Book Review of Jean Bricmont's "Making Sense of Quantum Mechanics"

Springer, 2016

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"Given that quantum mechanics was discovered ninety years ago, the present rather low level of understanding of its deeper meaning may be seen to represent some kind of intellectual scandal." [BFS]

Folklore has it that physicists, when they get "too old" for doing "real physics," turn into "hobby philosophers" pondering the elusive "deeper meaning" of quantum mechanics, very much to the bemusement of their more practically minded younger peers. Closer to the truth than such feel-good folklore is the realization that physicists who try to understand what our practically successful most fundamental theories¹ say about our world are also well aware of the professional mine field on which they are traipsing. Thus, with some notable exceptions, they simply don't dare to risk ruining their scientific reputation with an offering of their secret thoughts on the subject before reaching retirement age. Even then, with ones career no longer in danger, such a step requires courage — after all, who enjoys the thought of "gossip among physicists brand[ing one] 'senile'." But for Jean Bricmont, well-known

¹Beside quantum mechanics, I put general relativity theory in this category.

²I have adapted this quote from p.281 of the book, where Bricmont quotes John Clauser (his ref.[97]) saying furthermore: "I was personally told as student that these men [Einstein, Schrödinger, de Broglie] had become senile, and that clearly their opinions could no longer be trusted in this regard. This gossip was repeated to me by a large number of well-known physicists from many different prestigious institutions. ... Under the stigma's unspoken 'rules,' the worst sin that one might commit was to follow Einstein's teaching and to search for an explanation of quantum mechanics in terms of hidden variables, as Bohm and de Broglie did."

not only to mathematical physicists for his contributions, many jointly with Antti Kupiainen, to the renormalization group, but also to a wider audience for his sharp-tongued and witty criticism, jointly with Alan Sokal, of postmodern "non-science" [SoBr], the quest for understanding was too important to wait that long. He took the unusual step and opted for early retirement while still in his prime, so that he could focus his attention on writing this book about how to make sense of quantum mechanics, undistracted and uninterrupted by academic duties. The outcome is a superbly written monograph which in terms of logical clarity, intellectual depth, and scholarship is without equal in its field.

The first half of Bricmont's book is devoted to explaining the *central conceptual problem* of orthodox textbook quantum mechanics (QM): it "suffers from" what the great mathematical physicist Arthur Wightman called "the malaise of the measurement problem" [Wigh]. The name has historical reasons and does not in itself reveal what the problem is. Picking up on Wightman's quasi-medical lingo, a more appropriate diagnosis of QM's ailment would be "reality deficiency disorder."

For instance, (quoting from chapter 1) Werner Heisenberg (p.5)³ concluded that in QM "... the idea of an objective real world whose smallest parts exist objectively in the same sense in which stones and trees exist ... is impossible." John Wheeler in his theory of the "participatory universe" (mentioned on p.8) even suggested that the present observation of the universe through our telescopes creates the fact that the whole universe had a real past. More recently, Anton Zeilinger (quoted on p.10) "suggest[ed] that ... the distinction between reality and our knowledge of reality, between reality and information, cannot be made."

Hm.4

Denials of an objective reality are, in the opinion of the author, and also of the reviewer, aberrations of human thought, plain and simple. In the case at hand they represent an outgrowth of several of QM's founding fathers', or defenders', denial of their own failure to understand what is 'really going on' in the experiments, according to their theory: If 'nothing real is going on,' then nothing needs to be understood—problem 'solved'—but at what price? "They behave[d] like people celebrating defeats as if they were victories" (p.287). The claims by Bohr, Heisenberg, and others that any deeper explanation is impossible only shows "the hubris of the scientists, claiming that their understanding of quantum mechanics was somehow an ultimate

³All references to page numbers refer to the book under review.

⁴This comment is inspired by — in fact: copied from — a recent New York Times op-ed piece by the great economist Paul Krugman, where it was made in response to a different reality dismissal.

understanding" (p.287). (Both quotes are from the last section of the book.)

Be that as it may, what exactly did perplex these brilliant scientists so much that it enticed them to make such radical proposals? Bricmont, with his talent for explaining complicated things in a logically clear and compelling manner by stripping them down to their essentials without oversimplifying, identifies two key ingredients of QM (Bricmont calls them "mysteries") which have no counterpart in classical⁵ physics: "interference and superposition (of the fundamental state)" (chapter 2), and "(Einstein) nonlocality" (chapter 4). Inserted in between (and appropriately so!) is a chapter, called "Philosophical Intermezzo," on what it means to do science.

As to the first "mystery," the fundamental state of a material N-body system in, say, Newtonian physics is given by the positions and momenta of all the N (point) particles (relative to an inertial reference frame). A linear superposition of two such states is not a valid fundamental state in Newtonian physics. In colloquial language, you are either here or over there. It makes no sense to claim you were 32 % here and 68 % over there. But one could claim, for instance, that on 100 different occasions, on 32 % of them you were here, and on 68 % of them over there. In other words, such a superposition represents an ensemble of fundamental states in Newtonian physics. By contrast, in (non-relativistic) QM, the fundamental quantum state of an N-body system is its Schrödinger wave function, or its Pauli spinor wave function if the spin of electrons or other fermions is taken into account. Its time evolution, between "measurements," is unitary and given by Schrödinger's or Pauli's linear wave equation, respectively. What's more, a linear superposition of two fundamental quantum states (wave functions) is again a fundamental quantum state evolving according to the same unitary dynamics⁶ between "measurements." Bricmont uses the example of a Mach–Zehnder interferometer to explain in simple terms how this can lead to paradoxical phenomena which have no counterpart in classical physics.

In such situations the usual "quantum-speak" is to say things like "a quantum particle" (recall that by *particle* one conventionally means a localized microscopic

⁵More accurately, non-quantum physics.

 $^{^6}$ I have on occasion heard the criticism that the linearity of the unitary quantum evolution is not a distinctive feature of QM because Newtonian N-point mechanics is equivalent to the evolution by the linear Liouville equation, and therefore, like QM, "a linear theory." However, such claims overlook that the equivalence only holds for the fundamental state, which is represented by a Dirac delta function concentrated on a single point in N-particle phase space — the linear superposition of two such Dirac delta functions is a state which is not supported at a single point and therefore not a legitimate fundamental state of Newtonian N-point mechanics.

object) "travels two different paths at the same time," or such. But instead of admitting that such absurd conclusions suggest that maybe the quantum state (the wave function, or the density matrix if one prefers) is not all there is for a "quantum system," to avoid such absurd realities Bohr, Heisenberg, and other founding members of the so-called "Copenhagen interpretation of QM" rather prefered to deny the existence of an objective reality at the microscopic level unless the act of "measurement" by a real "observer" with a real "classical device" creates its reality.

To illustrate how absurd such claims are Schrödinger pointed out that the supposedly not directly experienceable weirdness of the microscopic quantum level can easily be magnified to the macroscopic everyday level by putting a cat into the story, which features also in Bricmont's chapter 2. The lamentable cat being both dead and alive at the same time is of course never observed in the real world, but the conclusion that the cat was never in such a limbo to begin with is not allowed if one insists, as done in orthodox QM, that the fundamental quantum state "is all there is" for "a quantum system." But then one is forced to conclude that the originally very real (and alive) cat, which was put into the box together with a radioactive nucleus and the detector coupled to (in Schrödinger's words) "a hell machine" which will kill the cat when detecting the radioactive decay, this cat will "cease to be real" upon sealing the box, only to "become real" again upon reopening the box to "measure" whether the radioactive nucleus has decayed and the cat is dead, or has not decayed and the cat is still alive. Schrödinger emphatically insisted that this is absurd, preposterous. (Incidentally, many physicists who reject the denial of an objective microscopic reality by the adherents of the "Copenhagen interpretation" but hold on to the idea that the quantum state "yields the complete description" try to extricate themselves from the dilemma by insisting that "all conflicting scenarios are simultaneously real," but each one in a "different world," without mutual interactions between the worlds once "they are created" in "measurement-like situations." Bricmont addresses various "Many-Worlds Interpretations," a notion prominently associated with Hugh Everett III, in chapter 6.)

The classical enlightenment period of physics had assigned human beings roles of essentially "passive observers of an objectively real universe unfolding in front of their eyes." Of course, a perfectly passive observer (in classical physics, poetical licence for a technical device which quantifies a quality of an object without disturbing it, registers the result, which is then read by a human without changing the result) is a fiction comparable to the notion of a "test particle," yet it is an idealization which in the framework of classical physics is in principle analyzable as an interaction between

an experimental setup and a physical object whose qualities are being quantified by the measurement — a good approximation, with controllable error terms. By contrast, orthodox textbook QM (and quantum theory in general) invokes the notion of "measurement" at a fundamental level, formalized mathematically by Johann von Neumann in his "measurement axioms" [Neu], though without stipulating what precisely constitutes "a measurement" — very much in line with Niels Bohr's insistance that in quantum physics the act of observation / measurement is fundamental and in principle not further analyzable in terms of more fundamental processes.

But how could a "measurement," i.e. the quantification of a quality of an object (if the word "measurement" really means what it stands for, linguistically) not be analyzable in terms of events and processes involving these objects, and the objects which constitute the measuring device — at all? As Bricmont explains, typically "a measurement in QM does not measure anything" in the proper sense of the word, and similarly "making an observation in QM usually does not mean we are observing anything." And then, if physicists when they say "measurement" do not actually mean "measurement in the sense of quantification of a quality of an object," the objection to Bohr's pronouncement does not apply. "Measurement" and "observation" are unfortunate choices of terminology in QM which have contributed their ample share to the confusion which befuddles the theory. Yet if we replace them, as John Bell has proposed, with a more neutral and more appropriate terminology such as "experiment" and "registration of a result," a crucial deficiency remains: QM fails to offer an objective explanation of how experiments could have any results at all.⁷

Some, and possibly even many physicists would strongly disagree with the claim that this is a deficiency of QM. If these physicists would basically agree on why the lack of an objective explanation is not a deficiency of QM, there possibly could be a serious issue to contemplate. However, as Steven Weinberg wrote recently [Wei]: "It is a bad sign that those physicists today who are most comfortable with quantum mechanics do not agree with one another about what it all means." The reason, it seems, is that quantum physicists disagree to an astonishing degree on what a scientific theory should be about. It is one of the merits of Bricmont's book that it includes a whole chapter on this issue, what it means to explain something in science, and why the lack of an objective explanation is a serious scientific deficiency of QM. Thus, in chapter 3, "Philosophical Intermezzo," Bricmont eloquently argues the case that "the conceptual problems of quantum mechanics are internal to the physical theory itself and do not have a 'philosophical' solution" (quoted from p.73). This

⁷Wightman put it thus: "Where do the facts come from?"

chapter is simultaneously a call for rational understanding and against positivistic, idealistic, or solipsistic attitudes, which were in vogue in scientific circles at the time QM was created, and which continue to influence the thinking of many physicists.

While Bohr declared that such an objective explanation is impossible, Einstein on the other hand was convinced that orthodox QM is an incomplete theory, and that a more complete theory which explains the quantum formalism in terms of objective physical processes is possible. Bricmont explains that Einstein favored the statistical ensemble interpretation of the quantum state, meaning the quantum state (the wave function Ψ) is not fundamental but rather representing (through Born's interpretation of $|\Psi|^2$) something akin to a Gibbs ensemble of more fundamental state variables which had yet to be discovered. Instead of more neutrally calling them "omitted," or "missing variables," the name "hidden variables" was given to these; another unlucky choice of terminology which suggests that those variables would be inaccessible — metaphysics to those with a positivistic attitude that "nothing is real unless you measure it." Whatever one calls these variables, Albert Einstein, Boris Podolsky, and Nathan Rosen in their famous EPR paper [EPR] concluded that the assumption of the correctness of the statistical quantum mechanical predictions in concert with Einstein locality (i.e., "no spooky action at a distance," as Einstein called it) implies that certain deeper "elements of reality" (read: hidden variables) must exist but are missing from QM. As Bricmont explains in chapter 7, there is evidence that Einstein was trying to convey this to Bohr already in 1927, to no avail.

By "spooky action at a distance" Einstein most definitely meant a violation of what his relativity theory postulated: an event A can influence an event B if and only if B lies in the forward lightcone of A. In plain language, Einstein took it for granted that once the two particles of an originally close pair of particles which "acted in concert" separated far enough spatially, each particle will be "on its own" and not immediately disturbed (at least not in any essential way) by acts of "measurement" of the other particle's state. Anything else is "spooky."

But "QM" has earlier been said to stand for "non-relativistic" quantum mechanics, so how can one coherently combine "non-relativistic" QM predictions with "relativistic notions of locality" and expect to come to a compelling conclusion? Fair enough, and this brings us to chapter 4 and the second "mystery."

In chapter 4.3 Bricmont explains what is at the bottom of Einstein's "spooky action at a distance" without running afoul of a naive mismatch of Lorentzian vs. Galilean relativistic structures. Bricmont formulates four points, with a subdivision, which in the non-relativistic setting distinguishes "spooky action at a distance" from

the usual "Newtonian action at a distance" (like Newtonian gravity, or Coulombian electricity). Basically, the distinction is that there is an instantaneous influence from one system on another which does not diminish with distance, and furthermore it cannot be used to send signals from one system to another. (There is also an "individuation" involved, stipulating that memory effects from earlier experiments could be prevented from influencing the outcomes of present experiments.)

In Newtonian physics, the change in position of a point particle with non-zero mass will instantaneously change the gravitational force it exerts on any other particle in the universe, but its strength diminishes with distance r as $1/r^2$, so that very distant particles are "essentially" undisturbed by each other. Even then one could in principle use this tiny influence for instantaneous controlled signaling. (Bricmont explains that in a Newtonian world this would only be limited by technical abilities to detect tiny forces.) In this sense, what Einstein identified as "spooky action at a distance" is a distinctly different nonlocality from Newton's "fading-away but controllable action at a distance" even in a "non-relativistic" theory. (The issue of relativity is briefly commented upon in chapter 4 and taken up again in chapter 5.)

After clarifying what Einstein meant by locality, Bricmont explains in a crystal clear manner John Bell's proof that Einstein locality is violated by quantum physics. In a nutshell, the logic is this: 1. EPR show that postulating the correctness of certain QM predictions together with postulating Einstein locality implies that "hidden variables" exist that have certain particular qualities; 2. Bell shows that postulating hidden variables with those particular qualities implies an inequality (the famous "Bell's inequality") which violates other predictions of QM. Conclusion: if QM makes the correct predictions, Einstein locality is false!

As Bricmont relates (in chapter 7), the simple logic of Bell's two-part argument is frequently misunderstood by physicists. This was frustrating to Bell (quoted on p.265):⁸ "It is remarkably difficult to get this point across, that determinism is not a presupposition of the analysis." The most common mistake is to ignore the EPR part of the argument and to insist that Bell did not prove that QM is nonlocal but only that "hidden variables do not exist," which therefore would demonstrate "the non-existence of microscopic reality." True, Bell proved that certain types of

 $^{^8}$ Essentially all quotations of John S. Bell in Bricmont's book are from the collection of Bell's works on the foundations of QM [Bel].

⁹N.B.: By "determinism" Bell here refers to the hidden variables whose qualities EPR concluded must (pre-)determine the outcome of the experiments. This becomes clear through the context.

¹⁰Bell's frustration is shared by others: "I can't take it anymore. Eventually [somebody] will win the Nobel Prize in physics for having shown that reality does not exist." [Dür]

hidden variables cannot exist if QM makes empirically correct predictions. But it was the existence of precisely those types of hidden variables that EPR established by assuming certain QM predictions and Einstein locality. Bricmont is very explicit about it (p.124): "[F]or Bell, his result, combined with the EPR argument, was not a 'no hidden variables theorem,' but a nonlocality theorem, the result about the impossibility of hidden variables being only one step in a two-step argument."

But there is another frequent objection to the claim that Bell proved that quantum physics is nonlocal, typically coming from mathematical quantum field theorists who point out that "quantum field theory is Lorentz-covariant and therefore local," so that "Bell must be mistaken." Bricmont, himself trained in constructive quantum field theory, and who states (p.172) that "The predictions of quantum field theory are extremely impressive," also has this to say (p.172): "... quantum field theory essentially allows us to compute 'scattering cross-sections'." [N.B.: This is done with the help of a so-called S-matrix which maps an asymptotically incoming state from (using relativists' terminology) "past timelike (or null) infinity" into an asymptotically outgoing state at "future timelike (or null) infinity" (cf. [GlJa]), but has nothing to say about what happens in between.] "The results are, it is true, invariant under Lorentz transformations," ... "but contrary to received opinion, it is not true that there exists a fully relativistic quantum theory. After all, such a theory should be a generalization of non-relativistic quantum mechanics and should include (as one of its approximations) the results of EPR-Bell experiments (or any similar experiments involving a collapse of the quantum state when the latter is an entanglement of states whose parts are spatially separated). But that would require a relativistic treatment of the collapse as a physical process, and such a treatment simply does not exist. Moreover, one would encounter enormous difficulties if one tried to formulate it, ..." And here is Bell himself (quoted on p.173): "[The usual quantum] paradoxes are simply disposed of by the 1952 theory of Bohm, leaving as the question, the question of Lorentz invariance. So one of my missions in life is to get people to see that if they want to talk about the problems of quantum mechanics — the real problems of quantum mechanics — they must be talking about Lorentz invariance." (N.B.: By "quantum mechanics" Bell here really means "quantum theory.")

The "1952 theory of Bohm" referred to above by Bell is explained in chapter 5. Bricmont calls it the de Broglie–Bohm theory, for it was Louis de Broglie who originally did suggest this theory at the 1927 Solvay conference [deB]. It seems that de Broglie had this theory in mind already when he wrote his doctoral dissertation, but at that time he had no wave equation for his "de Broglie waves" — Schrödinger's

equation came two years later, inspired by (but, curiously enough, also based on a misunderstanding of) de Broglie's proposal. Einstein, although initially encouraging de Broglie to continue along this line of research (see Bricmont's Einstein quote at the bottom of p.237 / top of p.238 — incidentally, de Broglie did not heed Einstein's advice for 25 ensuing years), after David Bohm rediscovered de Broglie's theory 25 years later [Boh], in a letter to Max Born (quoted on p. 270) wrote: "[The de Broglie-Bohm] way seems too cheap to me." Bricmont speculates that Einstein found the theory "too cheap" because it is manifestly nonlocal, something he could not accept (as Bricmont explained in chapter 4). But, as Bricmont points out (p.271): "Einstein was writing this 12 years before Bell's theorem."

The principles of the de Broglie–Bohm theory are very simple: In the non-relativistic version, there is the same Galilean three-dimensional physical space and one-dimensional physical time as in Newton's point particle mechanical theory of the physical world,¹² and in physical space there is matter which is made of a huge number N of point particles which move through space as time goes on, in a deterministic manner (this idea is also shared with Newton's theory), but the law of motion is decidedly non-Newtonian! The law of motion (in the spin-less version) says that the velocity of the k-th point particle is obtained by evaluating the k-th coordinate gradient of the phase Φ of the Schrödinger wave function $\Psi = |\Psi|e^{i\Phi}$ at the actual N particle configuration; the Schrödinger wave function in turn is just the solution of QM's Schrödinger wave equation on N-particle configuration space.

So here, in addition to the wave function $\Psi(t, \mathbf{x})$ with $\mathbf{x} \in \mathbb{R}^{3N}$ one does have an extra variable, the actual configuration $\mathbf{X}(t) \in \mathbb{R}^{3N}$, which is missing from the orthodox theory. The equation of (spin-less) motion for $\mathbf{X}(t)$ is the collection of "guiding"

¹¹Einstein, to the best of the reviewers knowledge, didn't elaborate what was "too cheap" about the "de Broglie–Bohm way" to quantum mechanics. Einstein did, however, write down some concrete criticism of the de Broglie–Bohm theory in his contribution to the Festschrift on the occasion of Max Born's retirement from the Tait Chair of Natural Philosophy at the University of Edinburgh (Hafner Pub. Co. Inc., N.Y., 1953), Ref.[172] in Bricmont's book. Remarkably enough, after Bohm refuted Einstein's criticism Einstein asked the editors that Bohm's refutation be included also in the Festschrift — and so it was. Basically, Bohm's argument was that Einstein had criticized the de Broglie–Bohm theory based on a particular solution which is not physically observable, similarly to criticizing Newtonian mechanics by pointing out that it allows (never observed) solutions showing a needle standing on its tip on a glass plate forever, without analyzing whether this is a stable (read: observable) situation.

 $^{^{12}}$ I ignore here that Newton wrote he thought that there is a preferred "absolute space," for his theory does not rely on this supposition.

equations" $\frac{d}{dt}\mathbf{X}_k(t) = \frac{\hbar}{m_k}\nabla_k\Phi(t,\mathbf{x})|_{\mathbf{x}=\mathbf{X}(\mathbf{t})}$ for all N three-dimensional components of $\mathbf{X}(t)$. Bricmont also explains how spin can easily be incorporated by replacing the N-body Schrödinger with the N-body Pauli equation, and by rewriting the guiding equation as $\frac{d}{dt}\mathbf{X}(t) = \frac{\mathbf{j}(t,\mathbf{X}(t))}{\rho(t,\mathbf{X}(t))}$, where $\mathbf{j}(t,\mathbf{x})$ and $\rho(t,\mathbf{x})$ are what in QM is usually called "quantum probability current" and "quantum probability density," respectively, computed from the solution of either the Schrödinger equation (the spin-less case) or the Pauli equation (when spin is included); note that in the de Broglie–Bohm theory these quantities do not fundamentally have Born's statistical (read: ensemble) meaning but a dynamical one. Note also that the de Broglie–Bohm theory does not postulate special "hidden spin variables" to incorporate "spin."

It is clear already what this theory says about the world: matter is made of point particles which move in a certain non-Newtonian way. There's nothing incomprehensible about that. In particular, the theory does not suffer from a "reality deficiency disorder." Now, the theory's aim is to explain everything QM says about matter in terms of how these fundamental constituents of matter, the point particles, move, including in particular an explanation of what happens in a "measurement." The question whether it succeeds is answered by Bricmont with a resounding "Yes!".

There are few expositions of the de Broglie–Bohm theory, for instance the book by Bohm and Hiley [BoHi] where it goes under the name Bohm gave it, "Causal interpretation of QM," and the one by Holland [Hol] on "The quantum theory of motion," and the one by Dürr and Teufel [DüTe] on "Bohmian mechanics," but there are also the collections of works by Bell [Bel] and by Dürr, Goldstein, and Zanghì [DGZ]. Bricmont closely follows the exposition of the theory given in the works of Bell, and of Dürr, Goldstein, Zanghì, and their collaborators. Of course, he doesn't merely repeat what others have written about the matter, but condenses its essence into the space of a single chapter.

After having explained what the problem is with orthodox QM, and how the de Broglie–Bohm theory overcomes this problem, Bricmont in chapter 6 raises the question whether other, much more popular attempts to overcome the "measurement problem of QM," offer an alternative.

¹³Incidentally, if in the guiding equation one sets $\hbar\Phi(t,\mathbf{x}) =: S(t,\mathbf{x})$, it becomes identical to the one in the Hamilton–Jacobi formulation of Newtonian point mechanics, except that $S(t,\mathbf{x})$ here does not satisfy the Hamilton–Jacobi PDE, but rather a PDE which differs from it by an additive term which depends only on $|\Psi|$. Since this $|\Psi|$ -dependend term symbolically vanishes as $\hbar \to 0$, one sees that Newtonian point particle mechanics is the classical limit of the de Broglie–Bohm theory whenever $S(t,\mathbf{x})$ converges to a regular function as $\hbar \to 0$. Hamilton–Jacobi theory is not addressed in Bricmont's book, who tries to keep the mathematics at a more elementary level.

Chapter 6.1 addresses some variations of the "Many-Worlds Interpretation," conceived of by Everett and advocated by (among others) Bryce DeWitt, David Deutsch, Lev Vaidman, and the philosopher David Wallace. (But, as Bricmont explains, also Erwin Schrödinger's early attempt, which he subsequently dropped, to extract objective physics from his wave function is a version of a "many-worlds" theory.) These "interpretations" reject the "Copenhagen postulate" that the unitary quantum evolution is "fundamental only between measurements" (and to be replaced by a nonunitary "collapse of the wave function" during "measurement") and try to account for "the real physical world 'out there' " in terms of a de facto "Pure Wave Function Ontology," ¹⁴ but (except for Schrödinger's) they are very vague about what precisely is "a world," of which they claim there is a proliferation. (Schrödinger didn't think of his as a "many-worlds" theory, for it does have a matter ontology in our real physical space, but as Valia Allori and her collaborators put it (p.208): "the world, in that theory, is like a TV set that is not correctly tuned so that a mixture of several channels is seen at any given same time" [except that one doesn't simultaneously see many movies, but many 'evolving material realities.'])

Chapter 6.2 addresses the "Spontaneous Wave Function Collapse" theories, in particular the Ghirardi–Rimini–Weber theory, which was followed up by Bell, made relativistic by Rodi Tumulka, and more recently contemplated also by Weinberg — these are theories in which the unitary evolution of the quantum state is replaced by a stochastic evolution which "collapses" the quantum state of a system every once in a while *objectively* without invoking a "measurement" for that purpose; they replace the vague orthodox talk of "collapse of the wave function" by implenting this notion in a mathematically precise manner. In this connection Bricmont also mentions other approaches based on modifying the unitary Schrödinger evolution, not into a stochastic but into a nonlinear deterministic evolution, associated with the names of Roger Penrose and of Steven Weinberg, amongst others. The crucial distinction of these approaches is that their predictions differ from those of orthodox quantum theory. This feature is welcomed by experimentalists, but so far no experimental discrepancy with the QM predictions has been discovered (within the error bounds).

Chapter 6.3 addresses the "Decoherent Histories" approach associated with Bob Griffiths, Roland Omnès, and Murray Gell-Mann – Jim Hartle, amongst others. "Decoherent Histories" are also known as "Consistent Histories," somewhat ironically for, as Bricmont reports, it was demonstrated by Shelly Goldstein, and independently Bassi and Ghirardi, that the "Consistent Histories" interpretation yields logical in-

¹⁴This means "the wave function is all there is."

consistencies (unless you're willing to dispute the meaning of the word "and").

Chapter 6.4 addresses "QBism" ("Quantum-Bayesianism"), which has its origin in the more recent application of QM called "quantum information theory" (started by Richard Feynman [Fey82], exploiting "quantum entanglement," and capitalizing on the path-breaking papers by EPR [EPR], Schrödinger [Sch], and Bell [Bel]), and which enjoys a growing following (associated with the names Charlie Bennett, Chris Fuchs, Asher Peres, David Mermin, ...). In brief, "QBism" seems to be based on the idea that "fundamental insights into QM" will be obtained by (paraphrasing Bricmont) "turning the logic upside down," by postulating some information-theoretical axioms and hoping to obtain QM. Thus, in "QBism" QM is viewed as a subjective theory. Here is Chris Fuchs (quoted on p.225): "'Whose information?' 'Mine!' Information about what? 'The consequences (for me) of my actions upon the physical system!' It's all 'I-I-me-me mine,' as the Beatles sang." Bricmont, himself an aficionado of the Bayesian (subjective) interpretation of "probabilities," disputes that QM (and by extension, physics) is fundamentally about "our subjective experiences" of the world (p.226): "QBists claim not to be solipsists (people who write articles and books to convince others of their views rarely claim to be solipsists), but if physics is all about updating my subjective experiences, then in what sense does it differ from solipsism? Travis Norsen calls it solipsism FAPP¹⁵ but it is rather solipsism in denial, since that approach does not deal with anything except ones subjective experiences; so the difference with solipsism is only that one denies being solipsist, without saying anything about what could exist outside ones conscious states of mind." (Chapter 3 comes in handy here to appreciate what Bricmont is trying to convey!)

Bricmont compares these approaches to the de Broglie–Bohm theory and, in chapter 6.5, summarizes his conclusions: "[W]e claim to have shown here that [the dBB theory] is the only theory that is free from any of the following problems:

- Inconsistency, like the decoherent histories approach.
- Making different predictions than quantum mechanics, hence also than the de Broglie–Bohm theory, as the spontaneous collapse theories do, while adjusting its parameters so that no empirical contradiction can be detected.
- Putting the observer back at the center of our physical theories, as QBism does, or as the defenders of the decoherent histories approach also do (sometimes).
- Being ill-defined or hard to make sense of, like the many-worlds interpretation, or the 'bare' GRW theory (the one without ... [an] ontology). 16"

¹⁵ "For All Practical Purposes;" the acronym is due to John Stewart Bell.

¹⁶Read: "without a clear statement of what exists."

Bricmont's list of "alternative" proposals to overcome QM's "measurement problem" is certainly incomplete, as the author himself points out, but it does compare the author's favorite (the dBB theory) with what appears to be the currently most popular "beyond-Copenhagen" proposals, and he makes a compelling (if harsh) case for the rational superiority of the de Broglie–Bohm theory. Some other well-known proposals, such as "'quantum logic,' 'quantum probabilities,' or the 'modal interpretation,' " are left aside, "partly because they are not that popular any more" (p.199). Also Jürg Fröhlich's very recent "ETH¹⁷ theory" (see [BFS]) is not addressed — time will tell whether it will withstand the scrutiny of inquisitive peers.

If the de Broglie–Bohm theory would itself have been an invention of the recent past, the book could have ended here, except for some technical appendices (I haven't yet mentioned any of these; chapters 2–6 have appendices which supply some technical details to the explanations of the main sections). However, the theory has been around pretty much since the inception of QM. And so Bricmont asks (p.228): "If the de Broglie–Bohm theory has so many qualities, why is it so generally ignored?" and answers: "To answer this, we must turn to the history of quantum mechanics and take into account some psychological and sociological factors." Chapters 7 ("Revisiting the history of quantum mechanics") and 8 ("Quantum mechanics and our 'culture'") are devoted to this. It is in these two chapters where Bricmont's long-time engagement in fighting unscientific irrationality, not only in the post-modern but in particular also in the scientific communities, is once again on full display.

So, at the end of the day, does Bricmont succeed in 'making sense of (non-relativistic) quantum mechanics'? Absolutely "Yes!", in the opinion of this reviewer. What's more, Bricmont inspires readers, in particular students and junior researchers, to stop to think, and not to submit to the gospels of false prophets. In particular, if you think that "quantum theory is incomplete because we haven't succeeded in quantizing gravity yet," then think again! Near the end of his final chapter 8.4 ("Understanding quantum mechanics: an unfinished story"), Bricmont points out: "A genuine merging of quantum mechanics and [not only general, but even already special] relativity is still an open problem, and might be called the great unrecognized frontier of physics."

¹⁷Standing, not for "Eidgenössische Technische Hochschule" but, for "Events, Trees, Histories."

¹⁸ Full disclosure: The reviewer is on record [Kie] for expressing the opinion that "the de Broglie–Bohm theory (a.k.a. Bohmian mechanics), which is presumably the simplest theory which explains the orthodox quantum mechanics formalism, has reached an exemplary state of conceptual clarity and mathematical integrity. No other theory of quantum mechanics comes even close."

I wish this book had been around already when I was a student. It is a *must read* for anyone who seriously cares about *understanding* what our "most fundamental scientific theories" say about the physical world.

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