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Book Review

SHAN GAO

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

Shan Gao, *The Meaning of the Wave Function: In Search of the Ontology of Quantum Mechanics*, Cambridge University Press, 2017, 205pp., $140, ISBN: 9781107124356.

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Shan Gao has written an exemplary book on the nature of the wave function—its theoretical role, the ontology it represents, and how understanding this ontology can contribute to solving the measurement problem. These themes are connected by a single line of argument that runs through the book from beginning to end. The argument is presented clearly and concisely, and the relevant philosophical and physical background is explained with admirable clarity and precision, without either excessive verbiage or unnecessary technicality. Gao's proposed solutions to the foundational problems of quantum mechanics are clear, novel, and well-motivated.

In the course of his argument, Gao offers three distinct contributions to understanding the foundations of quantum mechanics: first, that protective measurements show that the wave function describes an individual physical system; second, that the system described by a wave function is best understood in terms of a set of particles moving randomly and discontinuously in three-dimensional space; and third, that this random, discontinuous particle motion provides new tools for solving the measurement problem via a collapse theory.

Ordinarily, measurement provides us with fairly direct access to the world. If I use a tape measure to determine the width of a window, the reading on the tape measure reflects a physical property of the window, and it does so without affecting that property. But a typical (projective) quantum measurement does not provide us with such unequivocal access to the world: the measurement disturbs the measured system, and the pre-measurement wave function is connected only probabilistically to the measurement results. In this situation, it is hard to say whether measurement results reflect pre-existing physical properties of the system, and hence it remains an open question whether the wave function should be taken as a representation of a single physical system (rather than a representation of an ensemble of systems, or a representation of our knowledge of the system).

Protective measurements, Gao argues, provide us with more direct access to the physical world, analogous to that provided by a tape measure. During a protective measurement, the measured system is undisturbed, and the wave function *determines* the outcome of the measurement. For a protective measurement of observable A, the unique outcome is the expectation value $\langle A \rangle$. Hence Gao concludes that $\langle A \rangle$ must be a physical property of the measured system. This might seem like a category mistake: how could a statistical property like an expectation value be a physical property of a single system? But if the wave function is taken as a description of a single physical system, then $\langle A\rangle$ can be regarded straightforwardly as a property of the system, analogous to a center of mass. Since a series of protective measurements could in principle characterize the wave function completely, Gao concludes that the wave function should be interpreted as descriptive of a single system. To do otherwise, he argues, is to adopt a double standard, since in classical cases (like the tape measure) we take the measured value as descriptive of the system before us.

This result, as Gao recognizes, raises more questions than it resolves: it is far from clear *how* we can understand the wave function as descriptive. The wave function of an N-particle system is defined on a $3N$-dimensional configuration space; does that mean that our *world* is $3N$-dimensional, where N is the number of particles in the universe? How can the existence of an entity that is spread out over the whole of space explain the fact that when we measure the position of a particle (using an ordinary projective measurement) we find it at a precise location? How can the existence of such an entity explain the fact that the results of projective measurements are distributed probabilistically according to the Born rule?

Here Gao makes a simple but radical suggestion: the wave function for a single-particle system really does describe a localized *particle*, and the reason that the wave function is spread out is that the particle moves randomly and discontinuously throughout space. That is, the particle spends only an instant at each location, before jumping discontinuously and randomly to another, and the square of the wave function amplitude gives the probability distribution for this jumpy existence.

Although radical, this view is not unprecedented: as Gao points out, Schrödinger early on suggested that the wave function of a charged particle might be understood as a charge density. But he later rejected this view, both because of the high dimensionality of the wave function of a multi-particle system, and because the parts of a charge cloud ought to interact, yet the parts of the wave function exhibit no such self-interaction.

Gao addresses both these difficulties. Concerning the former, Gao suggests that the high-dimensional wave function for a multi-particle system describes the motion of a set of particles in three-dimensional space. Consider, for example, two particles in an entangled state, where each is in a superposition of occupying two distinct spatial regions. According to Gao, the two particles jump randomly and discontinuously between the two regions, and the fact that they are entangled means that their jumps are correlated, so that they always occupy the same region at the same time. The most convenient way to represent the probability distribution for two correlated particles is as a distribution over a six-dimensional configuration space, but that doesn't mean that the physical system represented is six-dimensional.

Concerning the latter, Gao notes that under his interpretation of the wave function, distinct regions of the wave function of a single particle represent distinct *temporal* parts of the particle: the particle never occupies two regions at the same time. This gives a neat explanation of the lack of self-interaction: we wouldn't expect distinct temporal parts of a charged particle to repel each other like the parts of a charge cloud repel each other. Hence Gao provides a defense of something like Schrödinger's original proposal: the squared wave function amplitude of a charged particle really does represent a charge density distribution, but understood as a probability distribution for a well-localized charged particle undergoing random, discontinuous motion.

Since Gao's proposal, like Bohm's theory, represents particles as always having precise locations, it might be thought that Gao's proposal also provides a solution to the measurement problem: a position measurement yields a determinate result precisely because the particle always has a determinate position. But Gao argues that his proposal should not be taken as a direct solution to the measurement problem. In Bohm's theory, a measurement of the position of a particle essentially confines the particle to one branch of the wave function, a branch corresponding to one particular measurement result. But under Gao's proposal, after a measurement the particle continues to jump randomly between branches of the wave function corresponding to every possible measurement outcome. So it looks like further work is needed to solve the measurement problem.

Gao undertakes this further work in the form of a spontaneous collapse theory: under certain circumstances, circumstances that typically obtain during a measurement, the wave function undergoes a spontaneous random process during which all but one branch has its squared amplitude reduced almost to zero. Then given the connection Gao proposes between squared wave function amplitude and probability, it becomes overwhelmingly likely that the particles remain in one branch.

Gao's proposal shares features with existing spontaneous collapse models, but it differs in two respects. First, the source of the randomness in the collapse process is precisely the random discontinuous motion of the particles, so unlike in other spontaneous collapse models, Gao does not have to postulate a source of randomness that does no other work. Second, Gao's model is constructed so that energy is conserved, unlike other models that entail a small violation of conservation of energy.

Gao's argument has three main parts: first, that protective measurement shows that the wave function represents a single physical system, second, that random discontinuous motion provides the best understanding of the nature of the wave function, and third, that a spontaneous collapse theory provides the best way to harness random discontinuous motion to solve the measurement problem. I will briefly assess these aspects of his argument in turn.

I have criticized the connection between protective measurement and quantum ontology before (Lewis 2014), and I remain skeptical that protective measurement provides conclusive evidence about the role of the wave function. In large part, my skepticism follows from a more general skepticism about "criteria of reality"—criteria that purport to establish a theory-independent connection between measurement and reality. Einstein famously relied on a criterion of reality in his EPR paper, and Gao's argument also appeals to a criterion of reality, albeit a weaker one than Einstein's: if a measurement returns a definite result, and the pointer shift rate during the measurement is determined by the result, then the measurement reflects a physical property of the measured system (p.39).

As it stands, I suspect this criterion is *too* weak: a device with a pointer which moves on a scale based on some internal degree of freedom of the *device* would seem to satisfy the condition, even though the reading on the scale is independent of the properties of any "target system" to which the device might be attached. Perhaps the response is that this shouldn't count as a *measuring* device, because it doesn't respond to a property of the target system. But any response along these lines seems to beg the question. What we need to ensure that this is a genuine measuring device is that it is responsive to a property of the target system. But since the criterion is supposed to tell us under what circumstances a measurement reveals a property of the target system, this response presupposes the answer that the criterion is supposed to provide.

Instead, I suspect that what counts as a measurement is always relative to a particular physical theory: a well-confirmed theory accounts for a particular set of empirical data, including telling us which of the processes by which the data were acquired should count as measurements (Albert 1992, 177). On this view, the role of the wave function and the account of protective measurement come together as a package deal. Views according to which the wave function represents a single physical system will (presumably) also count protective measurements as directly revealing a physical property of the system. Views according to which the wave function represents an observer's knowledge of a system will account for the results of protective measurements some other way, perhaps as some kind of artifact of the protective measurement procedure.

Of course, it is not easy to see how a protective measurement *could* return $\langle A \rangle$ without $\langle A \rangle$ representing a property of an individual system. (See Combes et al. (2017) for a recent proposal, and Gao (2018) for a criticism of that proposal). Epistemic accounts of the wave function face formidable difficulties, from the long-known challenges of accounting for single-particle interference, to the recent psi-ontology theorems (e.g. Pusey, Barrett and Randolph 2012). The best hope for developing an epistemic account of the wave function, I think, is the retrocausal program of Price (1994), Wharton (2010), and others, but this program has not yet produced a fully-developed theory. In principle, retrocausal accounts avoid the force of the psi-ontology theorems (Leifer 2014), and provide a means of explaining protective measurements without an ontic wave function (Lewis 2014).

The situation, as I see it, is that protective measurement provides some additional reinforcement to the already well-supported view that the wave function represents the physical state of a single system, but it does not provide a new way of ruling out possible alternatives to that view. The best way of deciding the question of the role of the wave function, I think, is not to start from a criterion of reality, but instead to examine proposed solutions to the foundational problems of quantum mechanics to see what they entail about the nature of the wave function.

So I am not convinced that Gao's attempt to motivate his account of the ontology of the quantum world by appeal to protective measurement is successful. But neither am I convinced that his account *needs* such a motivation: his theory of random discontinuous particle motion can stand on its own merits as an account of the nature of the wave function. Indeed, it has a good deal of explanatory power, including explaining the lack of self-interaction between parts of a single-particle wave function. Furthermore, it provides a satisfying concrete model of correlated particles in three-dimensional space, explaining why they are most readily represented in configuration space, and hence dissolving perennial worries about the dimensionality of the wave function. It is certainly worth exploring this model to see what further work it can do.

One of the most significant tasks for an interpretation of quantum mechanics, of course, is providing a solution to the measurement problem. Can Gao's proposal deliver a solution? Well, it can if supplemented with a collapse mechanism. But Gao's collapse proposal, although it has some nice features, inherits the main drawback of existing collapse theories, namely its reliance on a preferred frame for collapse. It is interesting to note that the preferred frame is *detectable* in Gao's collapse theory (p.160), and testability is a virtue. But I would not be willing to bet on such a direct violation of conventional relativistic wisdom.

However, I think there is a solution to the measurement problem that follows more naturally from Gao's random discontinuous motion model. This is Bell's (1981) Everett (?) solution, which Gao considers (p.92) and later dismisses (p.106). Bell's Everett (?) theory arguably rests on the same random discontinuous particle motion as Gao's interpretation, but without the additional collapse mechanism. Since there is no collapse, every post-measurement branch is retained, and the particles jump randomly between them. Bell takes this theory to be empirically adequate, in the sense that the jumping would be invisible to the observer: when the observer's particles jump from seeing outcome A to seeing outcome B, the observer's memories will jump from remembering outcome A to remembering outcome B. But it arguably involves an untenable degree of skepticism: Gao cites Barrett's (1999, 126) accusation that Bell's Everett (?) theory is empirically incoherent, in that it denies that our memories (or any other records) are reliable. Gao also argues that Bell's Everett (?) theory requires that the mental state of an observer supervenes on her instantaneous particle configuration, which is an implausible view given the dynamical account of conscious experience found in current neuroscience.

However, I think that Gao's particle model has the resources to respond to these problems. Even if the particles jump around radically, their jumps build up stable *patterns*, and given a suitably functionalist account of the mental, those patterns can constitute streams of consciousness. The mental state of an observer doesn't supervene on an instant, but on a dense set of instants, and patterns in this dense set of instants can instantiate the dynamical processes required for conscious experience. Moreover, an observer's memory (or any other record) can perfectly well be reliable, in that the pattern reliably correlates the outcome of the measurement with the memory.

Gao (110) mentions something like this possibility in passing, commenting that the supervenience of experience on a dense set of instants is "ad hoc", and that the resulting picture of observers that "interlace with each other in time" is "very strange". But the view seems to follow from Gao's ontology and quite plausible functionalist assumptions, so I don't immediately see why it should be regarded as ad hoc. As for the strangeness, that is undoubtedly true, but it is arguably no stranger than any other Everettian interpretation. If there is anything wrong with this reconciliation of Gao and Everett, I think, it is that it is disappointingly *familiar*: it is just Everett's interpretation armed with a new underlying ontology.

I have focused my critical comments on Gao's positive proposal, which I take to be ingenious, fruitful, and well worth careful consideration. But there is a lot more in the book that is worth thinking about, too, including many incisive criticisms of competing views concerning the nature of the wave function and how to solve the measurement problem. I highly recommend taking the time to engage with Gao's arguments.

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