Philosophical Foundations of Quantum Field Theory

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Introduction

The conceptual foundations of quantum mechanics have been the object of intense interest and debate for both physicists and philosophers ever since the birth of the theory. Providing a coherent and comprehensive interpretation of the non-relativistic quantum algorithm has proved to be an ongoing challenge, and the vast literature on the subject is a testament to both the perennial fascination of the problem and to the absence of any durable consensus about how best to understand the theory.

If the foundations of non-relativistic quantum mechanics (QM) have received and continue to receive the serious attention of large numbers of natural philosophers, the same can hardly be said of the foundations of quantum field theory (QFT). Yet QFT, in its various versions, is widely regarded today as the most fundamental theory of physics, and has achieved in some well-known applications the most accurate, corroborated predictions in the history of physics. The rise in prominence of the theory in recent decades, following a period of decline after its foundations had been laid in the late 1920s and 1930s, has largely failed to wrest the principal focus of philosophical interest away from QM.

There are no doubt many reasons for the relative paucity of detailed investigations into the philosophy of QFT. One of them is perhaps a hasty adherence to the not uncommon and certainly respectable view that the old conceptual problems in QM are simply carried over into QFT, where they are obscured by the mathematically more sophisticated formalism. Allied to this view is the contention that QFT, in turn, raises no new foundational issues that are not already present in QM. If all of this is so, it none the less needs to be established in detail. In doing so, careful consideration must be given to the viewpoint according to which at least some of the problems in QM, e.g. the nature of wave–particle duality, receives ultimate clarification in QFT. It can also be argued that serious new difficulties arise in the foundations of QFT, e.g. in connection with renormalization procedures, the status of virtual particles, and the question of particle localizability, which have no real counterpart in the older theory.

Those physicists and philosophers who have contributed studies in the history and foundations of QFT would almost certainly be the first to agree that such issues have to date enjoyed far less attention than they deserve. Thus, the objective of this volume of essays is to delineate and examine a range of topics in the foundations of QFT that might be considered worthy of further study.

Part I is entitled 'Quantum Field Theory as an Object of Philosophical Study: Two Views'. It contains essays by Michael Redhead ('A Philosopher Looks at Quantum Field Theory'), and James Cushing ('Foundational Problems in and Methodological Lessons from Quantum Field Theory'). In a seminal 1982 paper, Redhead analysed in considerable detail the metaphysical implications of QFT. His present work is an improved version of that paper, in which besides presenting his own re-examination of several issues, he replies to objections raised by several commentators of the paper, notably Robert Weingard and Paul Teller. As in his earlier work, Redhead lists and attempts to answer eight central questions in the foundations of QFT. They concern the particle/field distinction, wave–particle duality, the nature of the vacuum, the rôle of quantum statistics, particle species unification, and other related issues. The upshot of the essay is effectively to underline the importance and novelty of metaphysical issues arising out of the theory, justifying Howard Stein's 1970 remark that QFT is, or should be, 'the contemporary locus of metaphysical research'.

Cushing, in his essay, is far less convinced that QFT indeed introduces any strong reasons for shifting this locus away from QM. In his view, neither wave–particle duality, nor even the conceptual problem of particle creation and annihilation, are fundamentally affected in the transition from QM to QFT. An examination of these and other issues leads Cushing to conclude that although QFT may be of considerable interest for those studying the dynamics of theory growth and scientific practice, it holds out little that is new and challenging from the point of view of foundational studies.

Part II is entitled 'The Problems of Virtual Particles and Renormalization'. 'Virtual' mechanisms in quantum theory really pre-date QFT. In Louis de Broglie's original 1923 matter-wave theory, the wave group, and not the individual superluminal phase wave, was considered real, but somehow the latter did—virtually—all the work in the theory. In 1924, the Bohr–Kramers–Slater theory of (explicitly) virtual radiation appeared, and when Erwin Schrödinger remarked that such terminology was merely playing with words, he was essentially raising the question of the reality of the BKS mechanism.

This particular issue died with the early demise of the theory, but in more recent times some philosophers of physics have been given to Schrödinger-like doubts about the virtual particles that play such an important role in the standard interpretation of perturbation methods in QFT.

In his essay ('Virtual Particles and the Interpretation of Quantum Field Theory'), Robert Weingard argues that if certain elements of the orthodox interpretation of states in QM are applicable to QFT, then it must be concluded that virtual particles cannot exist. This follows from the fact that the transition amplitudes correspond to superpositions in which virtual particle type and number are not sharp. Weingard argues further that analysis of the role of measurement in resolving the superposition strengthens this conclusion. He then demonstrates in detail how in the path integral formulation of field theory no creation and annihilation operators need appear, yet virtual particles are still present. This analysis shows that the question of the existence of virtual particles is really the question of how to interpret the propagators which appear in the perturbation expansion of vacuum expectation values (scattering amplitudes). Finally, Weingard examines the so-called Fayddeev–Popov ghost fields in gauge theory which violate the spin-statistics theorem. He argues that they are fictitious not because, like other virtual processes, they are associated with internal lines in Feynman diagrams, but because they can be transformed away in an appropriate sense.

In the following essay ('Parsing the Amplitudes'), Rom Harré comes to the defence of the now-battered virtual particle, in the course of providing a more general view of the nature of quantum (field theoretic) reality. Harré begins with the uses and perils of Arthur Miller's notion of visualizability in fundamental physics, and remarks in this context on the importance of the 'iconic' style of representation in Feynman diagrams in the QFT research programme. He argues, however, that in opting for a corpuscular language in the interpretation of internal states, physicists are also, and perhaps more directly, influenced by the exigencies of actual material practice in the laboratory. This leads Harré to a discussion of dispositional concepts, and more specifically of Gibsonian 'affordances', which he connects with the familiar notion of the Bohrian 'phenomenon'. To talk of virtual particles is then to talk of affordances, where the corpuscular aspect of the description follows from the nature of the track-like phenomena in high-energy physics experiments. The message here is that virtual particles are indeed different from their real counterparts (and in some cases historically precede them), but they are just as philosophically respectable.

Second- and higher-order corrections to solutions of perturbation methods in QFT are divergent, and the infinities have come to be successfully removed by the technique of renormalization. The word 'successfully' here refers to both the enormous accuracy of empirical predictions (to over eight decimal places in the cases of the Lamb shift and the electron magnetic moment) that arise out of the procedure, and the important connection between the renormalizability condition and the imposing of gauge symmetries. But can such infinities be discarded in any way that does not raise serious doubts about mathematical propriety, and does not their very existence in the first place point to severe weaknesses in the foundations of the theory? In the last essay of this section ('Three Problems of Renormalization'), Paul Teller addresses these issues. Teller attempts in a series of steps to undress the renormalization procedure of its usual, daunting technical clothes, and reveal its bare logic in a form accessible to the non-specialist. He tries first to show that from a purely mathematical point of view at least, doubts concerning the consistency of the method are unfounded. He further discerns and critically evaluates three distinct attitudes in the physics community towards the physical/philosophical significance of the procedure.

Part III is entitled 'Covariance Principles in QFT', and the first essay is by Gordon Fleming ('Hyperplane-dependent Quantized Fields and Lorentz Invariance'). In this work, Fleming advances a general formalism for a non-local field in relativistic QFT, and presents a specific example in 1 + 1 dimensional space-time. The novel feature of the formalism is the non-local dependence of dynamical variables of the system on spacelike hypersurfaces, rather than individual space-time points, in the Minkowski continuum. Fleming examines, in his introduction to the theory, the reasons why such hyperplane dependence does not feature in the standard treatments of single quantum mechanical particles, nor in that of many-particle systems. In doing so, he claims that Lorentz covariance cannot be rigorously satisfied for particles with spatially local properties in the former case, and that in the latter, although hyperplane dependence is not strictly compulsory, it may prove to be advantageous. It may eventually furnish the basis of a finite fundamental theory, or failing that, shed light on non-perturbative methods in a fundamental renormalizable local field theory.

In the second essay ('Gauge Theory and the Geometrization of Fundamental Physics'), Tian-Yu Cao examines the interesting connection between non-gravitational gauge interactions in QFT and general relativity. After an introductory section dealing with the rise of gauge theory in QFT, Cao discusses the development of the fibre-bundle version of gauge fields, and compares the non-trivial mixing of space-time and internal space indices with the mixing of space and time indices in Minkowski geometry. He argues that the concept of gauge fields is at root geometrical, and carries his analysis over to the cases of modern Kaluza–Klein theory and superstring theory. Thus despite the apparent incompatibility between the programme of QFT, involving quantum fields with local coupling and propagation of field quanta, and the geometrical programme of relativity, Cao concludes that the essence of gauge interactions in QFT is as deeply geometrical as that of gravity in general relativity.

Part IV is called 'Mathematical Foundations of Quantum Field Theory'. Following Wigner's 1939 definition of an elementary particle in terms of a certain irreducible representation of the Poincaré group, it was possible to derive, rather than merely postulate, the relativistic free-field wave equations for all possible stable particles. In his essay in this section, Ray Streater ('Why Should Anyone Want to Axiomatize Quantum Field Theory?'), explains how the programme of axiomatic QFT arose with Wightman's attempt to do for fields with interaction essentially what Wigner had done for free fields. The author starts with a critique of the historical development of the Dirac equation, and then shows how by 1936, the existing relativistic free quantized fields adhered to certain proto-axiomatic desiderata, such as positive transition probabilities, no negative-energy solutions, primitive causality, locality, etc. The advent of theories of the nuclear force however raised new problems, giving rise to a host of models involving non-perturbative methods whose predictions differed significantly. Wightman's axiomatic approach, which relied on a number of the desirable features of the free field, was designed to separate the acceptable theories from the unacceptable ones. Streater discusses the ensuing progress made in this programme, the current status of the post-1972 triviality predictions, and the problem of fitting quantum chromodynamics into the axiomatic scheme.

The second essay is by Simon Saunders ('The Algebraic Approach to Quantum Field Theory'). The author examines the nature and historical roots of the abstract approach to QFT provided by the so-called C*-algebras. In such an approach, a distinction arises between abstract structures and their concrete representations, one which in Saunders's view requires further interpretation. He argues that no concrete representation captures the full scope of the theory, and is particularly interested in the significance of the availability of non-Fock representations. This leads to an exploration of the relevance of such representations in the high-energy regime and for the traditional problem of measurement in quantum theory. The paper also provides some insight into the far-reaching relationship between statistical mechanics and QFT.

The Sub-Faculty of Philosophy at the University of Oxford has in recent years been organizing an annual seminar in the philosophy of physics. Seven of the nine papers in this volume have their origin in contributions to the symposium on the philosophy of quantum field theory held in the Sub-Faculty from 30 May to 1 June 1986. We would like to thank Michael Redhead for his valuable advice in the course of organizing this symposium.

We also thank Angela Blackburn of Oxford University Press for her interest and help in overseeing the publication of this volume, and Simon Saunders for his help and particularly for his work in preparing the index.

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HARVEY BROWN
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I

Quantum Field Theory as an Object of Philosophical Study: Two Views

1

A Philosopher Looks at Quantum Field Theory

MICHAEL REDHEAD

At the PSA Conference at Philadelphia in 1982 I gave a paper entitled 'Quantum Field Theory for Philosophers'. As a motto for the paper I took a quotation from Howard Stein: 'The quantum theory of fields is the contemporary locus of metaphysical research.'[1]

Let me begin by listing eight questions of a more or less metaphysical character which quantum field theory (QFT) might be thought to throw light on:

Q. 1. Can QFT be given a particle interpretation and indeed is there a formal underdetermination between field and particle approaches to the so-called elementary 'particles'?

Q. 2. Does QFT resolve the problem of wave–particle duality in quantum mechanics (QM)?

Q. 3. What is the nature of the vacuum in QFT?

Q. 4. What is the status of so-called virtual particles?

Q. 5. Does the theory of indistinguishable particles in QM necessitate a field treatment due to the way many-particle states are weighted in quantum statistical mechanics (QSM)?

Q. 6. Does QFT allow a distinction between matter and force?

Q. 7. In what sense has QFT achieved unification in the theory of elementary 'particles'?

Q. 8. Can the idea of creation and annihilation of particles be incorporated in classical mechanics as well as in QFT?

In my 1982 paper I attempted to answer these eight questions. Today I want to look at these questions again. In some cases I believe that what I said in 1982 was broadly on the right lines. In other cases I

[1] See Stein (1970), p. 285.

have modified my position in the light of comments and criticisms or just by having thought harder about the questions!

In a moment I will tackle Q. 1. But as a preliminary that will also answer Q. 8, let us consider the case of classical point-particle mechanics. This is famously underdetermined as between a field and particle interpretation.[2] First some preliminaries:

A *particle theory* attributes to certain individuals (the particles) a variety of properties. These properties will include space-time location.

A *field theory* associates certain properties (the field amplitudes) with space-time points. Examples are the electromagnetic field, and Eulerian hydrodynamics as contrasted with Lagrangian hydrodynamics (a particle theory).

Already we have run into a number of metaphysical conundrums. What is an individual? For a particle individuation may be provided by some essential 'thisness' that transcends its properties. I will call this 'transcendental individuality' or TI for short. Or we may appeal to spatio-temporal (S-T) continuity of its trajectory. But this means we must be able to individuate space-time points. Do they possess TI? In field theories the space-time points play the role of the individuals. The problem of how they get individuated is then a very urgent one. Are they individuated by the fields which they carry? This view finds some support in general relativity, but this relies on an application of the identity of indiscernibles to space-time points! In QM, S-T individuation is not available. So if QM particles are to be treated as individuals then TI must be presumed. Any philosophical arguments against the admissibility of TI will then tell against a particle interpretation of QM.

Returning to the underdetermination thesis in classical mechanics: How does a single particle go from A to B?

Here are two answers: A material particle moves over from A to B carrying its individuality with it (on the TI assumption) as in Fig. 1.1;

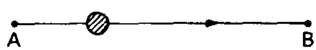

FIG. 1.1

[2] See the translation of Newton's 'De Gravitatione et Aequipondio Fluidorum' in Hall and Hall (1962), especially 138–40. Further discussion is given in Stein (1970).

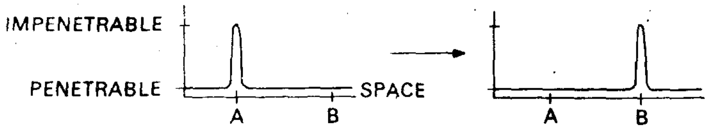

FIG. 1.2

or a property of impenetrability is assigned to a new spatial location B as opposed to A as in Fig. 1.2.

Can we break this up into a two-stage process? The spike at A (see Fig. 1.3) is annihilated leaving the vacuum configuration and then the spike at B is recreated out of the vacuum. But that is empirically wrong, since if we look we always find a particle between A and B. But if creation/annihilation followed each other sufficiently rapidly would we not get the *appearance* of continuous motion, just like the cinematograph screen?

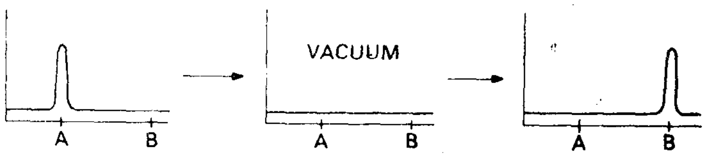

FIG. 1.3

The fact that we can never tell empirically which interpretation is right is a clear example of underdetermination by possible empirical data. This does not mean that field and particle ontologies are *heuristically* equivalent in generating theories that *are* testable.

Before giving our answer to Q. 1. We are now in a position to interpolate a quick answer to Q. 5. As we have seen, particles in QM cannot be individuated by S-T continuity of trajectory except in certain limiting cases of widely separated wave-packets. So we must invoke TI. But this leads to the following puzzle.

Consider the possible states available to two indistinguishable particles distributed among two distinct one-particle states denoted by *a* and *b*. Classical statistical mechanics (assuming TI) gives the possible ontologically distinct arrangements shown in Fig. 1.4. But in quantum statistical mechanics (iii) and (iv) are regarded as *one and the*

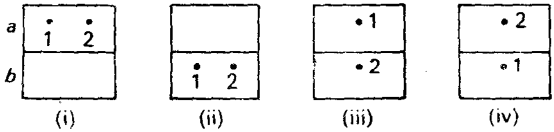

FIG. 1.4

same state for the purpose of assigning statistical weights. This is taken as showing that quantum particles do not possess TI, and must be treated like excitations of a field on which interpretation (iii) and (iv) *would* be the same state. But the argument is too quick. The statistical weights ascribed in QSM can be understood even if the particles do possess TI.

Consider the four possible product wave functions

$$\Psi_a(\mathbf{r}_1)\cdot\Psi_a(\mathbf{r}_2). \tag{1.1}$$

$$\Psi_b(\mathbf{r}_1)\cdot\Psi_b(\mathbf{r}_2). \tag{1.2}$$

$$\Psi_a(\mathbf{r}_1)\cdot\Psi_b(\mathbf{r}_2). \tag{1.3}$$

$$\Psi_b(\mathbf{r}_1)\cdot\Psi_a(\mathbf{r}_2). \tag{1.4}$$

These span a four-dimensional vector space which can equally well be spanned by the following wave functions:

Symmetric (S)

$$\Psi_a(\mathbf{r}_1)\cdot\Psi_a(\mathbf{r}_2). \tag{1.5}$$

$$\Psi_b(\mathbf{r}_1)\cdot\Psi_b(\mathbf{r}_2). \tag{1.6}$$

$$\frac{1}{\sqrt{2}}(\Psi_a(\mathbf{r}_1)\cdot\Psi_b(\mathbf{r}_2)+\Psi_b(\mathbf{r}_1)\cdot\Psi_a(\mathbf{r}_2). \tag{1.7}$$

Anti-symmetric (A)

$$\frac{1}{\sqrt{2}}(\Psi_a(\mathbf{r}_1)\cdot\Psi_b(\mathbf{r}_2)-\Psi_b(\mathbf{r}_1)\cdot\Psi_a(\mathbf{r}_2)) \tag{1.8}$$

Now for time-evolution under a symmetric Hamiltonian the symmetry character of the wave function is conserved.

So if we impose S or A as an initial condition then only one of the two states (1.7) and (1.8) is ever *available* to the system. This is why the statistical weights attaching to the *pair* of states get halved. In other words the statistical weights assigned in QSM can be regarded as arising from dynamical restrictions on the *accessibility* of certain states rather than on their ontological coalescence.

So at last we turn to Q. 1. First we consider the case of *non-interacting* fields. We distinguish *field quantization* from *second quantization.*