The Quantum Theory of Motion. Peter R Holland Cambridge University Press, Cambridge, England 1993. pp. 598 Price $120, £70

Quantum mechanics, whose creation spanned the entire first quarter of this century, is the work of many hands. The initial crucial insights and advances, coming from Max Planck, Albert Einstein and Niels Bohr, covered the period of the old quantum theory. Then around 1925–26 came the definitive mathematical formulations of Werner Heisenberg, Paul Dirac and Erwin Schrödinger, with important contributions by Louis de Broglie and Wolfgang Pauli as well. Unique among physical theories, it so happened that the formal structures were found first while the problems of physical interpretation were attended to later. To some extent it may be claimed that the situation was similar with Maxwell's discovery of the equations of classical electromagnetism – for quite a while Maxwell sought to find a 'gears and wheels' underpinning to his field equations, in keeping with the mechanistic traditions of his day. And it took close to four decades for the primary quality of electric and magnetic fields, with no substructure and on par with matter, to be fully accepted. However, in retrospect, the problems with interpreting quantum mechanics run much deeper, impinging on questions of existence, observation and human understanding – ontology and epistemology.

The prime architects of the generally accepted 'Copenhagen' interpretation of quantum mechanics are Bohr and Heisenberg, with important inputs from Max Born, Dirac and Pauli. Strange it is indeed, though, that seven decades after the advent of quantum mechanics, and notwithstanding its enormous empirical successes, its meaning is still not a settled matter, but a subject of debate. The original interpretation – involving the need for measurement and an external observer to endow microscopic systems with definite quantitative properties, and denying existence in the absence of observation – was vigorously objected to by both Einstein and Schrödinger. Added to these features was the ingredient of allowing only statistical predictions at the fundamental level of microscopic processes, a sacrifice of classical determinism. However, quite early in the story, there appeared a theorem due to von Neumann to the effect that, given certain 'reasonable' assumptions, there was essentially no escape from the conventional interpretation of quantum mechanics, no hope of ever extending it to recover a more or less classical view of substance and physical process. Indeed, Pauli – the most critical and discerning mind of his generation – believed the existence of an element of irrationality in nature at the deepest level and a limitation to a statistical form of causality as fundamental features of our understanding of phenomena.

As early as 1927, however, and at the same time when Einstein began his deep criticism of the Copenhagen interpretation, de Broglie offered an alternative view ascribing simultaneous reality to both particles and waves in the description of matter. He, however, withdrew his ideas in the face of severe criticism by Pauli and others. Another major challenge to the Copenhagen view was offered in the mid-thirties by Einstein, Boris Podolsky and Nathan Rosen, leading to their suggestion that quantum mechanics must be incomplete, and that it could be completed incorporating certain principles of reality and locality.

Much later, around 1952, David Bohm independently came up with a 'hidden variables' interpretation of quantum mechanics, evidently and fortunately unaware at the time of von Neumann's theorem. Soon it was realized that Bohm's ideas were very close to the much earlier efforts of de Broglie The latter took encouragement and revived his work, and this led to the de Broglie–Bohm (deBB for short) or causal interpretation of quantum mechanics. Bohm also rephrased the EPR ideas in more accessible form; these developments led to John Bell's celebrated analysis of how it was that Bohm had evaded von Neumann's theorem in the first place, and to his famous inequalities capable of experimentally distinguishing quantum mechanics from alternative theories of the type envisaged by Einstein, Podolsky and Rosen.

Peter Holland's book is a magnificent and exhaustive presentation of the work inspired by the deBB ideas and carried out by a whole generation of physicists who may be said to belong to the deBB school. The main aim is to show that, given the mathematical structure of (nonrelativistic) quantum mechanics as discovered in 1925–26, and involving the use of wave functions for describing the behaviour of localizable particles, one can give a physical interpretation which is much closer to classical attitudes than the Copenhagen interpretation. In the process the specific features that distinguish the quantum domain from the classical one are seen in a different light and in sharp focus. Thus, the ambiguous and 'unfathomable' separations and interactions between object, apparatus and observer are replaced by more uniform and even-handed approach to and treatment of all three.

Holland's style is eminently readable, cogent and leisurely. All the aspects he touches upon are dealt with in great detail and completeness. He emphasizes that while the usual view denies the possibility of visualizing atomic phenomena in concrete terms, the causal theory from the outset permits and constructs pictures of systems as they are on their own, independent of observation. Both the point particle and the wave function are treated as elements of objective reality, obeying deterministic equations of evolution The latter guides the former, and to that extent it is a sign of asymmetry between the two. To this is added a way of arriving at statistical predictions which are guaranteed to agree with usual quantum mechanics wherever comparison is possible – but statistical features are not unavoidable or irreducible ingredients in the deBB approach.

The main focus of attention is the nonrelativistic quantum mechanics of point particles. And in the causal theory the two crucial quantum features are the emergence of a quantum potential, and of a generally unavoidable nonlocality. Holland explores and explains these both in single-particle and many-body contexts – and one sees innumerable examples where 'causal quantum' behaviour can be strikingly different from the classically expected one Physical quantities – dynamical variables – have, in principle, definite numerical values at all times, and these are not quantized. Yet the analysis of an actual measurement process shows how the eigenvalues of conventional theory emerge as 'results of measurement'. Typical quantum phenomena of interference and tunnelling are shown to be recovered intact in this approach, without giving up pictures and particle trajectories at any stage.

The chapters devoted to the passage to the classical limit, and the measurement process, are particularly outstanding. Holland stresses how subtle and delicate the former is: in the present approach it is the vanishing of the quantum potential that is the key. An essential point made is that the underlying conceptual structures cannot change in the passage to the classical limit, only the quantitative details of processes can. From the treatment of the many-body problem one sees forcefully the emergence of the key quantum features of nonlocality and nonseparability, both due to the integrity of a common wave function. There are also two chapters devoted to particles with spin – one at the level of the Pauli equation, and another using a more elaborate model for particles with structure. Holland demonstrates that the same driving philosophy of the deBB theory can be successfully implemented here too.

The concluding chapter exploring the extension of these methods to relativistic field theory points out the need for new ideas – an unexpected and surprising conclusion is that Lorentz invariance may be only statistically valid!

At the end of Holland's superb effort, one is left wondering: why has this alternative to the conventional view of quantum mechanics not received more attention than it has so far? Why is there an apparent reluctance to consider it seriously? In any case, a critical and deep questioning of the conventional interpretation, by more than a small minority, is a relatively recent phenomenon. The causal theory deliberately highlights the role of physical space and position, and to that extent sacrifices the beautiful transformation theory of quantum mechanics. One cannot help asking why Bohr, Heisenberg and even Richard Feynman did not consider the deBB alternative more seriously. But in criticizing today those that fashioned the conventional interpretation, let us not underestimate the magnitude of the problems they faced and their efforts to find answers to utterly strange questions – it was no mean struggle. With the causal theory, in a sense the magical qualities of quantum mechanics are explained away by a return ultimately to a mechanistic point of view.

It thus seems after all that for some time to come, while Holland's presentation will make it possible for many more to come to know the causal theory in great detail, the question of accepting this as the right interpretation of quantum mechanics will remain unsettled. Individual reactions will probably continue to be based on preferences, beliefs and such subjective notions. The subject is thus rich also for a study from the viewpoints of the psychology of science and scientists, and in this sense the situation seems to share features common to some other areas of science.

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(Based on the invited lectures delivered at the National Seminar on Sixty Years of [the] Dirac Equation, Visva-Bharati University, Santiniketan, 28–30 January 1989.)

Much has been written about the two great revolutions in physics that have taken place in this century, altering profoundly our view of the arena of the universe (space–time) and the players in it (physical objects) – namely, relativity and quantum mechanics. Many would add a third – perhaps deterministic chaos and complexity – although we should probably wait for a better perspective afforded by the passage of 50 years or so before making a definite addition to the short list of genuine revolutions ('paradigm shifts' in more fashionable terminology). There are fundamental similarities, and equally fundamental differences, between these revolutions. One feature seems to stand out, however, as a hallmark of the deep content of each of them. Results of the surprisingly *basic* nature continue to emerge decades after the theory has been (apparently) fully thrashed out. Examples come to mind readily: in relativity, the rather late realization that geometrical distortion effects preclude direct observation of length contraction (a relativistic cube whizzing by would look like a rotated cube rather than a cuboid); in quantum mechanics, the geometric phase. When relativity and quantum mechanics are put together, few would disagree with the statement that we do not even have a complete, fully satisfactory theory as yet. It is, therefore, not surprising that new developments continue to occur in the venerable subject of quantum mechanics at all levels, ranging from its conceptual foundations to applications to novel systems that become accessible to experiment.

It is in this light, that of a subject in active and lively development, that the articles collected in *Dirac and Feynman – Pioneers in Quantum Mechanics* must be viewed. The collection does not constitute a textbook or monograph, or anything like it, even in the topics with which it is broadly concerned – the Dirac equation, the Feynman path integral, and their ramifications. Following (very) brief biographical sketches of Dirac (by N. Mukunda) and Feynman (by C. K. Majumdar), there are 17 articles by some of our leading theoretical physicists. The authors (and editors) must first be commended for the very existence of this collection, for we are all aware that promises of write-ups of lectures are like babies – fun to make, but hell to deliver. The articles are crisply written and cover a wide and interesting range of topics Although six years have gone by since the lectures on which they are based were given, and newer results have emerged in several cases, these articles are by no means outdated. By and large, they should continue to remain useful and instructive to students, teachers and other interested physicists for some time to come. In several instances they provide good, readily accessible introductions to the relevant literature – particularly, in the case of some of the slightly longer articles that are in the nature of reviews. These include 'Spinors in many dimensions' (N. Mukunda), 'Introduction to Feynman path integrals' (S. V. Lawande), 'Fermion number fractionization in quantum field theory' (A. Khare), 'Berry's phase and canonical transformation' (S. N. Biswas), 'Some aspects of relativistic electrons' (C. L. Roy), and the chronological perspectives offered in 'The discovery of Dirac equation and its impact on present-day physics' (G Rajasekaran) and 'The Dirac equation and aftermath' (A. N. Mitra).

There are some respects in which the value of this book could have been enhanced. The three-year delay in putting the collection together after the conclu-