \heartsuit, \spadesuit, \diamondsuit\}$$

Possible measurements for Alice

$$\mathcal{M}_A = \{A_1, A_2, \dots, A_9\}$$

Possible measurements for Bob

$$\mathcal{M}_B = \{B_1, B_2, \dots, B_9\}$$

Determinism There is a set X and functions $M_A : X \to \mathcal{M}_A$, $M_B : X \to \mathcal{M}_B$, $O_A : X \to \mathcal{O}$, $O_B : X \to \mathcal{O}$. Every $x \in X$ determines the measurements to be performed and their outcome.

Parameter Independence There is a function $F_Z : X \to Z$ and functions $\hat{M}_A : \mathcal{M}_A \times Z \to \mathcal{O}$, $\hat{M}_B : \mathcal{M}_B \times Z \to \mathcal{O}$ such that the diagram commutes:

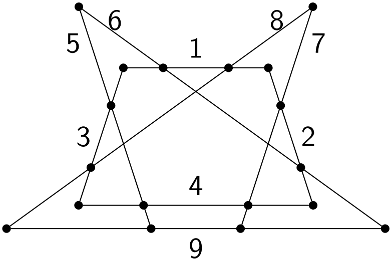
$$\begin{tikzcd}
\mathcal{O} & & X \arrow[ll, "O_A"'] \arrow[rr, "O_B"] \arrow[d, two heads, "{(M_A, M_B, Z)}"] & & \mathcal{O} \\
\mathcal{M}_A \times Z \arrow[u, "\hat{M}_A"] & & \mathcal{M}_A \times \mathcal{M}_B \times Z \arrow[ll] \arrow[rr] & & \mathcal{M}_B \times Z \arrow[u, "\hat{M}_B"']
\end{tikzcd}$$

Freedom (M_A, M_B, Z) is surjective: for every (a, b, z) there is an x such that

$$M_A(x) = a, \ M_B(x) = b, \ Z(x) = z$$

Constraints on determinism: the free will theorem 3

Nature The outcomes of the possible measurements $A_1, \ldots, A_9$ and $B_1, \ldots, B_9$ are correlated according to the diagram



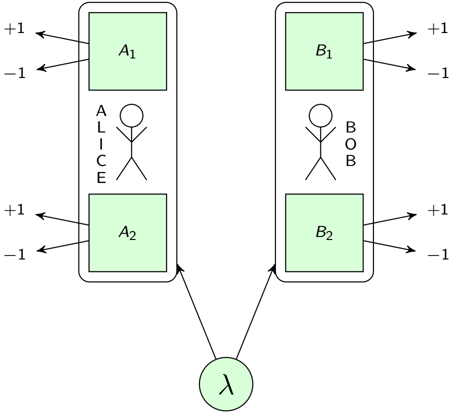
such that for every x if $M_A(x) = A_i$ and $M_B(x) = B_j$ and lines i and j intersect, then either *both* $O_A(x)$ and $O_B(x)$ correspond to the outcome of that intersection, or *neither* do.

Intermediate Conclusion

- There are no hidden variables that assign definite values to *all possible measurements*.
  - 'Super determinism' can reduce the set of 'possible measurements' to a singleton. This eliminates the choice for the experimenter.
  - Hidden variables are possible if one allows for non-local actions.
- Without hidden variables, quantum probabilities cannot express an ignorance concerning these variables.
  - Without determinism there is no definite future state to be ignorant about.
- Two options:
  1. Quantum probabilities are intrinsic properties of nature (chances)
  2. Quantum probabilities are epistemic judgments of something else

The Bell Inequality

$$\text{Source Independence} \wedge \text{Bell Locality} \wedge \text{Nature} \rightarrow \perp$$



Assumptions

Source Independence:

$$\rho_{A_i,B_j}(\lambda) = \rho(\lambda)$$

Bell Locality:

$$P_{A_i,B_j}(O_A = x | O_B = y, \lambda) = P_{A_i}(O_A = x|\lambda)$$

Bell Inequality:

$$P_{A_1,B_1}(O_A = O_B) \leq P_{A_1,B_2}(O_A = O_B) + P_{A_2,B_1}(O_A = O_B) + P_{A_2,B_2}(O_A = O_B)$$

Note: Probability occurs as a primitive concept; the interpretation of Bell's Theorem depends on the interpretation of probability.

The Bell Inequality 2

When is a violation of Bell Locality a violation of locality?

$$P_{A_i,B_j}(O_A = x|O_B = y, \lambda) \neq P_{A_i}(O_A = x|\lambda).$$

- Quantum probabilities are propensities; properties of experimental arrangements. These properties then change non-localy.
  (Compare ψ-ontic collapse theories.)
- Propensities could be field-like global 'objects' rather than localized properties. This field then still changes instantaneously and non-localy when Bell Locality is violated.
  (Compare ψ-ontic no-collapse theories/modal interpretations.)
- Quantum probabilities are Humean chances that supervene on a more fundamental structure. A violation of Bell Locality does not imply a non-local change in this fundamental structure.
  (Compare ψ-ontic no-collapse theories like Everettian QM.)
- Quantum probabilities are degrees of belief. Violations of Bell Locality are just Bayesian updates. (Compare ψ-epistemic theories.)

Conclusion

- To save 'locality' and 'free will', determinism in the form of *unique definite values* has to be given up.
  (The Free Will Theorem)
- For roughly the same reason, thick metaphysical notions of chances are also untenable.
  (Bell's Theorem)
- The options on the table then are some form of Humean Chances, or a Bayesian approach.
- How distinct these two options are, however, may depend on the extend to which one accepts the principal principle
  $\mathrm{Cr}(A|P(A) = x) = x$.

The end. . .

Thank You