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Introduction: philosophy of quantum field theory

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1. Introduction

Quantum field theory (QFT) is one of the main pillars of modern physics. Yet by comparison with other central areas of physics it has received relatively little attention from philosophers of physics.[1] Recently several scholars, notably including younger scholars, have contributed to understanding the distinctive foundational problems that arise in QFT. QFTs inherit the traditional problems associated with quantum mechanics that can be traced to the Hilbert space structure of the space of states and unitary dynamical evolution. But there are distinctive problems that arise, for example, in considering the fate of particles in QFT, the status of renormalization techniques, and the nature of gauge and other symmetries. The University of Western Ontario hosted a lively and stimulating workshop in the spring of 2009 that brought together many of the philosophers actively working on QFT. This issue collects some of the papers presented at the workshop, along with one (Earman's) that was intended for the workshop but not presented there. These papers approach the foundational problems of QFT from a variety of different technical and philosophical perspectives.

One issue confronts the would-be interpreter of QFT at the very beginning of her undertaking: what version of QFT is the appropriate target of her research? A gulf separates axiomatic treatments from the methods used by most working physicists. And in this case the gulf is deeper than the usual divide between physicists' relaxed standards of rigor and the sophistication of the mathematicians. History of physics offers several examples where apparently quite different formulations turned out to be equivalent versions of a single theory. But in this case it is clear that such a reconciliation of different approaches cannot be easily achieved. Conventional quantum field theory (CQFT) has accrued an impressive record of empirical success. This success initially came at a price, namely reliance on "renormalization" techniques that some of its most skilled practitioners regarded as "hocus-pocus" Feynman, 1985, p. 128. Axiomatic QFT (AQFT) developed partly in response to this unsatisfying state of affairs, reflected in Streater and Wightman's "kill it or cure it" approach.[2] They aimed to formulate a set of well-motivated axioms and then assess whether there are models of the axioms corresponding to the CQFTs studied by physicists. There is not yet a clear verdict. The question of whether there is a model of the axioms for an interacting QFT in four dimensions remains open. Models have been found for a variety of other cases — free field theories of various kinds, interacting theories in dimensions other than four — but there is still no AQFT model for successful CQFTs such as quantum electrodynamics.

In pursuing the Carnapian goal of finding the appropriate formal language in which to couch foundational and interpretative problems, many philosophers have sided with the mathematicians and focused on AQFT. The papers by Doreen Fraser and David Wallace debate whether this is an appropriate starting point for foundational studies. They agree in characterizing AQFT and CQFT as importantly distinct due to their different ways of handling field degrees of freedom at arbitrarily small distances. CQFT treats these as frozen out below a cut-off length scale, whereas AQFT (in its algebraic variety) maintains Poincaré covariance by assigning algebras of observables to arbitrarily small spacetime regions.[3] Wallace regards the two as distinct research programs embodying different responses to the problems posed by renormalization, whereas Fraser characterizes the contrast in terms of the distinctive theoretical principles the two approaches employ. There is rough agreement that these are two competing

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[1] Huggett (2003); Kuhlmann (2006) survey the philosophical literature; see also the edited volumes Brown & Harré (1990); Kuhlmann, Lyre, Wayne, & editors (2002); Cao (2044).

[2] See Wallace's paper, §3, for the full quotation from Streater & Wightman (1964). Note that AQFT sometimes refers to axiomatic QFT generally (our usage), and sometimes more specifically to *algebraic* QFT, the most well-developed version of the axiomatic approach.

[3] As both Fraser and Wallace note, this contrast will be clear for cases like quantum electrodynamics, but not for an asymptotically free theory.

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theories or programs that present philosophers of physics with an option when undertaking the interpretative project. But the agreement ends there, with Fraser advocating AQFT and Wallace CQFT as the proper focus for foundational work that "takes particle physics seriously".

Fraser appeals to the familiar language of the "no miracles" argument and underdetermination in making a case for AQFT. Empirical evidence is of limited value in making the choice between AQFT and CQFT, given that a wide range of different descriptions of the physics of short distance scales yields the same empirical consequences at lower energies. She introduces a new move in this debate, which we might call the "argument from conceived *near*-alternatives" (contrasted with the argument from unconceived alternatives). AQFT is only a *near*-alternative to CQFT because there are as yet no physically realistic models of AQFT. Should such a model be found it would be empirically equivalent to CQFT, in the sense of predicting the same *S*-matrix elements, but embody different theoretical principles. She then argues that the principles formulated in AQFT are more well-motivated than those in CQFT, in the sense of being firmly based on insights from relativity and non-relativistic quantum mechanics. One should be wary of drawing foundational conclusions based on CQFT while AQFT is waiting in the wings, given that the hoped-for AQFT model would then be clearly superior to existing CQFT models, and offer different foundational insights.

Wallace's position is that physicists have now achieved a satisfactory understanding of renormalization, removing the main impetus for the AQFT program. He briefly summarizes and defends a modern understanding of renormalization based on renormalization group techniques introduced by Kadanoff, Wilson, and others in the 1970s. On this view, QFT can be understood in roughly the same way as condensed matter theory: there are physical reasons to propose that the field degrees of freedom "freeze out" below some sufficiently small length scale, the "cutoff." Renormalization group techniques establish that the presence of this cutoff will only be manifested in rescaling of the parameters appearing in an effective Lagrangian describing lower energy physics. Wallace, in direct response to Fraser, argues that these ideas solve the problems facing earlier formulations of QFT and provide a satisfactory understanding of its "theoretical principles." In §6, he poses a challenge to AQFT by highlighting several signature successes of CQFT that can be directly traced to this way of understanding renormalization. Finally, from Wallace's viewpoint the AQFT program involves an unwarranted positive commitment regarding physics at arbitrarily small length scales, contrasted with CQFT's less hubristic agnosticism.

The central point of contention between Fraser and Wallace regards the appeal to renormalization group techniques. Fraser's positive argument in favor of taking AQFT as the starting point for foundational work is combined with a sustained critical assessment of the implications of renormalization group techniques. Against Wallace, she argues that although these methods help to elucidate the empirical content of a QFT they do not resolve the difficulties of CQFT. She further argues that the formal similarities between the application of renormalization group techniques in condensed matter theory and particle physics fail to underwrite Wallace's claim that there is a physical analogy. There are further questions regarding the formulation of the debate in terms of underdetermination. In what sense are the "theoretical principles" of QFT isolated from the empirical content of the theory, as a result of the separation of scales that allow for the application of renormalization group techniques? Why not instead take the theoretical principles as manifested in the successful empirical applications of QFT, and take on the project of isolating and clarifying the content of these principles?

This capsule summary of the exchange hopefully conveys the excitement and interest of the issues involved in this debate, and Fraser and Wallace each make their case forcefully. Perhaps the most striking contribution of this exchange is to focus attention on what kind of project philosophers of physics are undertaking in their reflections on QFT. Do philosophical projects demand a higher level of rigor than the work carried out by physicists, and if so why? What do philosophers gain, and what do they lose, by focusing on AQFT rather than CQFT? How would the task of interpreting CQFT differ from the task of interpreting other physical theories?

Ruetsche's paper focuses on an interpretative puzzle that arises in considering quantum mechanics for infinite-dimensional systems. In finite-dimensional quantum systems, a set of operators acting on a Hilbert space satisfying the canonical commutation relations that characterize the system is unique up to unitary equivalence. But infinite-dimensional systems, such as those studied in QFT and in the thermodynamic limit of quantum statistical mechanics, admit unitarily inequivalent representations. There is no dispute about necessity of an algebraic approach to investigate this aspect of QFT and the associated interpretative questions. Ruetsche has explored other aspects of the existence of unitarily inequivalent representations in earlier work, but here she focuses on the status of non-normal states.

The algebraic approach employs a more general concept of state than the familiar Hilbert-space based account of non-relativistic QM. States are introduced as (positive, normed, linear) functionals over the algebra of observables. Von Neumann algebras, a specific type of algebra used in the representations of global observables, come equipped with a topology that allows for a further distinction: states that are continuous with respect to this additional topology are called *normal*, and these correspond to states that are countably additive. But, as Ruetsche explains, *non-normal* states arise in various contexts in QFT and quantum statistical mechanics. And what is the interpreter of QFT to do with such states? Consider one of Ruetsche's cases in which there are reasons to treat them as physical states: the von Neumann algebras associated with open, bounded regions of spacetime in AQFT entirely lack pure, normal states — they are "atomless," in Ruetsche's terminology. Pure states are the preferred vehicles for representing quantum states due to their maximality, and this preference cannot be satisfied unless ones allows non-normal states to play a role. But, on the other hand, the non-normal states have a variety of features that seems to preclude their admission as physical. They are, roughly speaking, dynamically isolated in the sense that a non-normal state cannot unitarily evolve into a normal state. They also fail to instantiate lawlike relations, as in Ruetsche's simple example of a localized state drifting from one point to another in a manner that is incompatible with Schrödinger evolution.

Ruetsche's aim is not to deliver a universal verdict regarding the admissibility of non-normal states. Rather, she raises these questions about the interpretative status of non-normal states as part of an argument for a form of interpretative contextualism. She suggests that it is a mistake to answer the interpretative question in this abstract form without specifying the context in which the formalism is deployed. In some contexts the non-normal states may need to be pressed into use, despite their odd features, whereas in others the same oddities may undermine their utility.

The particle concept in QFT has been one focus of philosophical discussions. Conventional wisdom in physics has long held that the combination of quantum mechanics and special relativity yields a field theory, in which talk of localizable particles is at best a *façon de parler* for describing the interplay among fields. Philosophers have recently contributed no-go theorems supporting this conventional wisdom Malament, 1996; Halvorson and Clifton, 2002. A crucial part of these arguments has been clarifying how to represent "particles" in the formalism. Intuitively particles are localizable — located in some finite region — and countable. The no-go theorems show that a theory of localizable, countable particles satisfying other natural assumptions from relativity and quantum theory lead to absurd consequences.

But have we smuggled in stronger assumptions than we realized in the move from an intuitive particle concept to its mathematical characterization? Bain reconsiders the no-go theorems, using a comparison between relativistic and non-relativistic QFTs to bring just such assumptions into view. One way of introducing particles in QFT takes advantage of global structure of the spacetime: given a global time function, one can construct a Fock space equipped with total number operator. A unique, preferred global time function implies the uniqueness of this total number operator, underwriting the intuitive property of "countability." But the eigenstates of this total number operator (states with a definite number of particles) are not eigenstates of local operators. Localizability of particles further requires the existence of local number operators that count particles within a finite spacetime region. Bain shows that the no-go theorems do not hold for non-relativistic QFTs, thanks to the saving grace of an absolute temporal metric. The existence of this metric in Galilean QFT insures that: there is a unique total number operator, the differential operators appearing in the field equations are not anti-local, the vacuum is not separating, and interactions do not "polarize the vacuum." The "intuitive" properties assigned to particles in setting up the no-go theorems thus reflect the lingering appeal of classical spacetime. Any attempt to formulate a relativistic conception of "particle" should avoid these ways of implementing "countability" and "localizability."

Bain's paper suggests two further projects. First, how should a particle be characterized formally in order to avoid implicit commitment to an absolute time metric? Second, what does the empirical success of QFT actually require in terms of the particle concept — to what extent can the usual treatment be replaced with a different definition of "local particle states" that is sufficient to underwrite the empirical content of QFT?

Bain's paper contributes to a discussion of the status of *stable* particles in QFT. Gordon Fleming, in his contribution, introduces a host of interesting conceptual issues associated with *unstable* particles — or, in the terminology preferred by Fleming, to avoid unwanted baggage associated with the word "particle" — unstable quantons.

An unstable quanton is one that has some probability of decaying into some decay products, whose nature is determined by what sort of quanton it is. In the framework employed by Fleming, we start by supposing that the quanton is prepared in a state such that, at some time (to speak, for the moment, nonrelativistically), it is certainly in an undecayed state — i.e., there is zero probability that detectors for the decay products will fire at that time. The state evolution takes it into a state that, at later times, is a superposition of the undecayed state and a decayed state. In Minkowski spacetime, rather than describing the state as being an "undecayed state at some time," the states are described as "undecayed on some spacelike hyperplane." If the quanton is unstable, there can be at most one such hyperplane. In Fleming's terminology, a *single parent* (SP) state is a state for which there is some hyperplane, the *no-decay hyperplane*, on which the quanton certainly exists alone with no decay-product component.

As these states are unstable, they are not energy eigenstates. This means that an unstable quanton does not have definite mass, but, rather, has some mass distribution associated with it. Thus, the simple relation between momentum and velocity that obtains for particles or quantons of definite mass does not hold for unstable quantons, and velocity and momentum eigenstates are distinct. There has been some controversy in the literature about whether momentum eigenstates or velocity eigenstates form a more appropriate basis for the space of states.

Fleming sheds light on this controversy by examining the relations between momentum and velocity eigenstates. Because of spread in the mass spectrum, a Lorentz boost of an SP momentum eigenstate is not, in general, a momentum eigenstate. A Lorentz boost of an SP velocity eigenstate *is* an SP velocity eigenstate, but the boost not only changes the velocity, but also tilts the no-decay hyperplane. In fact, Fleming argues (§5), any SP velocity eigenstate has a no-decay hyperplane that is orthogonal to its 4-velocity (see also Fleming, 2009, §3). This means that any two velocity eigenstates with distinct velocities have distinct no-decay hyperplanes, and a non-trivial superposition of such states has no no-decay hyperplane at all; it is not an SP state. Fleming uses these considerations to clarify the significance of a claim by Shirikov that velocity eigenstates suffer lifetime contraction, rather than dilation, under boosts. Fleming also considers the momentum-dependence of lifetime of momentum eigenstates (which, it should be stressed, is not the same as dependence on reference frames, because, for unstable quantons, Lorentz boosts of momentum eigenstates are not momentum eigenstates), and demonstrates that this dependence exhibits a simulacrum of time dilation.

A distinct set of problems for the particle concept arises in considering curved spacetimes. As a kind of warm-up to defining QFT on a curved spacetime suitable for general relativity, one can construct an interesting QFT in Minkowski spacetime by restricting consideration to the "Rindler wedge." Studying this construction led Unruh to the striking discovery that an observer accelerating in flat space would see the Minkowski vacuum state as a thermal state with a temperature that depends on their acceleration. This result, now called the Unruh effect, stimulated a large literature in mathematical physics because it sits at the intersection of QFT, relativity, and thermal physics.

Earman's paper elucidates various ideas that have emerged in the study of the Unruh effect. But he characterizes the existing treatments of the effect as something like an incomplete jigsaw puzzle; even with a number of interlocking pieces in place, the gaps in the puzzle leave us without a complete picture of the effect. One approach to the Unruh effect starts by considering the vacuum state of Minkowski spacetime from within the QFT constructed by accelerated observers confined to the "Rindler wedge" (the Fulling representation). The accelerated observers will "see the Minkowski vacuum as a thermal state" with an acceleration-dependent temperature. Earman is most critical of this approach, which despite its heuristic value faces well-known obstacles — the Minkowski vacuum state cannot be forced into the Fulling representation, and it cannot be shown in this approach that the allegedly "thermal state" is a KMS state, the precise definition of an equilibrium thermal state. Earman further argues that the Fulling vacuum should be ruled physically inadmissible given that it cannot be extended to a non-singular state on the global algebra of observables. A second approach starts from the characterization of KMS states and the ideas of "modular theory." Earman provides a crash course in modular theory and its application to the Unruh effect, but he is unsatisfied with taking the Unruh effect to only consist of a set of theorems linking modular automorphisms, geometric actions, and KMS states. His main objection is that applying modular theory requires global assumptions, and this seems different in character than other idealizations employed in physics. Whether my steak is rare or well-done as a result of Unruh grilling depends on its *entire history*, on this approach, rather than any finite part of its trajectory. Thus it is unclear how to extend the sense of "thermal" employed in modular theory to the thermal properties of radiation as experienced by a particular observer. The final interlocking approach starts from an operational treatment of particle detectors. Here Earman argues, based on a review of some ways of modeling particle detectors in the literature, that the Unruh effect threatens to fracture into different effects corresponding to different detectors, unless a "privileged class" of detectors is singled out as the ones that accurately register the thermal properties of quantum fields.

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