Not Particles, Not Quite Fields: An Ontology for Quantum Field Theory*

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ABSTRACT

There are significant problems involved in determining the ontology of quantum field theory (QFT). An ontology involving particles seems to be ruled out due to the problem of defining localized position operators, issues involving interactions in QFT, and, perhaps, the appearance of unitarily inequivalent representations. While this might imply that fields are the most natural ontology for QFT, the wavefunctional interpretation of QFT has significant drawbacks. A modified field ontology is examined where determinables are assigned to open bounded regions of spacetime instead of spacetime points.

1. Introduction

Looking to current physical theories for insights into metaphysics and ontology has a long tradition in philosophy. Applying this principle today, it is natural to look at quantum field theory (QFT) for insights into the fundamental types entities in the physical world, or at least for constraints on possible ontologies. QFT is the successor to quantum mechanics and provides the mathematical framework for the standard model of particle physics. The predictions of QFT for electromagnetic interactions, also known as quantum electrodynamics, are extremely accurate when compared to experimental results. However, using QFT for insights into ontology is far from straightforward. The typical choice given for the ontology of QFT is either

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particles or fields.[1] Many people have argued that a particle ontology is incompatible with QFT, which implies that QFT is a theory about fields. However, new philosophical works by Halvorson (Halvorson and Mueger 2007) and Baker (2009) challenge a field interpretation of QFT called the wavefunctional interpretation. I will argue that a modified field ontology is possible that is consistent with the mathematical structure and physical assumptions of QFT. The modified field ontology to be developed is based on a mathematically rigorous version of "smeared" quantum fields, which has not been discussed very much in the philosophical literature on QFT. I then show how this ontology is carried over to the framework of algebraic quantum field theory (AQFT). AQFT generalizes this modified field ontology by assigning a collection of determinables to open bounded regions of Minkowski spacetime.

The plan for this paper is as follows. Section two of this paper examines two aspects of a particle: localizability and countability. It reviews various No Go results that undermine both localizability and countability in QFT. These results show that there is little hope for a particle ontology in QFT. Section three examines how the field concept changes in QFT. The notion of a field as assigning determinables to spacetime points cannot be correct mathematically in QFT, at least if the field is understood as an operator. However, the field can be "smeared" out so that the field, while no longer defined on spacetime points, is defined on spacetime *regions*. In section four, I discuss how this field ontology involving spacetime regions is generalized in AQFT. The appearance of "classical" observables in AQFT introduces a new aspect to field configurations in AQFT. Conclusions are given in section five.

2. THE PROBLEMS WITH PARTICLES

Many QFT books begin by constructing Fock space, which seems to suggest that QFT has a particle interpretation.[2] The Fock space can be created using the creation and annihilation operators, which satisfy the canonical

[1] Alternative ontologies for QFT have been proposed; see the articles in Kuhlmann et al. 2002.

[2] My discussion of QFT will necessarily be non-technical. For more details, the reader should consult the references citied in the paper and especially Halvorson 2007.

commutation relations (CCRs)[3], and a vacuum state.[4] When the creation operator acts on the vacuum state, a new state with one particle is produced.[5] If the creation operator is applied *n* times on the vacuum state, a state containing *n* particles is created. Roughly, the set of all such states created in this way can be used to construct the Fock space, which is a (infinite) direct sum of the Hilbert spaces for zero particles, one particle, two particles, etc. Using the creation and annihilation operators, a number operator can be constructed that counts the number of particles in a state. The Fock space construction might suggest that a particle interpretation is the most natural ontology for QFT. Particles *seem* to have existence independently of their properties, which makes a substance ontology a natural fit. In particular, particles exhibit a kind of primitive thisness, haecceity, or transcendental individuality.[6]

However, there are numerous diverse and devastating criticisms against *any* particle ontology in QFT. These attacks come from physicists such Weinberg (Feynman and Weinberg 1987, pp. 78-79), and Wald (1994, pp. 51-52) as well as from philosophers such as Malament (1996), Halvorson and Clifton (2002), and Fraser (2008). The connection between the "particle-states" used to build the Fock space and the particle concept are tenuous at best. There are two crucial features that characterize particles: (1) particles are discrete, localizable entities and (2) particles are countable or aggregated. (1) is undermined by results in relativistic quantum theory and QFT, while (2) is undermined in QFT.

[3] Requiring the creation and annihilation operators to satisfy the CCRs generates a Fock space for boson particles. We can also require that the creation and annihilation operators satisfy the canonical anti-commutation relations, which would generate a Fock space for fermion particles.

[4] The term vacuum state is a bit misleading. Though it is usually defined as the state with no particles in it, the state has energy fluctuations, which seems to suggest that the picture of the vacuum as a state where nothing is happening is incorrect. This already suggests that labeling the states of the Fock space as particle states is misleading (Kuhlmann 2006).

[5] Teller (1995) referred to such a state as having one *quanta* in it – not a particle. The distinction between particles and quanta is discussed below.

[6] Primitive thisness faces serious problems dealing with indistinguishable particles (bosons) in quantum mechanics, and particle indistinguishability is still an issue in QFT (Teller 1995). This is not to say that the notion of a particle in classical physics is without conceptual difficulties. For example, modeling electrically charged particles as point-particles would result in the particle having infinite energy.

2.1. ARGUMENTS AGAINST LOCALIZABILITY

Malament (1996) proved a theorem that excludes the possibility of localized particles in relativistic quantum theory. The idea behind the theorem is that a strictly localized particle cannot be detected in two disjoint spatial regions at the same time. Under certain mild assumptions, there is no position operator, which transforms covariantly, of a strictly localized particle. The theorem shows that there is a conflict between relativity and the localization condition for a fixed number of particles. One might think that a weaker notion of locality might save particles, but Halvorson and Clifton (2002) showed that there are no unsharp localized position operators either. All of these results hold in relativistic quantum mechanics, so a defender of particles might hope for more success in QFT. However, Halvorson and Clifton (2002) proved another result which shows that there are no localizable particles in *any* relativistic theory including QFT.[7] A result in axiomatic QFT known as the Reeh-Schlieder theorem shows that a strictly localized entity, such as a particle, in a bounded spacetime region is incompatible with the axioms.

2.2. ARGUMENTS AGAINST COUNTABILITY

Teller (1995, p. 29) rejected a substance ontology (primitive thisness) for quantum particles and argued that quantum particles are better characterized as *quanta*, which can be counted or aggregated. The idea behind countability is that there are states in which there is some definite number of quanta, so a state that has four quanta and a state that has five quanta can be added together and result in a state that has nine quanta. This property is undermined by the Unruh effect, interacting quantum field models, and the Reeh-Schlieder theorem.

2.2.1. THE UNRUH EFFECT

The Unruh effect involves a uniformly accelerating observer who will detect a thermal bath of particles in the Minkowski vacuum state, while an inertial observer will not detect any particles in the same region of spacetime. Wald

[7] Approximately local particle detectors can be constructed in algebraic quantum field theory; see Halvorson and Clifton 2002, pp. 21-22 and Halvorson and Mueger 2007, pp. 762-763 for details and how to make some sense of the notion of a "particle".

(1994, p. 116) has argued that this shows that the particle concept is observer-dependent. Others have argued that since the particle concept has to be observer-independent, there are no particles (Davies 1984). Using the Unruh effect, an argument against particles being fundamental entities has been given a concise formulation by Arageorgis, Earman and Ruetsche:

(A1) If the particle notion were fundamental to QFT, there would be a matter of fact about the particle content of quantum field theoretic states.

(A2) The accelerating and inertial observers differ in their attributions of particle content to quantum field theoretic states.

(A3) Nothing privileges one observer's attributions over the other's.

(C4) Therefore, there is no matter of fact about the particle content of quantum field theoretic states (from (A2) and (A3)).

(C5) Therefore, the particle notion is not fundamental (from (A1) and (C4)). (Arageorgis et al. 2002, p.166)[8]

It has been proven (Clifton and Halvorson 2001) that the accelerated observer will never count only a finite number of particles in the inertial observer's vacuum state and that the inertial observer will never count only a finite number of particles in the accelerated observer's vacuum state. Clifton and Halvorson (2001) argued that the Unruh effect shows that the accelerated observer and the inertial observer have different complementary particle concepts. The different counting results for the two observers are due to the fact that the accelerating observer's Fock space and the inertial observer's Fock space are *unitarily inequivalent* to each other.[9] The topic of unitarily inequivalent representations is one of the most important topics in the philosophy of QFT, and we will discuss it in more detail later. If Clifton and Halvorson's idea is to add a new complementary particle concept for each unitarily inequivalent representation, then the existence of a continuum of unitarily inequivalent representations would suggest that there would be a continuum of different complementary particle concepts. Unless other restrictions on the particle concept are imposed, the proliferation of different

[8] Arageorgis, Earman, and Ruetsche (2002) do not think that the Unruh effect undermines the particle notion in QFT and they attack this argument by challenging (A3). However, they do agree that particles do not have fundamental status in QFT.

[9] See Clifton and Halvorson 2001 for details.

complementary particle concepts might be another argument in favor of abandoning the effort to shoehorn in a particle concept into QFT.

2.2.2. INTERACTING QUANTUM FIELD THEORIES

The concept of quanta as being countable entities has also come under attack in the case of interacting quantum field theories (Fraser 2008). The Fock space contains a number operator, which can count the number of quanta in a state, but the Fock space can only be used for *free* (noninteracting) quantum fields. However, mathematically rigorous interacting quantum field models, such as the ϕ^4 and Yukawa interactions in two and three dimensions, cannot be interpreted as having states containing aggregable particles or superpositions of particles. The Fock space for the free field is unitarily inequivalent to the interacting field – a result sometimes referred to as Haag's theorem.[10] While the Fock space constructed for the free field has a total number operator, the Fock space constructed for the interacting quantum field theories do not have a total number operator that can count particles.

2.2.3. THE REEH-SCHLIEDER THEOREM

One of the consequences of the Reeh-Schlieder theorem is that local measurements are not able to distinguish the vacuum state from an *n* particle state. If particles or quanta are countable entities, then this result shows that there is no way to locally distinguish between two states that have different numbers of particles. The notions of localizability and countability associated with particles are also jointly ruined by the Reeh-Schlieder theorem because one of its corollaries is that no local number operators exist (Halvorson and Mueger 2007, p. 762). One last problem for the notion of particles in QFT, which is defined on a flat (non-curved) spacetime called Minkowski spacetime, is that there does not appear to be any way to have a particle interpretation of states in curved spacetimes (Wald 1994), which are crucial for any future theory of quantum gravity.

[10] See Fraser 2008 for details.

3. THE PROBLEMS WITH FIELDS

Both Malament (1996, p. 1) and Halvorson and Clifton (2002, p. 23) conclude that talk about "particles" must be understood in terms of the properties and interactions of quantum fields. How are fields and particles different? Here are two key differences that are often cited.

Particle: localized / discrete, finite number of degrees of freedom
Field: non-localized / continuous, infinite number of degrees of freedom

While a particle is supposed to be a discrete, localized entity, a field is defined on every point in spacetime; a field is a continuous entity. A field is not contained in any particular region which is a proper subset of all of spacetime. A point-particle can be described by its position and momentum in three dimensions, which implies that a single point-particle has six degrees of freedom. Since the field is defined on each spacetime point, the field has properties at each point, such as the value of the field at that spacetime point. Each property of the field at each spacetime point is a degree of freedom. Since spacetime has a continuum of points, the field has an infinite number of degrees of freedom. These properties or field values can be assigned a scalar, vector, or tensor at each spacetime point. Fields often must also satisfy a field equation(s) such as the Klein-Gordon equation or Maxwell's equations. What is most important for the purposes of this paper is that a field has been viewed as essentially an assignment of properties to spacetime points.

The argument for a field ontology often has the following implicit form:

(A1) QFT can only be interpreted in terms of particles or fields.
(A2) The No Go theorems in the previous section show a particle interpretation is not possible for QFT.
(C3) Therefore, QFT only admits an interpretation in terms of fields.[11]

There are other alternative ontologies, which undermines (A1).[12] A more compelling argument for why fields are the fundamental entities of QFT comes from what is called "field quantization". Heuristically, this involves taking a

[11] See Huggett 2000 and Teller 1995.

[12] Some of the proposed alternative ontologies for QFT include events, processes, or tropes; see the articles collected in Kuhlmann et al. 2002. For the purposes of this paper, I will focus on what type of field ontology is consistent with the mathematical structures and physical assumptions of QFT.

classical field theory, such as electromagnetism, and replacing the classical field with a quantum field. The procedure for generating a quantum field from a classical field is similar to the quantization of a classical theory: take the classical observables of position and momentum, promote them to operators, and impose the CCRs. Similarly, we take the classical field $\phi(x)$ and its conjugate momentum $\pi(x)$, promote them to operators $\hat{\phi}(x)$ and $\hat{\pi}(x)$, and impose the (equal-time) CCRs.[13]

However, there are important differences between a classical field and a quantum field. Teller (1995, pp. 94-97) has argued that quantum fields, unlike classical fields, do not assign definite values of physical properties to each spacetime point. Rather, a quantum field assigns a *determinable* to each spacetime point (Teller 1995, p. 95). For example, 'having mass' is a *determinable* property which has no specific value. The property of 'having a mass of five kilograms' is a *determinant* property – that is, it is a specific value of a determinable property. A *field configuration* for a determinable is a specific assignment to each spacetime point of the value of a determinable. A field configuration for the classical electromagnetic field assigns definite values for the electric and magnetic field to spatial points as well as a direction of the field at each spatial point.

While a field configuration can be specified for classical fields, Teller (1995, p. 101) argues that quantum fields do not by themselves constitute a field configuration. The reason that quantum fields only assign a determinable(s) to each spacetime point is that they are operators. More precisely, they are operator-valued fields.[14] Operators are mathematical entities that do not represent definite values of a physical quantity. The eigenvalue spectrum of an operator is a list of the possible specific values for that property. $\hat{\phi}(x)$ is an observable. It has possible specific values, but no specific value is assigned to each spacetime point by the field operator $\hat{\phi}(x)$ alone. $\hat{\phi}(x)$ does not by itself specify a field configuration. According to Teller (1995, p. 101), a field configuration requires $\hat{\phi}(x)$ and states. Given a state $|\psi\rangle$, an expectation value $\langle\psi \mid \hat{\phi}(x) \mid \psi\rangle$ for all possible products of $\hat{\phi}(x)$,

[13] The CCRs are used for free bose fields. The canonical anti-commutation relations are imposed for free fermion fields. For the purposes of this paper, I will focus on free neutral scalar Bose fields.

[14] We will learn later that quantum fields cannot be thought of as operator-valued fields due to various No Go results.

where $\langle\psi|\hat{\phi}(x)|\psi\rangle$ is evaluated at arbitrarily chosen spacetime points, constitutes a field configuration (Teller 2002, p. 145). It is these expectation values that assign specific values of the field determinable to spacetime points.[15] The actual state is a contingent fact. Thus, $\hat{\phi}(x)$, by itself, does not encompass all of the ontology of QFT.

There are problems with Teller's notion of a field configuration. Expectation values are an *average* expected value. No specific actual value of the field is being assigned to the spacetime point x by $\langle\psi|\hat{\phi}(x)|\psi\rangle$, which Teller (1995, p. 101) acknowledges. If field configurations require the assignment of *actual* values to each spacetime point, then $|\psi\rangle$ would have to be an eigenvector of $\hat{\phi}(x)$ *for every spacetime* point! The problem is that while the eigenvalue spectrum of the field operator is invariant, field operators at different spacetime points such as $\hat{\phi}(x)$ and $\hat{\phi}(x')$ (where $x \neq x'$) will have different eigenvectors (Wayne 2002, p. 129), so one state by itself will not be an eigenvector for the field operators at every spacetime point. We could salvage a notion of a field configuration by defining an *average field configuration* as the assignment to each spacetime point the expectation value $\langle\psi|\hat{\phi}(x)|\psi\rangle$ given a state $|\psi\rangle$. When are two average field configurations different? Two average field configurations are different when their expectation values differ in at least one spacetime point. This will be important later when we discuss unitarily inequivalent representations. It is the states and $\hat{\phi}(x)$ that are the basis of the *wavefunctional interpretation* of QFT.[16]

In the wavefunctional interpretation, the free quantum field operators, which satisfy the CCRs, have states defined on a Hilbert space of wavefunctionals $\Psi(\phi)$. The states can be interpreted as superpositions of classical field configurations in the way that states in Fock space are interpreted as superpositions of classical configurations of particles. Each state is a probabilistic propensity of a certain classical field in the event of a measurement. Expectation values of $\hat{\phi}(x)$for a particular state give the mean expected value of the classical field strength at *x*. However, there are significant

[15] The reason Teller includes all possible products of the field operators is due to a criticism of Wayne's (2002) that the content of the field operators can be reconstructed from *n*-point vacuum expectation values, which involve *n* field operators defined at *n* different spacetime points. That reconstruction theorem is proved in Wightman and Streater 2000, pp. 117-126.

[16] My explanation of the wavefunctional interpretation below comes largely from Baker 2009 and Halvorson and Mueger 2007.

obstacles for the wavefunctional interpretation. For example, interpreting the states in the Hilbert space of wavefunctionals as probability distributions over classical field configurations is ruled out because determinate field configurations are identified with the zero vector in the Hilbert space (Halvorson and Mueger 2007, p. 779). Thus, there is no state of the quantum field which is in a specific configuration. Another criticism of the wavefunctional interpretation given by Baker (2009) is based on the unitary equivalence of the wavefunctional Hilbert space and the Fock space. Based on that unitary equivalence, Baker argues that the Malament-Clifton-Halvorson arguments used against particles being localized at or around points and Fraser's argument that rigorous forms of interactions in QFT cannot be given a quanta interpretation can be used as arguments against the wavefunctional interpretation. The appearance of unitarily inequivalent representations also raises substantial problems for the wavefunctional interpretation, according to Baker. However, a modified field ontology is possible without assuming the wavefunctional interpretation.

3.1. No Go results for $\hat{\phi}(x)$

One problem for Teller's account of quantum fields is that no non-trivial field operator $\hat{\phi}(x)$ exists. There are a number of No Go theorems that show that no non-trivial field operators can be defined on spacetime points.[17] To make the field operators mathematically well-defined they must be "smeared" across spacetime *regions*. The "smearing" works by convoluting the field operator $\hat{\phi}(x)$ at a spacetime point x with a test function f defined on a finite spacetime region O that includes the point x. The test function f is a smooth function with compact support, which means that the function is zero outside the region O and can be non-zero inside O. The quantum field is no longer an operator-valued field, but an operator-valued (tempered) distribution:

[17] See Halvorson and Mueger 2007 for details about the various No Go theorems. It is possible to define a quantum field at spacetime points if the field is a sesquilinear form – not an operator (Halvorson and Mueger 2007, pp. 774-777). Roughly, every operator defines a sesquilinear form, but it is not clear if a sesquilinear form admits a representation as an operator. There is a further question of whether a sesquilinear form can represent a physical quantity or whether a sesquillinear form can be thought of as a field defined at a spacetime point. A sesquilinear form can be defined in the Wightman axiomatic formulation of QFT, but it is not clear whether these results hold in the algebraic approach to QFT.

$\hat{\phi}(f) = \int dx\, f(x)\hat{\phi}(x)$. $\hat{\phi}(f)$ is a linear map from test functions $f(x)$ to operators and $\hat{\phi}(f)$ represents the average field value in the region O.[18] Thus, the quantum field is no longer an operator defined on spacetime points, but an operator-valued defined on a finite spacetime region.

Using smeared fields requires other mathematical changes. The CCRs for the smeared fields will have a slightly different form involving the inner product of test functions. The expectation values for $\hat{\phi}(f)$ can also be arbitrarily large for certain states (Streater and Wightman 2000, p. 97), which suggests that $\hat{\phi}(f)$ behaves like an unbounded operator. An unbounded operator is not defined on every state in the Hilbert space. If the expectation value of $\hat{\phi}(f)$, in a certain state, is infinite, then the field operator cannot be defined on that state. Infinite field strengths are supposed to be unphysical because they would require an infinite amount of energy. Thus, even if the field operator is smeared out around the spacetime point *x* by a test function and a state is chosen to represent some physically contingent fact, the expectation value may not yield an average value for the field because the expectation value is infinite. In cases like that, no average field configuration is possible.

One way to deal with domain questions is to use the Weyl form of the CCRs for the field operators. This makes the field operators bounded, which removes the problem of specifying the domain on which the operators are defined. Bounded operators are defined on all states in the Hilbert space. The Weyl operators $W(f)$ are constructed by taking an exponential of the field operator $\hat{\phi}(f)$: i.e., $W(f) = e^{i\hat{\phi}(f)}$. These operators generate a C^*- algebra called the Weyl algebra, which allows us to use the powerful mathematical framework of algebraic quantum field theory (AQFT). I will discuss AQFT more in section four.

3.2. Unitarily inequivalent representations

The CCRs are formal constraints. Many operators will satisfy them. For example, we can create a new field operator $\hat{\phi}(f)$ by essentially adding a

[18] We are smearing the fields in both *space and time*. For a free Bose field, it is only necessary to smear the field over space alone by test functions. Some authors have suggested that the fields must be smeared in space and time in the case of interacting fields, but there are no theorems that prove that interacting fields must be smeared in space and time (Halvorson and Mueger 2007, pp. 779-780).

complex constant *c* multiplying the identity operator *I*: $\hat{\phi}'(f) = \hat{\phi}(f) + cI$.[19] This new field $\hat{\phi}'(f)$ will also satisfy the CCRs. Are these two fields $\hat{\phi}(f)$ and $\hat{\phi}'(f)$ different determinables? In one sense, they are not. They both generate isomorphic Weyl algebras – that is, they both have the same abstract algebra, but their form as operators acting on a Hilbert space are different. Does that make any difference with respect to their expectation values? One way answer this question precisely is to determine whether the representation π_{ϕ} of $\hat{\phi}(f)$ and the representation $\pi_{\phi'}$ of $\widehat{\phi}'(f)$ are unitarily equivalent. When two representations are unitarily equivalent, there is a bijective mapping between the set of observables belonging to both representations and a bijective mapping between the set of states belonging to both representations. Another consequence of unitary equivalence is that two unitarily equivalent representations are empirically equivalent, i.e., they have the same expectation values. However, if they are unitarily *inequivalent* representations, they do not have the exact same expectation values.[20] Thus, they are not the same average field configuration.

Each representation has a set of states defined on its associated Hilbert space and each of those states can be used to define an average field configuration. Thus, a representation is a collection of average field configurations. If the representations π_{ϕ} and $\pi_{\phi'}$ are unitarily inequivalent, then the wavefunctional Hilbert spaces associated with them are also unitarily inequivalent. Assuming that both representations are irreducible (i.e., that there are no non-trivial subrepresentations), the wavefunctional spaces have no states in common and have disjoint collections of possible average field configurations.[21] Once we start using the Weyl algebra and discussing representations, we have the tools of AQFT at our disposal. We shall see that the field ontology developed thus far is further modified in AQFT.

[19] The complex constant involves an integration of the test function *f* (Baker 2009, p. 597).

[20] The expectation values for two unitarily inequivalent representations of C*-algebra can be *weakly equivalent* to each other. Roughly, weak equivalence means that the expectation values in one representation can be approximated in a unitarily inequivalent representation. For a full discussion of the issue and the limitations of weak equivalence, see Lupher 2008.

[21] The folium of an abstract state ω is the set of all abstract states which can be expressed as density operators defined on ω's representation. Two irreducible unitarily inequivalent representations have folia that are disjoint from each other, i.e., they have no abstract states in common.

4. AN ONTOLOGY FOR QFT

Let's see where we are. We started with the idea that a field is an assignment of properties, which can be represented by scalars, vectors, or tensors, to spacetime points. Teller argued that the quantum field operators assign determinables (not properties) to spacetime points. However, the No Go theorems discussed in the last section show that the quantum field cannot be an operator defined on spacetime points; the quantum field operator must be smeared with a test function over a finite spacetime region. The appropriate modification of the field ontology in QFT involving "smeared" quantum fields is that a quantum field is the assignment of a determinable to a finite spacetime region. This modified field ontology is consistent with Wightman's axiomatic approach to QFT and the No Go results for quantum fields. However, the unbounded smeared field operators are mathematically difficult to use. Bounded versions of the smeared field operators can be used to construct the Weyl algebra and that allows us to use the powerful mathematical tools of AQFT to further explore the field ontology developed so far.

Algebraic quantum field theory (AQFT) also assigns determinables to spacetime regions by mapping an algebra of observables A to an open bounded region of spacetime O. The mapping $O \to \mathrm{A}(O)$ of these open bounded regions O to an algebra of observables $\mathrm{A}(O)$ generates a net of algebras. Setting up a net of algebras satisfies the basic field ontology discussed: it is an assignment of determinables to open bounded spacetime regions. Different nets $O' \to \mathrm{A}(O')$ can be constructed by using different open bounded regions. They are different ways of carving up spacetime into finite regions. The resemblance between AQFT and smeared fields is more than superficial. Given a field smeared by test functions having support in the open bounded region O, a von Neumann algebra on O can be generated.[22] If we work with the Weyl form of the smeared fields, then a net of C^*-algebras over spacetime can be defined (Halvorson and Mueger 2007, p. 760).

To what extent does the notion of a field configuration change in the algebraic approach? If we are interested in the assignment of definite values of observables, then a partial field configuration is possible in AQFT. An algebra of observables can contain a commutative subalgebra, which is a collection of

[22] For some of the connections between smeared fields and AQFT and further references, see Haag 1996, pp. 105-106.

observables that commute with every element of the entire algebra. These observables in the commutative subalgebra could be considered the "classical" observables in the algebra. It can be proven that every abstract state of the algebra will have a definite value for each of these "classical" observables. Thus, once the algebra of observables $\mathbf{A}$ is mapped to a particular open bounded region of a spacetime O, a partial field configuration can be given for these "classical" observables. Call this a "*classical*" *field configuration*, which is a kind of partial field configuration in that definite values for *some* of the observables can be assigned to an open bounded spacetime region. States are not necessary to have a "classical" field configuration.

There are many different types of classical observables such as electric charge, chemical potential, mean magnetization, macroscopic order parameter, chirality, the algebra of observables at infinity, which can be examined in AQFT. Temperature plays a role in explaining the Unruh effect. When the inertial observer's vacuum state is restricted to the right or left Rindler wedge, the state is a thermal state and has a temperature (Wald 1994, p. 115). For a particular representation of the abstract algebra, there may be no non-trivial "classical" observables.[23] If such classical observables do exist and they are relevant for describing the system under investigation, they should certainly be part of the field ontology just as temperature is part of the ontology involved in the Unruh effect. Another advantage of having classical observables as part of our field ontology is that they provide a way of distinguishing between different unitarily inequivalent representations. Roughly, two different unitarily inequivalent representations (more precisely, two disjoint factor representations) will maximally differ in their expectation value for at least one "classical" observable (Lupher 2008).[24] However, "classical" observables are only a part of the field ontology discussed so far. Now we have

[23] If the von Neumann algebra is a type III_1 factor, which is the predominant algebra for open bounded spacetime regions, then the center of the algebra consists of scalar multiples of the identity (Halvorson and Mueger 2007, p. 766). The construction of classical observables may involve using the central projections of different unitarily inequivalent representations instead of using just one representation.

[24] The "classical" observables belong to a larger abstract algebra called the bidual, which is a W*-algebra. Briefly, the observables belonging to the abstract C*-algebra are a subset of the observables belonging to the bidual. A nontrivial "classical" observable in the bidual may take the form of the zero operator in the Hilbert space of a particular representation while in another representation the classical observable may be a non-zero operator in that representation's associated Hilbert space.

to look at the quantum observables which belong to the non-commuting part of the algebra of observables.

Once the algebra of observables has been specified for a particular open bounded region of spacetime, a representation and a Hilbert space can be constructed through the GNS theorem. This provides a realization of the operators of the algebra as bounded operators acting on a Hilbert space and a set of states in the Hilbert space. The state of the system will be an eigenvector for some of the (non-commuting) observables in the Hilbert space, which gives us a collection of (quantum) beables.[25] That provides a more complete field configuration than the "classical" field configuration described above. A different state in the Hilbert space will have a different set of quantum beables, but the same classical beables. Every state in the Hilbert space will have the same value for a particular classical beable. For example, a representation of an equilibrium state at temperature T will have a Hilbert space in which each state has a temperature T. Classical beables and the quantum beables for a particular eigenstate give definite values. Thus, a *beable field configuration* assigns specific values of classical and quantum beables to an open bounded region of Minkowski spacetime. There are still a number of quantum observables for which the Hilbert space state will not give definite values. For those quantum observables and a particular state in the Hilbert space, we can only compute the average expectation value. We would then have definite values or average expectation values for all of the observables, which would provide the most complete notion of a quantum field configuration assuming the net of algebras has already been chosen.

There are a number of worries about underdetermination that can be raised about this field ontology. (1) Is there more than one type of abstract algebra? (2) Is there a preferred net of algebras? These are important philosophical questions to which I will make a few brief comments. With respect to (1), as I discussed in section three, all of the different concrete representations of the Weyl relations give rise to the same abstract algebra: the Weyl algebra.[26] In

[25] The term "beable" was originally introduced by Bell (1987). A beable is an observable that has a determinate value. Though Bell used the term in the context of quantum observables, classical observables also qualify as beables since they have determinate values.

[26] AQFT typically assumes that the abstract algebra contains all bounded operators. The Weyl algebra contains bounded versions of the field operators. One might worry that AQFT is leaving out important unbounded operators such as position and momentum. Self-adjoint (possibly unbounded) operators can be affiliated with a von Neumann algebra by considering the operator's family of spectral

that case, the abstract algebra is not underdetermined.[27] With respect to (2), while there is freedom to choose different nets, there are constraints on the net. For example, the net must satisfy the axioms of isotony and microcausality. The choice of a net describes a particular way of carving up spacetime according to regions and assigning determinables. Haag (1996, p. 105) claims that fields are ontologically dispensable since a field corresponds to a particular coordinatization of the net of algebras, i.e., a particular mapping $O \rightarrow \mathrm{A}\ (O)$. Different nets $O' \rightarrow \mathrm{A}\ (O')$ are possible, but there may be no physical differences between $O \rightarrow \mathrm{A}\ (O)$ and $O' \rightarrow \mathrm{A}\ (O')$. Support for this point of view comes from the concept of Borchers classes. Different nets may belong to the same Borchers class and thus have the same S-matrix. If that is correct, then choosing a particular net would lack any physical significance. It would be similar to the lack of physical significance in the choice of Cartesian coordinates to solve a particular problem instead of using polar coordinates. However, that view may be incorrect because there may only be one possible net in certain circumstances. The Doplicher-Roberts reconstruction theorem shows that there is a unique field net and gauge group that are compatible with the algebra of observables and its vacuum state (Halvorson and Mueger 2007, p. 849).[28] One of the remarkable achievements of AQFT is that the net of algebras is sufficient to uniquely reconstruct the fields and the gauge group including items such as isospin, baryon number, and other observables.[29] Thus, there is no underdetermination of the net of algebras in terms of the reconstruction of what is called the field algebra. The field algebra, which includes the gauge group, is generated by local algebras whose elements represent local fields that have excitations within a bounded spacetime region. A field algebra and a gauge group acting on a Hilbert space give a preferred set of representations, i.e., those that can be created from the vacuum state by the action of local fields. [30]

projections (Clifton and Halvorson 2001, p. 424). There still remains the question of whether to work with abstract C*-algebras or W*-algebras. For reasons why an abstract W*-algebra should be preferred, see Lupher 2008.

[27] Unitarily inequivalent representations show that there is not a unique representation of the abstract algebra.

[28] For a discussion of when two field systems are theoretically equivalent, weakly observationally equivalent, or observationally equivalent, see Halvorson and Mueger 2007, section 11.3.

[29] See section 10 of Halvorson and Mueger 2007 for details.

[30] The Doplicher-Roberts reconstruction theorem and the Doplicher-Haag-Roberts treatment of superselection sectors are discussed in more detail by Halvorson (Halvorson and Mueger 2007).

5. Conclusions

While there are significant challenges in finding a suitable ontology for QFT, a modified field ontology is consistent with mathematically rigorous versions of QFT such as Wightman's axiomatic QFT, which uses "smeared" quantum fields, and AQFT. The field ontology, which assigned properties to spacetime points, has been modified in QFT. The new modified field ontology assigns determinables to open bounded regions of spacetime rather than spacetime points. It shows how Teller's account of a field is modified by the No Go results involving quantum fields that are defined on spacetime points and how classical and quantum observables impose changes on our understanding of a field configuration. There remain many open questions. The ontology discussed so far did not discuss the role of dynamics, superselection sectors, nor interactions. The answers to these questions will further illuminate the nature of the field ontology in QFT.

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