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# Introduction: The Metaphysics of Quantum Mechanics

**Anna Marmodoro**[1]

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The study and interpretation of quantum phenomena have generated a lively debate not only among physicists but also among philosophers, from a multiplicity of perspectives. There seems to be broad agreement among physicists that the worldview depicted by quantum mechanics is radically different from the one of classical mechanics. Because of this, many philosophers have identified the transition from classical to quantum mechanics as a prototypical example of a paradigm shift, and identified the 'discovery' of quantum mechanics as a scientific revolution, as famously described by Thomas Kuhn, whereby there is no possible way of understanding the quantum phenomena with the allegedly obsolete concepts and metaphysical underpinnings of classical mechanics. In the first part of this special issue, Allori's and Rosaler's essays address the question of how irreducibly novel the quantum paradigm is. Related to Rosaler's essay, Zalamea discusses how the defining features of a physical system can be best captured via mathematical formalisms. These three essays are briefly introduced in what follows.

In her essay 'Quantum Mechanics and Paradigm Shifts', Valia Allori engages critically with the widespread way of thinking of quantum mechanics as necessitating a paradigm shift in science and philosophy. Allori identifies the origin of this line of thought in Bohr's (1949) argument that quantum object cannot be described with our 'old' concepts, and that all science can do for us is to predict the results of measurements derived in terms of a mathematical object that evolves in time according to an equation typical of a wave, and therefore has been interpreted as a wave, called "the wave function." Allori argues that the alleged necessity of taking the wave function to describe physical objects is what motivates the alleged necessity of a paradigm shift. But recently it has been acknowledged that we do not have to interpret quantum theories as theories of the wave function. Various proposals have been made, whereby, as in classical theories, the world is described by trajectories of microscopic stuff in space–time that compose macroscopic objects. In this way, Allori argues, we can develop a new but clear explanatory scheme, on the lines of the classical one, to account for the macroscopic world in terms of its microscopic constituents. The particles in Bohmian mechanics, the mass density in GRWm and Sm, and the flashes in GRW are the so called "primitive ontology" of the quantum theory. If we take this route, there is no quantum revolution, or at least not the one that has been advertised so far by many as a necessary transition to a new scheme.

Also on the topic of the relationship between quantum and classical theories is Joshua Rosaler's essay '"Formal" versus "Physical" Approaches to the Quantum–Classical Correspondence'. Rosaler identifies two approaches used in the literature to address the issue of the relationship between classical and quantum mechanics; he calls the two approaches the "formal" and the "physical" one. The formal approach investigates whether there are abstract correspondences between the mathematical frameworks of quantum and classical mechanics. The physical approach by contrast is more directly concerned with the manner in which structures characteristic of classical and quantum models are exhibited in the behaviour of real physical systems. Correspondingly, Rosaler discusses two different types of reduction of classical physics to quantum mechanics that have been explored in the literature. A formal reduction of one to the other would require the

✉ Anna Marmodoro
anna.marmodoro@philosophy.ox.ac.uk

1 University of Oxford, Oxford, UK

mathematical formalism of classical mechanics to be in some sense a special or limiting case of the mathematical formalism of quantum mechanics. On this approach the question of whether one theory reduces to the other is an a priori question to be resolved entirely through mathematical analysis of the two theories. On the other hand, a physical reduction of classical to quantum mechanics would require that every circumstance under which the behavior of a real physical system can be modeled classically would also be one under which that same behavior can be modeled at least as accurately, and in at least as much detail, quantum mechanically. In other words, a physical reduction would require that quantum mechanics wholly subsumes the physical domain of application of classical mechanics; but does not necessarily require that the theories' formal structures subsume one another. In his paper, Rosaler argues that while certain formal results have been taken to preclude *any* possibility of reduction between classical and quantum mechanics, an account of the *physical* reduction of classical to quantum mechanics is made available by work on decoherence.

Federico Zalamea also looks at the relation between a formal and a physical approach to a given system, but from a different angle than Rosaler's. In his essay 'The Mathematical Description of a Generic Physical System' Federico Zalamea probes the assumptions behind the current practice, in classical as well as quantum mechanics, of characterizing a generic physical system by appeal to some specific class of mathematical objects. Zalamea argues that if the mathematical definition is all there is to know in order to completely determine a physical system, it must be possible, in practice, to qualitatively identify any specific physical state within the mathematical structure used to define the system. But, Zalamea maintains, there are not enough "qualitative" properties in an abstract Hilbert space for such identification to be possible. Thus such a space fails to provide what is needed for a full and unambiguous characterization of a given physical system. Zalamea commends group theory as an alternative and valid tool for overcoming this difficulty in using mathematical formalisms to define physical properties.

The second part of this special issue considers another set of philosophical concerns that quantum mechanics has raised. Many philosophers have voiced the worry that it is impossible to give, at least at this stage, an ontological analysis of quantum phenomena, because it is still controversial how quantum theory should be formulated, given that there are various proposals still under discussion and no consensus has been reached yet. Furthermore, with quantum theory it looks that our "manifest" and "scientific" image of the world [to use Sellar's (1962) terminology] come apart, and irreconcilably so. Maudlin's essay in this issue argues for the importance and viability of bridging such a gap; and broadly along the same lines, Dunlop's essay argues for the need to make metaphysical commitments to underpin the quantum paradigm. Assuming that such underpinnings can be worked out, despite the existing competing interpretations of quantum phenomena, Dorato identifies them with an ontology of events. Wolff explores the possibility of modeling metaphysically quantum indeterminacy by treating quantum properties, like spin, as indeterminate determinables. Darby concludes this special issue with an essay examining the question of how familiar or indeed unfamiliar would the Metaphysics of quantum mechanics look to a Clapham Omnibus metaphysician. These six papers are introduced in more detail in what follows.

In his essay 'The Universal and the Local in Quantum Theory', Tim Maudlin remarks how scientific inquiry must start from the world as it appears to us independently of any theoretical postulates: from objects and their behavior at the scale of everyday life (the so-called manifest image), to postulated entities that are not directly observed (the scientific image). Having postulated the physically fundamental but not-directly-observable, one must also be able to derive consequences of the postulates at the scale of everyday life. Were this not possible, the fundamental physical theory would have no empirical consequences and so could not become part of empirical science, notes Maudlin. Against the backdrop of these methodological considerations, Maudlin argues that quantum theory faces a problem in that, as it is usually formulated, contains no clear ontology, and thus cannot meet the methodological requirements that would allow it to count as sound science. This situation creates strong demands for any precise formulation of quantum theory. Maudlin examines those constraints, and illustrates in his paper some ways in which they can be met. He points to the example of Bohmian mechanics as an undisputable proof-of-concept for one sort of solution. In the standard physics literature it is clear, neither what local beables are being postulated, nor how they relate to the mesoscopic objects that populate the manifest image; nor further is there an explanation of how to relate the wave functions of small systems to the wave function of the larger system they are part of. All these problems must be solved if the ontology of a quantum theory is to be made clear.

Lucas Dunlap takes his cue from the same problem as Maudlin's, of an apparent gap between the manifest and the physical image of the world, in his essay, 'On the Common Structure of the Primitive Ontology Approach and the Information-Theoretic Interpretation of Quantum Theory'. He argues against Bub's and Pitowsky's quantum information-theoretic interpretation that an interpretation without clear ontological commitments would not count as a theory. Mauro Dorato, in his paper 'Quantum Mechanics as a Ontology of Events', argues in favour of an ontology of events as the best candidate for underpinning quantum theory. Dorato notes how one of the most frequent points of misunderstanding between physicists and philosophers of physics or metaphysicians in the case of quantum mechanics is that interpretive questions calling for ontological analyses become murky since, at least according to philosophers, it is still controversial how quantum theory should be formulated, given that there are various proposals still under discussion and no consensus has been reached yet. Dorato argues that the metaphysical category of events is precise, flexible and general enough so as to cover the three main alternative formulations of quantum mechanics that advocate a primitive ontology (Bohmian mechanics and the two versions of GRW theories of collapse, flashes and density of stuff), as well as some anti-realist views about the wave function. However, to the extent that one wants to defend a form of indirect realism about the wave function, Dorato claims that one needs to endorse also the idea that the latter is a disposition possessed by all the particles in the universe. This further thought is explored in the paper in connection with Lewis' suggestion that events are to be regarded as *properties* of regions of spacetime.

In her essay 'Spin as a Determinable' Joanna Wolff focuses on the issue of quantum indeterminacy. The jury is still out on whether quantum mechanics, as we currently understand it, underpins metaphysical or merely epistemic indeterminacy. For argument's sake, Wolff assumes in her essay that the issue is a metaphysical one, as per the so-called orthodox reading (by Dirac and von Neumann) of quantum mechanics. Wolff investigates whether quantum indeterminacy can be modeled, metaphysically, by treating quantum properties such as spin as indeterminate determinables. Her conclusion is ultimately negative, but the investigation illuminates issues related to quantum determinacy and also the determinable/determinate model.

George Darby's essay 'Entanglement and the Metaphysician on the Clapham Omnibus' explores how the 'discovery' of quantum entanglement impacts on mainstream Metaphysics. Does it make it all 'obsolete', to recall the starting point of this journal issue? Darby's answer is negative. He focuses on some questions of detail that occur when attempting to make contact with current debates, as they occur in the Metaphysics literature. Such detailed accounts broadly concern the failure of Humean supervenience—details that matter less, Darby argues, when the aim is just to show that there is some novelty in entanglement, but more, when articulating its precise nature. Darby's conclusion is broadly that the differences are not as great as is sometimes supposed between entanglement and more familiar phenomena already accommodated in prominent philosophical schemes that a metaphysician on the Clapham Omnibus would be familiar with.

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