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Edited by Jeremy Butterfield and Constantine Pagonis
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From Physics to Philosophy

This collection of essays by leading philosophers of physics offers philosophical perspectives on two of the central elements of modern physics, quantum theory and relativity. The topics examined include the notorious 'measurement problem' of quantum theory and the attempts to solve it by attributing extra values to physical quantities, the mysterious nonlocality of quantum theory, the curious properties of spatial localization in relativistic quantum theories, and the problem of time in the search for a theory of quantum gravity. Together the essays represent some of the most recent research in philosophy of physics, and break new ground within the philosophy of quantum theory.

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Preface

Most of the essays in this collection were presented as papers at a two-day conference, held in the History and Philosophy of Science Department, Cambridge University, in June 1997. The editors are very grateful to the Department, to the British Society for the Philosophy of Science, and to the Mind Association for their generous financial support of the conference.

The conference was held on the occasion of Michael Redhead's retirement from the Professorship of the History and Philosophy of Science in the University of Cambridge; and the authors and editors are delighted to honour him with this volume. A bibliography of his writings is included.

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Introduction

JEREMY BUTTERFIELD AND CONSTANTINE PAGONIS

Physics is a vast discipline, rich with topics inviting philosophical analysis. In undertaking that analysis, the philosophy of physics can be pursued in different styles. There is a spectrum: ranging from the 'theorem-proof' style as used in expounding a piece of mathematical physics (though here the theorems will be motivated by philosophical ideas), through philosophical-cum-physical argument that adverts in detail to pieces of physics (e.g. in displayed equations), to purely philosophical argument that is in some way based on, or influenced by, physics. For the most part, the essays in this collection are examples of the second of these three styles: they aim to combine detailed presentation of some technicalities in theoretical physics with the dialectical rigour of analytic philosophy.

The essays also have, with one exception, a common subject-matter: the philosophy, or if you prefer foundations, of quantum theory. The first six essays fall squarely in that subject-matter. The seventh and eighth broaden the discussion: they address, respectively, philosophical aspects of (i) the search for a theory of quantum gravity, and (ii) quantum theory's use of group theory. The final essay, by Abner Shimony, is much more speculative: it assesses the conjecture that the fundamental laws of nature are products of evolution.

Arthur Fine's essay starts the volume, on a central topic in philosophy of quantum theory: proofs of quantum nonlocality. Fine analyses a proof by Lucien Hardy, which as Fine says, is a characteristic example of a new generation of proofs that apparently make less use of probabilities and thereby dispense with inequalities. However, Fine shows that this appearance is misleading. Probabilities are substantially involved in Hardy's proof; and once we see this, we see that inequalities are also involved. Furthermore, Fine brings out how the theorem depends on the 'product rule', i.e. an algebraic condition on the assignment of values to physical quantities, which is used as a premise in Kochen–Specker-style no-hidden-variable

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proofs – and whose role in nonlocality proofs Fine long ago exposed! So Fine concludes that this unnoticed assumption means that Hardy's proof, though 'interesting and significant', is not 'a demonstration that quantum mechanics is nonlocal'.

Rob Clifton's essay is about the assignment of values to quantities in quantum theory. Clifton follows John Bell in wanting to promote some observables to the status of 'beables' – for which the probability of the quantity being a particular value is the probability of observing that value. But Clifton allows, in accordance with recent so-called 'modal' interpretations of quantum theory, that which observables are beables could depend on the quantum state; (unlike Bohmian mechanics, where position is picked out once and for all as the beable). Working in the framework of C^*-algebras, Clifton proposes an algebraic characterization of those sets of (bounded) observables which can be beables: namely, that the set be closed under all continuous self-adjoint functions of its members. Clifton calls such sets 'Segalgebras' in honour of Segal. He goes on to discuss assignments of values to these beables (as linear functionals on them). The idea is then that the measurement statistics given by a quantum state should be representable as an average over the actual values of the beables. Clifton then shows (his theorem 7) that this representation will be possible provided the Segalgebra is what he calls quasicommutative (roughly: the quotient Segalgebra, defined by factoring out the beables which are assigned 0 by the state, is commutative). (This result generalizes, and transposes to the algebraic setting, previous work by Bub & Clifton.) Clifton goes on to investigate maximal Segalgebras (having as many beables as possible), and to discuss two possible motivations for requiring commutativity, not just quasicommutativity.

The main purpose of Brown's essay is to explore aspects of the Galilean and gauge covariance of non-relativistic quantum mechanics, and their implications for the interpretation of the theory. He reviews first the nature of such covariance in relation to the single-body Schrödinger equation (for *arbitrary* background fields in the case of Galilean transformations) and he assesses the claim that the Maxwell field can be 'generated' by the local gauge principle when applied to the relativistic (Dirac) equation. He then describes how the geometric phase associated with Schrödinger evolution is not invariant under time-dependent spatial translations of the coordinate system (and hence under Galilean transformations), and briefly analyses the significance of this result. The remaining sections of Brown's paper concern the objectivity of 'sharp values' of observables (in particular as they appear

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in certain versions of the modal interpretation), in the light of recent work done jointly with M. Suárez and G. Bacciagaluppi, and the theory of quantum reference frames due to Aharonov and Kauffher. Brown emphasizes that it is only relational properties that can be considered frame- or gauge-independent elements of reality.

The next two essays are about the versions of quantum theory developed by de Broglie and Bohm. The first, by Saunders, presses a problem about these theories' ability to resolve the quantum measurement problem, in the relativistic domain. It has been suggested that the theory can be formulated using classical (c-number or Grassmanian) field configurations as 'beables'; the idea is to use a connection between the support of the non-relativistic 1-particle state, and the classical field configuration for associated states of the bosonic field. However, Saunders argues that this connection, far from ensuring that the beables are well-localized in measurement situations, implies exactly the opposite: the beables too are likely to develop into superpositions. He concludes that, since the *raison d'être* of the beables is to select one component, rather than another, of superpositions in the measurement context, the de Broglie–Bohm theory is undermined. He then explores the remaining interpretative options for the theory. *Prima facie*, there are three options; but Saunders argues that only the third – involving a commitment to the Dirac negative energy sea, in the fermionic case – can work.

Cushing & Bowman's essay is about Bohm's non-relativistic version of the theory, where particle-position is the beable; so-called 'Bohmian mechanics'. But their concern is not the measurement problem but that of empirically distinguishing this theory from orthodox 'Copenhagen' quantum theory. They begin by reviewing Bohmian mechanics, and its remarkable empirical equivalence, so far, to orthodox quantum theory. This makes it natural to look for some new domain, where one of the theories is better equipped conceptually to make a prediction. In view of the controversies surrounding the definition of 'quantum chaos' in the orthodox theory, and Bohmian mechanics' having the trajectories that are the prerequisite of classical chaos, Cushing & Bowman suggest quantum chaos as such a domain. This seems an especially promising domain, since Bohmian mechanics has a 'classical limit' quite unlike those of the orthodox theory; viz. that the quantum potential be zero. Work on chaos in Bohmian mechanics has only recently begun; but Cushing & Bowman's review suggests some tentative conclusions. The most tantalizing is that, since there are classical chaotic systems that cannot be reached as the limit of a Bohmian mechanical system, the ubiquity of classical chaos suggests that perhaps

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Bohmian mechanics cannot account for all the physical phenomena we encounter.

Fleming & Butterfield's essay is about localization and associated concepts in Lorentz-invariant quantum theory: a controversial topic, on account of the apparent violation of Lorentz covariance and the superluminal propagation of localized states. They first review Newton & Wigner's fundamental work, stressing the similarities with the Galilean case; and this prompts them to review the difficulties of defining position operators for the Klein–Gordon and Dirac equations. The difficulties prompt the question: is there any standpoint from which the strange properties of relativistic localization make physical sense? The second half of the essay answers 'Yes' to this question: the standpoint is given by previous work by Fleming. Here, the exposition begins with *classical* Lorentz-covariant position variables; more specifically, three different parametrizations of them. These are equivalent for a point-particle; but for a localizable property of an extended system (such as the centre of energy or of charge), only one parametrization, the hyperplane-dependent parametrization, is convenient. Of the three, it is also the only one that can be consistently quantized. This in effect establishes the Yes answer to the above question. The essay ends by discussing some recent criticisms of this standpoint, by Malament and by Saunders.

The next two essays broaden the discussion, going beyond the philosophy of quantum theory. Belot & Earman's essay is a case-study in the 'symbiotic relationship' between physics and philosophy. They describe how the principal issue in the philosophy of general relativity, viz. the debate between substantivalism and relationism, is bound up with the difficulties facing the development of a quantum theory of gravity. They first point out how ironic, indeed unfortunate, it is that the recent philosophical debate, especially about Einstein's famous 'hole argument', has been conducted apparently in ignorance of the fact that the same issues were being debated in the quantum gravity community. Then they describe how formulating general relativity as a gauge theory makes clear the connections between the substantivalism–relationism debate, and physical questions about the definition of observables in classical general relativity – and above all, the disturbing fact that all gauge-invariant quantities in the theory are constant in time. This is the classical 'source' of quantum gravity's so-called 'problem of time': Belot & Earman go on to briefly survey four different approaches to it.

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Steven French first discusses presentations of physical theories in terms of function spaces, and in terms of classes of models. French advocates a version of the latter approach: a version which uses partial models. He then reviews Wigner's and Weyl's great work on group theory in quantum physics as a case study of his model-theoretic approach. He ends by discussing how the case study, and this approach, bear on 'structural realism', as advocated by authors such as Worrall.

Abner Shimony's essay closes the volume in a suitably speculative and metaphysical way. He assesses the conjecture that the fundamental laws of nature are products of evolution. To do so, he first notes that for this conjecture to be coherent, there had better not be a fundamental law of natural selection; and indeed, according to other work by Shimony, there isn't. He then goes on to sketch some aspects of what one might call the 'cosmogonies' of two philosophers – Peirce and Whitehead – and two philosophical physicists – Wheeler and Smolin. He concludes on a sceptical but sympathetic note. He cannot endorse the conjecture; but the appeal to natural selection has several merits – for example, it provides 'a humble acknowledgement of the pervasiveness of contingency in the world and the futility of aiming at a completely rational world picture', and 'a multitude of instances of attaining an understanding of the emergence of order out of disorder'.

To conclude: our title reflects our belief that physics offers philosophers a vast store of topics that merit philosophical analysis. Though the philosophy of physics is at present a vigorous branch of philosophy, so much remains to be done! So, in the spirit of encouraging further work, we offer these essays to the community of philosophers of science and philosophically inclined physicists.

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