Shan Gao: The Meaning of the Wave Function. In Search of the Ontology of Quantum Mechanics.

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Book review

"The Meaning of the Wave Function. In Search of the Ontology of Quantum Mechanics", by Shan Gao.

Reviewed by Carlo Rovelli

Shan Gao is a philosopher of physics at the Research Center for Philosophy of Science and Technology, in Shanxi, and a prolific writer, with nineteen books, both technical and for the large public, covering a variety of topics in fundamental physic. For some time, Gao has been developing an original perspective on quantum mechanics, based on the idea that the wave function describes the random *discontinuous* motion of real particles: a quantum particle jumps around discontinuously, and the wave function gives the density of its presence in a region during an arbitrary small time interval. The idea is supplemented by a model of physical collapse, which modifies the the quantum dynamics adding a stochastic, nonlinear evolution term, resulting from the random motion of the particles. Gao argues in favour of this view starting from the existence of *protective measurements*, a particular class of interactions allowed by quantum theory, where the expectation value of any observable of a system can be recorded by a second system, without altering the quantum state of the first. In the book "The Meaning of the Wave Function. In Search if the Ontology of Quantum Mechanics", he gives a detailed and meticulous illustration of this view, and the arguments supporting it, engaging in a careful discussion with many arguments present in the literature.

Up to discriminating empirical results, or proven logical inconsistencies, "interpretations" of quantum mechanics cannot be truly proven or disproven. They give us a way to think about the theory, and about nature in general, they can orient scientific research, and they interact strongly with our general philosophical orientations. The interaction is in both directions: on the one hand, they question or support general philosophical perspectives (realism/empiricism, for instance), showing these to be more or less capable of accounting for our present scientific knowledge; on the other, our preference for this or that interpretation is often strongly coloured by our inevitable philosophical prejudices.

The problem is hard because no interpretation of quantum mechanics is costless. Each has a cost, which is viewed by those who do not like it as too high a price to pay with respect to the gain. Examples of these "costs" are the multiplication of "worlds" in the *many-worlds* interpretation; the in principle un-observability and breaking of Lorentz invariance of postulated entities in *Bohmiam* interpretations; the perceived artificiality of *physical collapse* interpretations; the weakening of realism in the *relational* interpretation; the ambiguous status of the classical world in the common *"Copenhagen"* interpretation, which is still the popular view of quantum theory in physics labs; and so on. In whatever way we think about quantum theory, we always give up something cherished that many of our colleagues consider too high a price to pay for a coherent understanding of nature. Opinions do evolve, but so far no perspective has proven to be definitely more fruitful or widely convincing than the others.

Gao's *random discontinuous motion* interpretation adds itself to the list. Its strength is its realism and a certain physically intuitive concreteness. Among its weaknesses is the fact that it still needs a physical collapse mechanism to account for measurement. Perhaps the publication of the book will prompt a critical evaluation of its merits and difficulties; here I limit myself to a couple of very general considerations.

There are two general overall ways of understanding quantum theory. According to the first, the theory is about the values taken by *variables* of physical systems in interactions. This is Heisenberg's original view, which led to the actual discovery of the theory. According to the second, the theory is about an entity ψ, the wave function or, more in general, the *"quantum state"*. This view was initiated by Schrödinger one year *after* Heisenberg, Born and Jordan had already developed the full mathematical apparatus of what we call quantum mechanics today. I myself find Heisenberg's view (values of *variables*) more coherent and I think that this view is going to be more fruitful in the future, but Schrödinger's view (entity ψ) is still very popular. Gao's perspective can be seen as an attempt at a compromise: a particle has position, but because of its random everywhere discontinuous motion position is spread during each arbitrary small time interval, and ψ describes this spread.

The argument the book offers to introduce such realistic interpretation of ψ is the existence of protective measurements. A protective measurement is an interaction between a system and a device, at the end of which the device records the expectation value of a physical quantity A of the system, and the state of the system remains unaltered. Contrary to naive expectation, this is indeed possible for any ψ and any A. At first sight, this seems to contradict the common idea that it is impossible to measure an arbitrary quantity A in a state ψ without altering ψ. The existence of such protective measurements is therefore often presented as good argument in favour of a realistic interpretation of the wave function. `If I can measure it without altering it, it must be real.'

I am unconvinced by this interpretation of protective measurements. The catch, seems to me, is the ambiguity in the word *measurement*. To be able to concretely perform a protective measurement we need to have *already* measured ψ almost entirely: in fact, only up to a single number. The reason is that in order to perform a protective measurement we need to know *preventively* one of the observables, O, of which ψ happen to be an eigenstate of, and the `measuring' device must be built accordingly. But if we know that ψ is an eigenstate of O, we already know everything there is to know about ψ up to a single number (the eigenvalue); and this number, according to quantum theory, is precisely the number that can be measured without further altering ψ. This clarified, the existence of protective measurements is far less telling than what it looks at first sight: it just tells us that if we know almost everything about ψ we can then ascertain the last bit without altering it. It is then unsurprising that we can build a device that interacting with *this* largely known ψ can record any ψ-dependent quantity we wish. The same device would not work on a different ψ. It is a bit as if the information to be measured was already largely coded into the device itself.

This consideration does not discount Gao's interpretation, of course. It exemplify how in the debate on the meaning of quantum theory often arguments that seem convincing to one appear less so to another. One of the best aspects of Gao's book, actually, is the punctilious account of many arguments and counterarguments given in the literature; as such, the book is also a useful source and an overview of number of debates around the interpretation of quantum theory.

After the great initial debates of the early days of the theory, and the long subsequent period of neglect, the grand debate on the meaning of quantum theory is now receiving ever-increasing attention. I think that this is healthy, and we need this debate to go ahead in science. I do not expect rapid convergence, but technical points are clarified, ideas are emerging and opinions evolve. At some points, the dust will begin to settle, as it has happened to similar great debates on the past, which appeared undecidable for a while. What have we precisely learned about nature, in discovering that this spectacular formalism is so effective in predicting its ways?