(DRAFT) Approaching wave function realism from a historical perspective: A reply to North

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May 20, 2019

Introduction

The advent of quantum mechanics catalyzed the archetypal Kuhnian paradigm shift in physics. The beginning of the development of the theory brought about a crisis in classical physics. Although quantum mechanics is a century old and a highly corroborated theory, the application of which bolsters nearly every aspect of modern technology, the crisis it begot has yet to be tamed.

At the heart of quantum mechanics lies the wave function. The wave function is said to encapsulate a complete description of the physical system and is the entity to which the dynamical laws refer to. Thus, at the top of the long list of persistent questions stemming from the theory is “What is the wave function?” I do not attempt to answer this question here. Rather, I formalize the approach to realism throughout the history of physics and relay what this tells us about being a realist about the quantum mechanics and about the ontological status of the wave function.

Traditional wave function realism asserts that the wave function has the same status as classical particles and fields; it is a physical and fundamental ontology. These traditional interpretations of the wave function support its ontological status in a multitude of ways; everything from being a field on a high-dimensional space to being a “multi-field” on physical space (see e.g., Chen (2018) for a review of these ontological interpretations).

Here I argue against traditional wave function realism based on what I call the *standard realist approach* to physics. In lieu of arguing directly against wave function realism for conceptual or technical reasons, I take a historical approach. I offer a menu-driven procedure to realism that is evidenced by the history of physical theory formulation. This approach can be contrasted with the general principles established by North (2013) in advocating for traditional wave function realism and the fundamentality of wave function's space.[1] Taking history as a guide, I argue that the only justifiable realist approach to quantum mechanics as it stands is that the wave function is *sui generis*. That is, if the wave function is to be considered real, then it is a new kind of entity that cannot be thought of as being what we currently consider ontological.

The structure of this paper is as follows. I first juxtapose the tradition of realism in physics as characterized by North (2013) and myself. This is followed by a discussion of how quantum mechanics does not fit into the realist tradition and requires a new treatment, thereby warranting a discussion of the ontology problem and the *sui generis* status of the wave function. After concluding remarks, I include an epilogue as a pedagogical aside discussing how quantum mechanics is taught and the need to make students aware of the main philosophical issues of the theory.

Realism in physics

The principles I use to argue against traditional wave function realism stem from my characterization of the realist tradition in physics. North (2013) summarizes this tradition in slogan form as "the dynamical laws are a guide to the fundamental nature of a world".[2] However, North's (2013) slogan mischaracterizes the history of the practice of realism in physics. To develop the key components of the realist tradition, I suggest the opposite

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1. Jill North, "The Structure of a Quantum World," in *The Wave Function: Essays on the Metaphysics of Quantum Mechanics*, ed. Alyssa Ney and David Albert (New York: Oxford University Press, 2013), 184–202.

2. Ibid.

of using "dynamics as a guide to what is fundamental".[3] Instead, it is our intuition that determines what we consider fundamental, and our observation (along with constraints from intuition) that form the dynamical laws that describe the world.

In agreement with North (2013), the fundamental level of the world is three-fold. First there is the fundamental ontology. These are the irreducible physical elements of the world (particles, fields, etc.). The second and third aspects of the fundamental level are the fundamental space and structure in which the ontology exists. Some proposed fundamental space-structure pairs are $\mathbf{R}^3$ equipped with the Euclidean topology or Minkowski spacetime. The role of dynamical laws is to link the fundamental aspects of the world while generalizing observation. For instance, laws describe how the fundamental ontology moves though the fundamental space (Newton's laws of motion) or how the fundamental ontology affects the fundamental space (mass warping spacetime).

The categories of fundamental aspects of the world (ontology, space, structure) and the role of dynamical laws is clear. However, North (2013) makes a bold, and I believe incorrect, assertion about our general theorizing: since our dynamics are "a guide to the fundamental nature of a world" we therefore infer the three-fold fundamental level from the dynamics. That is, we posit whatever fundamental ontology, space and structure the dynamical laws presuppose in order to remain a truthful description of the world. This 'realism from dynamics' approach suggests that the dynamical laws precede our idea of the fundamental ontology, space and structure. In this view, Newton posits that particles exist in 3-dimensional Euclidean space because the dynamical laws he formulated presuppose that

3. North, "The Structure of a Quantum World."

of the fundamental world. Moreover, Einstein posits that there exist particles in spacetime because his dynamics presuppose such an ontology, space, and structure.

This characterization of our theorizing appears to me to be backwards. In practice, it is our intuition and intuition-based assumptions about all or some of the fundamental ontology, space and structure that precondition and constrain the formation of dynamical laws. Our preconceived idea of the world plays the dominant role in the formation of our theories. For instance, Newton asserted *a priori* that particles exist (likely due to his intuition based on observations of the world). Furthermore, he asserts *a priori* that these particles exist in 3-dimensional Euclidean space. So, before the dynamics are a formulated, the three-fold fundamental level of the world was already posited. The dynamics in Newtonian mechanics then correspond directly to the already-posited fundamental entities if they are to describe them. It is because we presupposed the fundamental level first that we claim classical dynamics suggests a world in $\mathbf{R}^3$ consisting of N particles rather than the mathematically and dynamically equivalent world in $\mathbf{R}^{3N}$ with just a single point. Dynamics does not distinguish between these worlds, though dynamics coupled with our presuppositions tells us that N particles in $(\mathbf{R}^3, \mathcal{T}_{Eu})$ is fundamental. Our presupposed idea of the world made the fundamental ontology, space and structure fundamental, not the dynamics. We create our dynamical laws to reflect our presupposed notion of the fundamental nature. For this reason, it is not that "a match in structure between dynamics and world indicates that we have inferred the correct structure to the world" like North (2013) claims. Instead, it is a match in structure between dynamics and world that indicates we have formulated the correct dynamics for the presupposed world of our intuition. The same goes for ontology and space.

This approach of 'dynamics as a result of our presupposed fundamental level' along with intuition-based assumptions and constraints is also be seen in Einstein's special and general relativity. As a preface to formulating dynamics, Einstein postulates that the speed of light is the same in all reference frames (special relativity) and that, roughly speaking, gravitational acceleration is indistinguishable from frame acceleration (general relativity). These serve as constraints on any future formulation of dynamical laws. That is, if the dynamical laws are to describe the world, they must capture the sameness of gravitational and ordinary acceleration along with the uniformity of the speed of light. These constraints come from Einstein's intuition about how the world ought to be. On top of the intuitive constraints on dynamics, relativity comes with a presupposed fundamental level. The existence of particles as the fundamental ontology remains from classical mechanics. The space and structure are posited to support the imposed constraints. Lastly, the dynamics of general relativity are formulated to describe the links between the fundamental ontology, space and structure. The case for classic electromagnetism follows a similar theme, though the case is slightly more complicated and will be addressed later in the paper.[4]

Although I have no slogan to compete with North's (2013) "the dynamical laws are a guide to the fundamental nature of the world", I offer a menu-driven realist procedure that I call the *standard realist approach* of physics:

4. The added complication comes from the fundamental role of the electric and magnetic fields. The dynamical laws (Maxwell's equations) refer directly to these entities, though there existed a lack of consensus about their ontological status. Therefore, although electromagnetism came equipped with a presupposed fundamental ontology (particles and the fields), it was not immediately clear whether the ontology should be accepted as fundamental or merely a mathematical tool.

1. Posit an ontology, space and structure for the world at the fundamental level that the (later formulated) dynamical laws will correspond to.
2. (Optional) Suppose constraints that shape the dynamics.
3. Formalize dynamical laws that abide by constraints, correspond to the presupposed ontology, space and structure and generalize observation.
4. For as long as the dynamics generalize observation, our world according to theory is real. That is, the presupposed ontology, space and structure along with the dynamical laws that link them is the fundamental nature of the world.

Maudlin (2013) asserts that "studying the mathematics in which a theory is couched is not the royal road to grasping its ontology."[5] To this point, dynamics is simply not a guide to what's fundamental. However, dynamical laws, rather than providing us with a fundamental level to infer, provide us with previously unknown events to infer. This is evidenced by the recent gravitational wave detections and black hole imaging. The existence of black holes and gravitational waves are not aspects of the presupposed fundamental level of the theory but are inferred from the dynamics even without previous observation. We have all been black hole and gravitational wave realists for decades prior to detection because the dynamical laws suggest their existence.

5. Tim Maudlin, "The Nature of the Quantum State," in *The Wave Function: Essays on the Metaphysics of Quantum Mechanics*, ed. Alyssa Ney and David Albert (New York: Oxford University Press, 2013), 126–153.

Against traditional realism in quantum mechanics - the ontology problem

What about quantum mechanics? What is the fundamental nature of the world according to this theory? To answer (rather, avoid answering) this, let's briefly review the history of the theory.[6]

At the turn of the 20^{th} century, as we began to probe the world of the microscopic, our dynamical laws from classical mechanics failed to generalize the observed dynamics. This Kuhnian paradigm shift brought an end to our ability to be a realist about classical physics as it brought an end to the agreement between dynamics and observation (element 4 in the standard realist approach above). This calls for either new dynamics or a new idea of the three-fold fundamental level.

The fundamental ontology, space and structure of classical physics was posited due to observations from our human experience. However, experimental results from early quantum mechanics experiments (actually, all quantum mechanics experiments) were baffling. Since these observations clashed with our human experience and were so out of tune with standard intuition, the founders of quantum mechanics skipped the step of positing a new three-fold fundamental level and dove into the realm of formulating dynamics.

For Neils Bohr, quantum mechanics was a formal, precise mathematical scheme rather than an attempt to accurately describe the world of the microscopic.[7] Of course, he sub-

6. For simplicity, I only consider non-relativistic quantum mechanics. A case for the need to include relativity in metaphysical accounts of quantum mechanics is found in David Wallace, "Against Wavefunction Realism" (preprint, February 2017), `https://dornsife.usc.edu/assets/sites/1045/docs/%20againstwfrealism.pdf`.

7. Travis Norsen, *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory* (San Bernardino: Springer International Publishing, 2017), 146–148.

scribed to a Kantian approach to quantum mechanics and claimed that the nature of the microscopic world was unreachable to us, but the problem is still extant: from the advent of the theory, we haven't known what quantum mechanics is fundamentally *about.* There is no presupposed ontology similar to what previous theories contain. The dynamical law of (non-relativistic) quantum mechanics is the Schrödinger equation which refers only to the wave function. The wave function is considered to be the complete description of the physical system. In undergraduate quantum mechanics, the question of "what is the wave function" would be answered as "it is a mathematical entity, whose norm squared represents the position probability distribution of the system it is describing" (assuming the position representation was chosen). This hardly sounds like much of a fundamental ontology. Indeed, it was never posited to be so. It's original intention was to serve as a predictive tool to save physicists from embarrassing disagreement with experiment.

This brings us to the main question of this work: without a presupposed ontology, how can one be a realist in quantum mechanics? In North's (2013) view, we take our dynamics as a guide to what is fundamental. This approach tells us to follow the "minimum structure" principle and posit, at the fundamental level, the minimum of what the dynamics require of the ontology, space and structure.[8] This leads North (2013) to conclude that it is the wave function space that is fundamental and that $(\mathbf{R}^3, \mathcal{T}_{Eu})$ is non-fundamental since that is what the dynamics require us to infer. Such a view leads to staggering consequences. The wave function space for the universe contains around 3×10^{80} dimensions and as Wallace (2017) points out, with particle spin considered, the wave function is not merely a function to single

8. North, "The Structure of a Quantum World."

complex-values, but is a map onto a $2^{10^{80}}$ dimensional complex-valued space.[9] Considering the wave function space (or configuration space or Hilbert space) to be real must contain a mechanism for ordinary space to be emergent. This is still lacking. However, I agree with Wallace (2017) in that "as metaphysical underdetermination goes, indeterminacy as to whether there is fundamentally one thing or $2^{10^{80}}$ things isn't bad going."[10]

By contrast, the menu-driven approach does not rely on the dynamics to infer the fundamental level. Rather, realism relies on the presupposed ontology for as long as the dynamics adhere to observation. But quantum mechanics never had a presupposed ontology! This makes being a realist in quantum mechanics fundamentally different than in other physical theories. In the case of quantum mechanics, where the dynamics precede ontology, I say that the theory is ontologically underdetermined. In a way, it is "not even underdetermined". This is the ontology problem.

An important point is that the present state of quantum mechanics requires a post-dynamics characterization of the fundamental level that has been absent in previous physical theories. The motivation for the plethora of existing choices is given by Chen (2018) and is summarized in the appendix. Moreover, the present state of the theory does not allow the choice to eliminate perspectives, since each choice results in the same prediction for observation. There is no difference in observed physics, only metaphysics. Thus, we cannot use interpretation of the mathematical formalism to settle the wave function ontology dispute.

9. Wallace, "Against Wavefunction Realism."

10. Ibid.

Recall that electrodynamics can be considered to have suffered a kind of ontology problem with the electric and magnetic fields. At the time of the theory's conception, many wondered if these were merely mathematical constructs. However, a major disparity exists between this example and the quantum ontology problem; no experiment can *detect* the wave function of a system, while electric and magnetic fields are detectable (and have been detected). It is for this reason, along with the observational indistinguishability of different interpretations, that being a realist about quantum mechanics calls for a so-called *sui generis* interpretation. That is, if one considers the wave function to be real, it cannot be categorized into any of the familiar classes of ontology (like particles and fields). As Chen (2018) says, "perhaps it is [not] ontological. In that case, the wave function has its own category of existence that is distinctive from anything we have considered."[11]

Conclusion

Throughout the history of physical theorizing, the dynamical laws have been generalizations that capture a presupposed fundamental level of the world and observation. Traditionally, to be a realist about a theory, one accepts the presupposed fundamental level of a theory as real. Quantum mechanics lacks a presupposed ontology, thereby necessitating a new realist treatment. To be a realist about the wave function in the current state of quantum mechanics requires the wave function's status to be *sui generis* – of its own kind.

11. Eddy Keming Chen, "Realism about the Wave Function," preprint, 2018, `http://philsci-archive.pitt.edu/15153/`.

Epilogue: Should the students know?

It has come to my attention that there exists a sort of blind faith in quantum mechanics among students that carries on into their post-graduate careers. The unsettling foundational aspects of the theory are overlooked due to its success. A "shut up and calculate" mentality exists when only half of that mentality is justified. The mathematical formulation of quantum mechanics works. Although we do need to calculate, we cannot just shut up and do so.

Early quantum mechanics textbooks completely evaded the philosophical issues at hand. One account includes the authors immediately denying the physical existence of the wave function due to the fact that it is a complex-valued function.[12] Although quantum mechanics textbooks have stopped completely evading the issues at hand they are still not handled with completeness. Griffith's *Introduction to Quantum Mechanics* text is the staple for introductory undergraduate quantum mechanics.[13] There is a chapter included for quantum paradoxes like the Einstein, Podolsky, Rosen (EPR) Paradox.[14] However, in a very brief discussion of the philosophy of quantum mechanics, Griffiths (2014) only mentions three possibilities of interpretation: realist, orthodox, and agnostic. The realist position as described by Griffiths (2014) is the so-called ignorance interpretation which has been

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12. Not being real-valued does not mean not real. The (real) electric and magnetic fields can be represented as a single complex-valued vector with ease. Similarly, the complex-valued wave function can be represented as a linear combination of two real-valued functions with complex coefficients. This example is provided in Norsen, *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory*

13. David J. Griffiths, *Introduction to Quantum Mechanics* (Great Britain: Pearson Education Limited 2014, 2014).

14. Albert Einstein, Boris Podolsky, and Nathan Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?," *Physical Review* 47 (1935): 777–780.

disproven by Aspect's experiment[15] and Bell's inequality.[16] The orthodox interpretation is the standard Copenhagen interpretation and the agnostic approach is Bohr's Kant-inspired refusal to acknowledge that microscopic information is accessible to us.

With only these three ideas in mind, students are not adept to tackle the leading foundational questions in quantum mechanics. The multitude of other formulations (Pilot-Wave Theory, Many Worlds, Spontaneous Collapse) go unbeknownst to them. Simply put, this complacency with the orthodox is counterproductive. Physicists, for whom quantum mechanics is their daily language, need to be encouraged and equipped to think about it from the start of their careers. No profession is more equipped with the tools to take physics to the long overdue next step; have quantum mechanics say something about the world or replace it with a theory that can.

Acknowledgements

I am grateful to Dr. Vernon Davis for helpful discussions about the foundations of quantum mechanics and input on earlier versions of this paper.

Appendix

How does one choose an interpretation?[17] Chen (2018) explains how the choice is derived from the rejection of one of the three inconsistent premises that result in the con-

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15. Alain Aspect, Philippe Grangier, and Gerard Roger, "Experimental Realization of Einstein-Podolsky-Rosen-Bohn Gedankenexperiment: A New Violation of Bell's Inequalities," *Physical Review Letters* 49 (1982): 91–94.

16. John S. Bell, "On the Einstein Podolsky Rosen Paradox," *Physics* 1 (1964): 195–200.

17. An overview of interpretations of quantum mechanics that guided my understanding is given by Norsen, *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory.*

tradictory measurement problem.[18] He lists the following as individually plausible premises about the world and quantum theory:

1. The wave function is the complete description of the physical system.
2. The wave function obeys the Schrödinger equation as the dynamical law.
3. Every experiment has a single unique outcome.

The combination of these seemingly inconspicuous premises leads to a contradiction, best highlighted by Schrödinger's cat.[19] Chen (2018) continues to explain that the rejection of P1 (as the Pilot-Wave Theory does) or P2 (as Spontaneous Collapse theories do) requires new dynamical elements. The extra dynamics take the form of the guidance equation in Bohmian mechanics and wave function collapse in Spontaneous Collapse theories. The rejection of P3 (as the Many Worlds Theory does) requires a radically new idea of the nature of the world(s).

18. Chen, "Realism about the Wave Function."

19. Erwin Schrödinger, "The Present Situation in Quantum Mechanics: A Translation of Schrödinger's 'Cat Paradox' Paper," trans. John D. Trimmer, *Proceedings of the American Physical Society* 124 (1980): 323–338.

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