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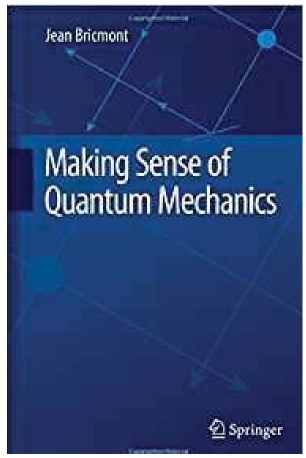
BOOK REVIEW

Making Sense of Quantum Mechanics by Jean Bricmont. Springer, 2016. 331 pp. $69.99 (hardcover). ISBN 978-3319258874.

Quantum mechanics is both perhaps our most successful scientific theory and the least understood. The standard or Schrödinger equation of quantum mechanics fits the experimental data remarkably well. Within the traditional (Copenhagen) framework, this equation describes the evolution of a wave function (a grouping of potential states) until a measurement discontinuously triggers the wave function to "collapse" into the observation of an experiment. As is well known, this interpretation provides no mechanism or ontology to account for this instantaneous collapse. Currently, there is no consensus that favors an interpretation for this measurement problem.

Jean Bricmont's *Making Sense of Quantum Mechanics* is a welcome contribution toward helping us navigate through the complex and paradoxical nature of quantum mechanics, as well as the various attempts to explain it. While Bricmont offers a great deal of technical rigor, he focuses on the conceptual problems in a relatively straightforward and accessible way. To be clear, Bricmont does not eschew mathematics. However, the level of mathematics involved here is what would typically be required in a first or second year course for scientists and engineers: linear algebra, complex numbers, Fourier transforms, basic differential equations, and classical mechanics. And most of the formal proofs and analyses are relegated to the appendices. In addition, many technical aspects and references to more advanced literature are placed in the footnotes. This book is therefore organized in a way to serve a wide range of interested readers.

Bricmont begins by reviewing key aspects of the philosophical debate that emerged among the founders of quantum mechanics and their students. What evolved to be a primary thread of the Copenhagen interpretation, championed by Niels Bohr, Werner Heisenberg, Max Born, as well as others, gave the experimental observer a deus ex machina role in supplying definite properties to objects without explaining how this occurs. Bricmont provides to us quotes to demonstrate how Bohr, Heisenberg, and their followers argued that quantum mechanics did not deal with elementary particles per se but rather our conception of them. As a result, they argued, quantum physics ends up primarily dealing with what we can or cannot say about the subatomic realm. And these views have prevailed and persisted



throughout the history of quantum mechanics via later advocates such as Eugene Wigner and John Wheeler.

However, Albert Einstein and Erwin Schrödinger were opponents of arguments that put such emphasis on awareness, observation, or measurement at the expense of objective reality. Einstein believed that the statistical nature of quantum mechanics reflected the fact that the theory was incomplete and that a more complete description would eliminate the need to refer to an observer. Einstein eventually formalized his thinking (with his colleagues Podolsky and Rosen) into what is now referred to as the EPR argument, which held that the nonlocality inherent in quantum mechanics implied that the theory is incomplete; that is, some form of hidden variables was needed to make sense of the results and rule out action at a distance. However, John Bell later showed, in the context of the EPR framework, that assuming both locality and hidden variables leads to a contradiction. And Bell's argument was eventually verified by experiment. Bricmont not only takes us through the arguments of EPR and Bell, but he discusses the confusion on the part of many who misinterpreted Bell's results to rule out the role of hidden variables. As Bricmont notes, Bell argued that his work demonstrated the nonlocal nature of quantum mechanics, not that hidden variables of some sort were ruled out.

Bricmont also addresses the confusion on whether or not Bell's work vindicated Bohr. Despite Bell's demonstration of the nonlocal nature of quantum mechanics, he was firmly opposed to the role assigned to the observer by Bohr and Heisenberg. Here are two sample Bell quotes Bricmont uses to illustrate this:

> One wants to be able to take a realistic view of the world, to talk about the world as if it is really there, even when it is not being observed. I certainly believe in a world that was here before me, and will be here after me, and I believe that you are part of it! And I believe that most physicists take this point of view when they are being pushed into a corner by philosophers. (p. 13)

> But experiment is a tool. The aim remains: to understand the world. To restrict quantum mechanics exclusively about puddling laboratory operations is to betray the great enterprise. A serious formulation [of quantum mechanics] will not exclude the big world outside the laboratory. (p. 15)

Bricmont's layout of this debate prepares the reader for his primary aim throughout the book: advocating for the de Broglie–Bohm interpretation of quantum mechanics (sometimes elsewhere referred to as Bohmian mechanics). The theory was introduced at approximately the same time as the Copenhagen interpretation by Louis de Broglie, but it was rejected by a large majority of physicists. After de Broglie abandoned the theory, David Bohm rediscovered and developed it. John Bell later became a strong advocate. Bricmont's presentation also relies on more recent work by Detlef Durr, Sheldon Goldstein, and Nino Zhangi, as well as by their collaborators.

As Bricmont explains, under the de Broglie–Bohm theory subatomic particles have well-defined positions and (highly non-classical) trajectories regardless of whether one measures them or not. (The particle positions are the hidden variables in this approach.) This is achieved through a guidance equation that acts on each particle. This guidance equation, which depends on the wave function, can be compared to the Hamiltonian in classical mechanics. Since this system is deterministic, the randomness can be traced to the uncertainty of the various particle positions or initial conditions. Thus the de Broglie–Bohm theory provides a relatively straightforward story about the way the subatomic world behaves without requiring the epistemological quandaries demanded by Bohr and Heisenberg.

However, you might say there is a catch. The guidance equation depends not only on the wave function, but the system configuration, that is, the positions of all the particles in the system. Further, this relationship is inherently nonlocal. Thus the wave function's influence on a particle may also depend on some other particle (or group of particles) at an arbitrary distance away. Also, within the de Broglie–Bohm framework, the subatomic system under investigation is entangled with every aspect of the process of measurement, which is after all another physical system influenced by the same laws. Therefore the particles under investigation, guided by the wave function, cannot be completely isolated from the measurement apparatus. The configuration of the system, which includes both particles under investigation and its environment, functions as a whole to determine the outcomes of observation. (Bricmont does not make explicitly clear that the relevant system in Bohmian mechanics is the universe, because of this entanglement between the system under investigation and the process of measurement.) Thus the wave function ends up inhabiting an extraordinarily large dimensional space of 3N, where N is the number of particles in the universe. I'll add more on this below.

Bricmont also discusses why the de Broglie–Bohm theory survives various "no hidden variable" arguments. One influential case was due to von Neumann; however, Bell has shown that he imposed some questionable mathematical assumptions. Another hurdle includes work by Kocken and Specker, which was also thought to rule out hidden variable arguments. Kocken and Specker showed that measurements were essential aspects of the overall "context" of any quantum system under investigation. As a result, they and others argued that it was incorrect to posit that various properties of a quantum system had pre-assigned values that some process of measurement was supposed to detect. But the de Broglie–Bohm theory not only respects this "contextuality," it helps us to understand it. That is, the entanglement of the measuring process with the system under investigation leads the measuring process to influence the values of the various observables under investigation.

Bricmont also discusses in considerable depth and clarity the various alternatives available to the de Broglie–Bohm theory (as well as the Copenhagen interpretation). These include the Everett (many worlds) interpretation, spontaneous collapse theories, the decoherent histories approach, and QBism. Of course, Bricmont is not unbiased, but he does a decent job of providing arguments for both sides for each explanation. I'll focus here on the Everett interpretation, which posits that there is no "collapse" of the wave function at all; that is each possible outcome manifests. Hence the universe is continuously branching into a vast number of parallel realities. In addition to this ontological peculiarity (at least to some), Bricmont discusses the problem of reconciling the Born probabilities (the different probabilities associated with different outcomes or branches) with Everett's claim that all branches are actual (none are more real than the others). The author also dives into various permutations within the many worlds framework. These include functions describing mass densities, weighting factors applied to physical existence, and a "many-minds" scheme (where the splitting occurs inside a set of minds). He notes that all of these seem to depart from common sense realism and suggest we are radically deluded about existence itself.

Needless to say, the paradoxes of quantum mechanics have given rise to a bewildering array of theories, interpretations, and models that might lead us to abandon any hope of arriving at something resembling our experience. Bricmont endeavors to argue that the de Broglie–Bohm theory deserves our attention for providing an ontology most congruent with our world. This might raise the question: How is it that after a century of debate we are still no closer to a consensus theory? Bricmont addresses this too by exploring some of the history of thought behind quantum mechanics. He notes that the brilliant minds at the early Solvoy Congresses were grappling with unprecedented paradoxes. But Bricmont suggests how the power of authority within academia has arguably been used to lead physicists and philosophers astray. He also explores how and why most physicists have managed to overlook the proposals of de Broglie and Bohm, as well as more recent efforts by Bell. A key question here is why de Broglie's proposal didn't receive more favorable attention at its original presentation. Apparently, an important factor was that de Broglie himself had doubts about his own theory because it posited a wave function existing in a space with an unusually high number of dimensions.

It is at this point that we might note some ways where Bricmont's admirable efforts perhaps fall a little short. The ontological status of the wave function's high-dimensional space remains an unresolved and baffling question, even among advocates of de Broglie and Bohm. Does our reality truly contain, as Albert (1996) argues, a mind-numbingly large number of dimensions? If so, how is such a reality linked with our familiar 3-dimensional space? On the other hand, perhaps the high-dimensional space of the wave function is merely a mathematical convenience, as Goldstein and Zanghí (2013) have argued. Goldstein and Zanghí maintain that the high-dimensional space of the wave function most likely demonstrates a nomological (lawlike) aspect of how subatomic particles behave in 3-dimensional space. Another important question is how can a wave function that requires a configuration space of 3N (again where N is the number of particles of the system) be reconciled with quantum field theory, where particles fluctuate in and out of existence. Ney (2013) suggests that we might deal with this through positing that the wave function inhabits an infinite dimensional space. It is perhaps regrettable that Bricmont stopped short of exploring a fascinating debate on this high-dimensional space that apparently led de Broglie to have misgivings about his own theory.

Of course, such questions lead us into Bohm's (1980, 1993) later work. Unlike de Broglie, Bohm embraced the reality of a space with perhaps infinite dimension. According to Bohm, this "space," which he termed "implicate reality," was an inherently nonlocal and holistic substratum of reality through which our familiar physical reality unfolds. And Bohm's implicate order was the foundation, not only for physical matter, but for conscious experience as well. It is perhaps unfair to criticize Bricmont for stopping short of exploring Bohm's later and more controversial work. This limit likely reflects a consensus opinion among physicists and philosophers of physics, which include advocates of the de Broglie–Bohm theory, that Bohm had gone beyond physics into mysticism. Few physicists are willing to seriously consider the possibility that consciousness may be in some sense fundamental. Thus Bohm's implicate order appears to breach a no-go zone within physics.

However, I believe that Bohm's implicate order deserves more attention.

A growing number of philosophers of mind are arguing that physicalist explanations cannot account for consciousness. David Chalmers has dubbed consciousness "the hard problem" and has persuasively argued that progress requires considering that consciousness may indeed be fundamental (Chalmers 1997). Given the persistence of both the "hard problem" and the measurement problem of quantum mechanics, it is hard to justify ignoring Bohm's implicate order while mainstream physics continues to make room for interpretations that in some ways are arguably even more radical.

Bohm's implicate order also departs from the more deterministic nature of the de Broglie–Bohm theory. That is, Bohm argued that the more fundamental space of the implicate order was composed of pure potentiality, which was likely the ultimate source of the Born probabilities in quantum mechanics. This underlying strata of potentialities, as the basis for both consciousness and matter, provides an interesting framework for explaining various anomalous behavior such as psi. Bohm himself explored the possibility that precognition and psychokinesis could be explained within his implicate order framework. It is perhaps the case that such efforts will win him few mainstream advocates anytime soon. Yet it is perhaps commendable that Bohm was unusually unconstrained in his thinking. Perhaps such radical proposals are needed in order for us to make advances on the stubborn problems of quantum mechanics and consciousness.

The possibility suggested by Bohm's implicate order that mind and matter may be subtly linked raises a rather important philosophical point that I skipped over above: whether scientific realism holds within the domain of quantum mechanics. Bricmont notes that arguments limiting our ability to truly probe the quantum realm have assumed various forms of idealism. Overall, I am sympathetic to Bricmont's argument that we ought to be able to discuss the underlying ontology of our world without getting snared within our own processes of observation and experience. But Bohm's implicate order, as well as the persistent mystery of consciousness, suggests that more open-mindedness about how we treat consciousness and matter is justified. At the least, scientific realism's demand that the physical world remains independent of human consciousness may end up requiring some caveats.

It's interesting that Bricmont begins his discussion on scientific realism by quoting Bertrand Russell: "I see nothing impossible in a universe devoid of experience. On the contrary, I think experience is a very restricted and cosmically trivial aspect of our tiny portion of the universe" (p. 73). We can note that this quote does not well represent all of Russell's thinking. He favored idealism at an early stage in his career. More importantly, Russell's (1927) thesis on the intrinsic aspect of matter has been recently gaining currency among philosophers of mind. A key point for us is that this argument led Russell to a view that can be fruitfully compared with Bohm's implicate order. The heart of this argument is that while science provides us with a sophisticated mathematical understanding of our world, it is nevertheless silent on its intrinsic aspect. That is, science informs us about the quantified relationships between ultimates such as mass while telling us little about the ultimates themselves. Russell noted that our most basic experiences are perhaps the best candidate for something intrinsic. Thus he proposed that experience itself is intimately connected with this intrinsic aspect of reality. This is the foundation of Russell's neutral monism; however most contemporary philosophers have been using it to explore the possibility of panpsychism. In any case, those who consider together Russell's argument, Bohm's implicate order, as well as such persistent mysteries as the high-dimensional space of quantum mechanics and consciousness, can consider themselves on solid ground for refraining to follow the more conventional thinking that divides mind from matter.

In many respects, Bricmont succeeds and covers an impressive amount of ground. He provides a clear, in-depth, and wide ranging exploration on the problems of quantum mechanics and various proposed explanations (with emphasis on his preferred choice of course). The mathematics is constrained, but only a bit, with most of the heavy lifting relegated to technical appendices. And I find it refreshing that Bricmont has devoted so much space around philosophical debate and historical context. This book is a welcome contribution toward making sense of a highly abstract and puzzling subject. However, the possible links between consciousness and the subatomic realm will need to be explored elsewhere.

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