Particles in Quantum Field Theory

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Abstract: The consensus view among philosophers of physics is that relativistic quantum field theory (QFT) does not describe particles. That is, according to QFT, particles are not fundamental entities. How is this negative conclusion compatible with the positive role that the particle notion plays in particle physics? The first part of this chapter lays out multiple lines of negative argument that all conclude that QFT cannot be given a particle interpretation. These arguments probe the properties of the 'particles' in standard formulations of QFT and the limited applicability of 'particle' representations. The second part of the chapter surveys proposals for non-fundamental roles that the particle concept plays in particle physics. The conclusion suggests directions for future philosophical research.

The consensus view among philosophers of physics is that relativistic quantum field theory (QFT)[1] does not describe particles. That is, according to QFT, particles are not fundamental entities. This assessment is apparently at odds with the fact that QFT is the theoretical framework for particle physics. The Standard Model presents a taxonomy of particle species (e.g., electron, photon, quarks, neutrinos). At the Large Hadron Collider (LHC), protons with high energies are smashed together. The recent detection of the Higgs boson at the LHC was heralded as a major discovery because the existence of the Higgs boson was finally experimentally confirmed. Clearly, particles play a central role in both theory and experiment. How does the negative conclusion that QFT does not sustain a particle interpretation square with the positive role that the particle notion plays in particle physics?

The first part of this article lays out multiple lines of negative argument that all conclude that QFT cannot be given a particle interpretation. These arguments probe the properties of the 'particles' in standard formulations of QFT and the limited applicability of 'particle' representations.[2] The second part of the article surveys proposals for non-fundamental roles that the particle concept plays in particle physics. The conclusion suggests directions for future philosophical research. The

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[1] In this entry, QFT is taken to be special relativistic quantum theory. Non-relativistic condensed matter physics is considered separately below.

[2] Approaches that posit localized particles and then modify QFT to accommodate this posit (e.g., variants of Bohmian relativistic quantum theory) fall outside the scope of this review.

pressing question of what sorts of fundamental entities QFT does describe will be set aside. This is an outstanding question that is a topic of current research. The natural candidate is fields. However, the fields which feature in the QFT formalism are mathematical expressions; work needs to be done to determine the ontological properties of the entities that are represented by the mathematical field formalism. Several suggestions about how to carry out this project have been made. This is a challenging task, a point that has been underscored by arguments that the most straightforward field interpretation of QFT fails for reasons that are closely related to the reasons for which the quanta interpretation fails (Baker 2009).

1 The quanta interpretation of Fock space

QFT is formulated as a field theory: the mathematical formalism contains fields (i.e., mathematical expressions that associate operators with regions of spacetime). The question of whether QFT describes particles amounts to the question of whether the field formalism can be given an interpretation in terms of particles. For massive free bosonic systems in Minkowski spacetime and inertial observers, there is a natural way of giving the field formalism a particle interpretation. A system in this category can be represented using a Fock space representation of the equal-time canonical commutation relations (ETCCR's) that, for a fixed value of mass m, is unique (up to unitary equivalence). This representation is constructed by effecting a positive-negative Fourier decomposition of a classical free field and then promoting the coefficients to Heisenberg picture operators.[3] A Fock representation for a free bosonic real scalar field with $m > 0$ on Minkowski spacetime possesses the following formal properties:

1. *Field operators* There exist well-defined annihilation and creation operators $a(\mathbf{k}, t)$, $a^\dagger(\mathbf{k}, t)$ where $\mathbf{k}^2 = k_0^2 - m^2$. $a(\mathbf{k}, t)$, $a^\dagger(\mathbf{k}, t)$ obey the ETCCR's

   $$[a(\mathbf{k}, t), a(\mathbf{k}', t)] = 0,\ [a^\dagger(\mathbf{k}, t), a^\dagger(\mathbf{k}', t)] = 0,\ [a(\mathbf{k}, t), a^\dagger(\mathbf{k}', t)] = \delta^3(\mathbf{k} - \mathbf{k}') \quad (1)$$

   At any given time t the quantum field $\phi(\mathbf{x}, t)$ can be defined as follows (where $\omega_{\mathbf{k}}^2 = k_0^2 = \mathbf{k}^2 + m^2$)

   $$\phi(\mathbf{x}, t) = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\mathbf{k}}}}[a^\dagger(\mathbf{k}, t)e^{ik\cdot x} + a(\mathbf{k}, t)e^{-ik\cdot x}] \quad (2)$$

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[3] For a detailed discussion, see Fraser (2008). Fock space is also discussed in Wallace (this volume).

The conjugate momentum field $\pi(\mathbf{x}, t)$ is defined using $\pi(\mathbf{x}, t) = \frac{\partial \phi(\mathbf{x}, t)}{\partial t}$ and $\frac{\partial a(\mathbf{k}, t)}{\partial t} = \frac{\partial a^\dagger(\mathbf{k}, t)}{\partial t} = 0$:

$$\pi(\mathbf{x}, t) = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\mathbf{k}}}}[i\omega_{\mathbf{k}} a^\dagger(\mathbf{k}, t)e^{ik\cdot x} - i\omega_{\mathbf{k}} a(\mathbf{k}, t)e^{-ik\cdot x}] \tag{3}$$

Inverting and solving for $a(\mathbf{k}, t)$, $a^\dagger(\mathbf{k}, t)$ gives

$$a(\mathbf{k}, t) = \int \frac{d^3x}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\mathbf{k}}}} e^{ik\cdot x}[\omega_{\mathbf{k}}\phi(\mathbf{x}, t) + i\pi(\mathbf{x}, t)] \tag{4a}$$

$$a^\dagger(\mathbf{k}, t) = \int \frac{d^3x}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\mathbf{k}}}} e^{ik\cdot x}[\omega_{\mathbf{k}}\phi(\mathbf{x}, t) - i\pi(\mathbf{x}, t)] \tag{4b}$$

2. *No-particle state* There exists a unique (up to phase factor) 'no-particle state' $|0\rangle$ such that
$$a(\mathbf{k}, t)|0\rangle = 0 \quad \text{for all } \mathbf{k}$$

3. *Number operators* Number operators $N(\mathbf{k})$ can be defined for any t:
$$N(\mathbf{k}) = a^\dagger(\mathbf{k}, t)a(\mathbf{k}, t) \tag{5}$$
$$N(\mathbf{k})[a^\dagger(\mathbf{k}, t)^n|0\rangle] = n[a^\dagger(\mathbf{k}, t)^n|0\rangle]$$
where $n = \{0, 1, 2, \ldots\}$.[4]

   In addition, for any t, the total number operator $N = \int d^3k N(\mathbf{k}) = \int d^3k a^\dagger(\mathbf{k}, t)a(\mathbf{k}, t)$ is well-defined.[5]

4. *Fock space* The one-particle Hilbert space $\mathcal{H}$ has as a basis the set of vectors generated from $|0\rangle$ by single applications of $a^\dagger(\mathbf{k}, t)$ (for any $\mathbf{k}$ satisfying $\mathbf{k}^2 = k_0^2 - m^2$). The Fock space $\mathcal{F}$ for $\phi(\mathbf{x}, t)$ is obtained by taking the direct sum of the n-fold symmetric tensor product of $\mathcal{H}$: $\mathcal{F}(\mathcal{H}) = \oplus_{n=0}^{\infty}(\otimes^n\mathcal{H})$ (Wald 1994, 192). $|0\rangle$ is cyclic with respect to the $a^\dagger(\mathbf{k}, t)$'s.

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[4] When normalized, the n-particle state becomes $\frac{a^\dagger(\mathbf{k},t)^n|0\rangle}{\sqrt{n!}}$.

[5] That is, when the number operators are properly defined using a test function space $\mathcal{T}$ $N = \sum_{j=1}^{\infty} a^\dagger(f_j)a(f_j)$ converges in the sense of strong convergence on the domain of N where $\{f_j\}$ is an orthonormal basis of $\mathcal{T}$ and N exists only if N exists and is the same for every choice of orthonormal basis $\{f_j\}$ (Dell'Antonio et al. 1966, 225–226).

These formal properties naturally lend themselves to a particle interpretation. The total number operator N can be physically interpreted as an operator that counts the number of particles because eigenstates of N can be physically interpreted as possessing a determinate number of particles. $|0\rangle$ is interpreted as a state in which there are no particles because it is the unique ground state (i.e., state with the lowest energy) and the unique state that is invariant under the unitary operators that give a representation of the Poincaré group (and thus looks the same to all inertial observers) (Streater and Wightman 2000, 21). $a^\dagger(\mathbf{k},t)|0\rangle$ is a state containing a single particle of momentum $\mathbf{k}$ and mass m because it possesses the correct energy for a single non-interacting particle, $\sqrt{\mathbf{k}^2+m^2}$. Similarly, each of the eigenvectors $a^\dagger(\mathbf{k},t)^n|0\rangle$ is identifiable as an n-particle state because each possesses the correct relativistic energy. The particles can be aggregated: a system which possesses n particles can be combined with a system which possesses m particles to yield a system which possesses $n + m$ particles.

Quantum particles are particle-like in these respects: they can be counted, they can be aggregated, and they have the expected relativistic energies. However, there are also respects in which these quantum particles seem decidedly un-particlelike. For this reason, the term "quanta" (the singular form is "quantum") is typically used to refer to these quantum entities and the term "particle" is typically reserved for entities that satisfy our ordinary conception of particles (Teller 1995, 29). The most obvious difference is that some physical states are superpositions of eigenstates of particle number. A further respect in which quanta differ from particles is that quanta are not capable of bearing labels. Consider a system of two quanta. It does not make sense to name one of these quanta "Fred" and the other "Sally." Put another way, it is not possible to make reference to *this* quantum in a way that distinguishes it from *that* quantum Quanta cannot be considered individuals in this sense.[6] Nevertheless, we can still count them and aggregate them. On this basis, Teller (1995, 30) argues that quanta are sufficiently particlelike to count as a species of particles. However, subsequent arguments undermine this basis for giving QFT a particle interpretation.[7]

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[6] See Ladyman (this volume) for more on individuality and identity.

[7] Teller (1995, 85–91) recognizes that in the Fock space for a massive free system for a Klein-Gordon field the position eigenstates are not localizable in a finite region of space, but holds out hope that a "salvage operation" can be undertaken for exact localization. The subsequent work described in Sec. 2.1 clarified the situation.

2 Negative arguments: QFT does not describe particles[8]

2.1 Quanta cannot be localized in any finite region of space

A more serious respect in which quanta are not particle-like is that they cannot be localized in any finite region of space. Malament (1996) proves a theorem intended to formalize the "dogma" that "there cannot be a relativistic, quantum mechanical theory of (localizable) particles" (1). In other words, the unification of special relativity and quantum theory leads to a field theory. Malament establishes that, given a set of reasonable conditions on a relativistic quantum theory, the probability of finding a particle in any bounded region of space is zero. Halvorson and Clifton (2002) strengthen Malament's result by proving it under weaker assumptions. They also prove a theorem stating that, again given reasonable relativistic assumptions, number operators such as those in a Fock space representation cannot be defined on finite regions of space. Strictly speaking, then, quanta cannot be conceived of as occupying any finite region of space.

While some have taken these results to be sufficient grounds for concluding that quanta are not particlelike entities, others have argued that these results are not fatal to a particle interpretation (Fleming 2004). I will not pursue this issue here because it turns out that there are other sources of trouble for the quanta interpretation of QFT.

2.2 Accelerating observers disagree on the number of quanta

An important way in which QFT differs from non-relativistic quantum mechanics is that in QFT systems generically possess an infinite number of degrees of freedom. In non-relativistic quantum mechanics (with a finite number of degrees of freedom), the Stone-von Neumann theorem typically guarantees that all irreducible Hilbert space representations of the canonical communication relations that satisfy natural assumptions are unitarily equivalent to the standard Schrödinger representation (Ruetsche 2011, Chapter 2). (That is, there is a unitary map $U : \mathcal{H}^1 \rightarrow \mathcal{H}^2$ from the set of operators $\{O_i^1\}$ on the first Hilbert space to the set of operators $\{O_i^2\}$ on the second Hilbert space such that $U^{-1}O_i^2U = O_i^1$ for all i. This map preserves

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[8] Recall that "QFT does not describe particles" means that particles are not part of the ontology of fundamental entities picked out by QFT.

the expectation values in all states.[9]) In QFT, the Stone-von Neumann theorem does not hold because the assumption of a finite number of degrees of freedom is violated. As a result, in QFT there are continuously many representations available as mathematically possible representations. The availability of these representations is a valuable expressive resource. Of course, each of these mathematically possible representations may or may not have physical significance.

One situation in which unitarily inequivalent representations seem to be physically relevant is for accelerating observers, a phenomenon known as the Unruh effect.[10] Imagine two observers in flat spacetime, Jack and Jill, who are both observing the same free system.[11] Jack is moving inertially (i.e., has zero acceleration) and Jill is accelerating uniformly. Jack employs the Fock space representation described in Sec. 1, with the Minkowski vacuum and number operators. For Jill, it is most natural to represent the system using Rindler spacetime coordinates. She performs a positive-negative frequency decomposition with respect to her Rindler spacetime coordinates[12] and then obtains a Fock space representation by following the same procedure outlined in Sec. 1. Jill's "Rindler" Fock space representation is unitarily inequivalent to Jack's "Minkowski" Fock space representation. Jill's Rindler total number operator is not defined on Jack's Minkowski vacuum state; conventionally, applying Jill's Rindler total number operator to Jack's Minkowski vacuum state returns the value infinity. Jill's Rindler total number operator is not defined on any of Jack's Minkowski n-particle states either. Similarly, Jack's Minkowski total number operators are not defined on Jill's Rindler vacuum state or Rindler n-particle states.

What does this mean for the possibility of a particle interpretation of the system? Different conclusions have been defended. Clifton and Halvorson (2001) argue that Jack's and Jill's descriptions of the particle content of the system are *complementary* in the sense that "neither the Minkowski nor Rindler perspective yields the uniquely 'correct' story about the particle content of the field, and that both are necessary to provide a complete picture" (459). In experimental terms, the idea is that Jill's and Jack's particle detectors couple to different particle observables associated with the field. While Clifton and Halvorson's assessment that Jill's and Jack's particle notions are complementary could be used to defend a fundamental particle ontology

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[9] See Ruetsche (2013) for a more sophisticated discussion of the relationship between unitary equivalence and physical equivalence.

[10] The Unruh effect can also be characterized without reference to particles. See Earman (2011) for a thorough discussion.

[11] The exposition in this paragraph is derived from Chapter 9 of Ruetsche (2011), which can be consulted for further details.

[12] More precisely, she performs the positive-negative frequency decomposition on the right Rindler wedge, which is itself a spacetime (Ruetsche 2011, Sec. 9.6).

by salvaging objective quanta descriptions from the apparently conflicting subject-dependent descriptions, Clifton and Halvorson are unequivocal in their rejection of the fundamental particle interpretation: "quantum field theory is 'fundamentally' a theory of a field, not particles" (459). Arageorgis et al. (2003) argues that Jack's and Jill's particle concepts are *incommensurable* in the sense that "Jack's and Jill's particle assessments aren't different descriptions of the same set of facts (however complicated), but descriptions of disjoint sets of facts" (Ruetsche 2011, 219). On the surface, this appears to spell disaster for a fundamental particle ontology. However, this is not the end of the story. Arageorgis, Earman and Ruetsche further argue (following Wald (1994)) that Jill's Rindler Fock space representation is not physically acceptable because it fails to satisfy a physical condition pertaining to stress-energy.[13] Jack's Minkowski Fock space representation is the only representation that is physically acceptable. On this reading of the situation, a fundamental particle ontology is not threatened. However, Arageorgis, Earman and Ruetsche agree with Clifton and Halvorson that–for reasons unrelated to the Unruh effect–"the particle notion should be demoted in QFT from fundamental to derivative status" (165). Thus, on either reading, the Unruh effect does not undermine a fundamental particle ontology; however, this is cold comfort because other arguments are fatal to particles.

2.3 No unique Fock space representation in general in curved spacetimes

General relativity introduces curved spacetime to treat gravity. The procedure for constructing a unique (up to unitary equivalence) Fock space representation for a free system of mass m that is outlined in Sec. 1 is particular to Minkowski spacetime. This procedure can be generalized to stationary spacetimes (i.e., spacetimes possessing a time translation symmetry). (See Ruetsche (2011, Sec. 10.2) and Wald (1994, Chapter 4).) However, the procedure cannot be generalized to non-stationary spacetimes. The obstacle is that the requirement that the vacuum state in the Fock representation be invariant under time translations plays a crucial role in picking out a unique vacuum state. In non-stationary spacetimes, there is no time translation symmetry to play this role. The absence of time translation symmetry also poses difficulties for ascribing physically appropriate energies to one-particle states. As a result, infinitely many unitarily inequivalent analogues of a Fock space representation can be constructed for a free system of mass m in a non-stationary spacetime

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[13] The requirement is that Jill's vacuum state on the right Rindler wedge be extendable to a state on the full Minkowski spacetime that satisfies the Hadamard condition, which guarantees that a stress-energy observable is well-defined. See Ruetsche (2011, Sec. 10.3).

and there is no physical reason to privilege one (unitary equivalence class) of these analogue Fock representations over the others. Thus, in generic curved spacetimes, the availability of a particle description is not guaranteed. Wald (1994) argues that, as a result, the particle concept should not be regarded as fundamental.[14]

2.4 Interacting systems cannot be given a quanta interpretation

Another difficulty for the quanta interpretation of QFT is that the analysis in terms of quanta offered in the preceding paragraphs is restricted to free systems. Free systems are systems in which there are no interactions. As a consequence of Haag's theorem, an interacting system cannot be given a quanta interpretation by representing it using the Fock representation for the corresponding free field (Haag 1955; Fraser 2008). Fraser (2008) argues that the Fock representation cannot be generalized to interacting systems in a way that preserves the quanta interpretation. One approach would be to quantize a classical interacting field by carrying out the same mathematical construction that, for a free field, generates a Fock representation. This approach fails because the Fourier decomposition of a classical interacting field is not relativistically covariant, and therefore is not a candidate for representing physical fields in relativistic QFT. A second strategy would be to pick out a unique (up to unitary equivalence) Hilbert space representation of the canonical commutation relations by stipulating that it share the formal properties of the Fock representation laid out in conditions 1-4 in Sec. 1. This strategy fails because the Hilbert space representation that is picked out in this way cannot be physically interpreted in terms of quanta in the same manner as a Fock space representation for a free system. In particular, for all non-trivial interactions, the no-particle state does not coincide with the vacuum state and, typically, the argument that one-particle states have the energy expectation values that special relativity assigns to single particle states is undercut. It is worth noting that this is, in a way, a more severe blow to the particle interpretation of QFT than the result that the quanta counted by number operators in Fock representations for free systems are not localizable. The unavailability of either the Fock representation or a physical analogue of the Fock representation means that there is

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[14] Again, the Hadamard condition can be invoked to reduce the number of instances in which there is no unique physically privileged particle concept, but cases of non-uniqueness will remain. In particular, the Hadamard condition only secures uniqueness for a spacetime with a compact Cauchy surface; for an "open universe," the non-uniqueness remains (Wald 1994, 96-97).

no support for even non-localizable quanta in interacting systems![15]

2.5 The role of relativity

Multiple lines of argument corroborate the negative conclusion that QFT cannot be given an interpretation in terms of particles that are aggregable and localizable. There is a common element to all of the arguments surveyed in this section: relativity theory is a key determining factor in the availability of a particle interpretation of QFT. On the one hand, the special theory of relativity makes a quanta interpretation of Fock space possible by introducing the mass-energy relation. Without the mass-energy relation, there would be no grounds for interpreting the eigenstates of total number operator N as representing definite numbers of particles rather than merely more examples of discrete energy level states that are the hallmark of non-relativistic quantum mechanics. However, what special relativity gives, special relativity also takes away. For free systems, relativistic assumptions are required to obtain the result that quanta are not localizable in a finite region of space. For interacting systems, Haag's theorem relies on relativistic premises;[16] the Fourier decomposition is not covariant under Poincaré transformations; and, in the formal analogue of the Fock space representation, the no-particle state is not invariant under Poincaré transformations and special relativity typically does not supply the correct assignment of energies to one-particle states. (For a free system, special relativity and the linear field equation conspire to produce a quanta interpretation; for an interacting system, the combination of special relativity and the non-linear field equation is not so fortuitous.) Bain (2011) argues that it is specifically the absolute temporal structure of non-relativistic spacetime that is required to support quanta that are countable and localizable. General relativity undermines quanta from a different direction, by (in general) dispensing with the stationary spacetime structure that in the context of Minkowski spacetime picks out a unique Fock space representation.

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[15] Of course, a particle ontology could be restored by finding a way to give a particle interpretation of QFT that does not rely on Fock space, but this is not a plausible option until there is a concrete proposal for how this interpretation would proceed.

[16] Evidence for this claim is that Haag's theorem does not hold in Galilean QFT, for which there are models of non-trivial interactions in which vacuum polarization does not occur (Lévy-Leblond 1967).

3 Particles as non-fundamental entities: A survey of options

There are many reasons to think that the arguments for the negative conclusion that QFT does not support an ontology that includes particles as fundamental entities are not the whole story. Particles do seem to play an important role in the phenomenology associated with QFT. Cloud chamber photographs are taken to show trails of particles such as electrons and positrons traveling on approximately localized trajectories. Experimental tests of QFT often take the form of scattering experiments, which are taken to involve colliding particles, such as the collisions of protons at the Large Hadron Collider. Particle decay has been the subject of other experimental tests. If particles are not fundamental entities, then how are we to understand these experiments?

The theoretical side of QFT also supplies a strong rationale for following up on the negative conclusions with a positive investigation of the non-fundamental roles played by the particle concept. The content of the Standard Model of particle physics is typically cashed out in terms of families of particles of different types (leptons, quarks, bosons) and their properties (mass, charge, etc.). In the history of particle physics, the development of models has been motivated by puzzles concerning particles and solutions to puzzles have involved proposing new particles. For example, the infamous introduction of spontaneous symmetry breaking and the massive Higgs boson into the electroweak theory was prompted by the (apparent) puzzle that spontaneously broken symmetries are necessarily accompanied by massless Goldstone bosons, which had not been observed. More generally, within particle physics and outside of it, the atomic hypothesis is widely regarded as being one of the best-confirmed theoretical posits in all of science. Writing about thermal systems, Norton opines "a thesis of ontological reduction asserts that thermal systems just are systems of many molecules, spins, radiation modes, and so on. ... While the ontological thesis is quite ambitious, the evidence in its favour is so massive that, now, no one who doubts it is or should be taken seriously" (2014, 206).[17] How are we to reconcile the empirically well-supported components of the atomic hypothesis with the conclusion that particles are not among the fundamental entities? For example, Perrin's famous argument for the truth of the atomic hypothesis involved agreeing measurements of Avogadro's number, which is taken to represent the number of particles in a mole of a substance.

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[17] This is an overstatement. For example, Healey argues that the "decompositional strategy" of decomposing matter into atomic and sub-atomic parts that is an element of the atomic hypothesis has "probably run its course" in particle physics (2013, 56).

In this section, proposals for the non-fundamental role played by particles will be surveyed. Presumably, the nature of the fundamental constituents of the ontology of quantum field theory is relevant for fleshing out most of these proposals, but the important issue of how to determine the fundamental ontology will be set aside. The notions of approximation and idealization will play a prominent role in the taxonomy. To fix our terminology, we will adopt the definitions introduced in Norton (2012). An *approximation* is “an inexact description of a target system” and “it is propositional” (209). An *idealization* is “a real or fictitious system, distinct from the target system, some of whose properties provide an inexact description of some aspects of the target system” (209). The simple example of a body falling in a weakly resisting medium treated using classical mechanics illustrates the difference (210). The equation for velocity as function of time that neglects velocity $v(t) = gt$ is used as an approximation when it is applied as an inexact description of the falling body. An idealization is a body falling in a vacuum, which is (exactly) described by the same equation $v(t) = gt$.

3.1 Operationalism: Particles are what particle detectors detect

In an article entitled “Particles do not exist,” Paul Davies defends an operational interpretation of quanta:

> There are quantum states and there are particle detectors. Quantum field theory enables us to predict probabilistically how a particular detector will respond to that state. That is all. That is all there can ever be in physics, because physics is about the observations and measurements that we can make in the world. We can’t talk meaningfully about whether such-and-such a state contains particles except in the context of a specified particle detector measurement. (69)

Davies’ slogan is “particles are what particle detectors detect” (75). On its own, this brand of operationalism about particles addresses the first motivation for a non-fundamental particle notion–namely, to account for the phenomenology of particle detection–but it does not address the other motivations. The other motivations require a connection between the experimental context of particle detectors and the theory. How does QFT enable us to predict the response of particle detectors? Moreover, in the context of a fundamental ontology for QFT which does not include particles, it seems mysterious why particle detectors would reliably behave as if they detect particles without some further explanation.

3.2 Particles are an approximation

Like Davies, Halvorson and Clifton (2002) regard talk about particles as mere talk which has no referents in the actual world. They maintain that talk about particles is a "useful fiction" (20). Halvorson and Clifton add to Davies' operationalism a proposal for grounding particle detector phenomenology in the theory of QFT. They are particularly concerned with addressing the nonlocalizability of n-particle states of free systems. The idea is that *what particle detectors actually detect approximately fits the description of particles.* n-particle states in Fock space are an inexact description of the states actually measured by particle detectors. Halvorson and Clifton use the algebraic QFT framework and take fields to be part of the fundamental ontology. What particle detectors actually measure is some local observable (i.e., an observable that is measurable within spacetime region O) which is represented by an element C of the local algebra of observables $\mathcal{R}(O)$. This local observable is not a particle observable because (by the Reeh-Schlieder theorem) it does not have an expectation value of zero in the vacuum state. However, this local observable gives the appearance of being a particle observable because FAPP ("for all practical purposes") it is observationally indistinguishable from an observable that is "almost localized" within O and does have zero vacuum expectation value. That is, if we allow ourselves some error bound δ on our measurement of C, then there exists some almost localized observable C' that has expectation values that are within the error bound δ of the expectation values of C.

Colosi and Rovelli (2008) offers a different account of how particles are an approximation. Their primary motivation is (pace Wald) to formulate a particle notion that is well-defined in curved spacetime, and thus could furnish a starting point for a theory of quantum gravity. Like Halvorson and Clifton, they take the states that particle detectors actually measure to be localized. Unlike Halvorson and Clifton, Colosi and Rovelli identify "local particle observables" associated with particle detectors. Rodríguez-Vázquez et al. (2014) further develop this proposal.[18] Local particle number observables are defined for each particle detector at each time. Malament's theorem is evaded by rejecting the very first step in the construction of the Fock space representation: the local n-particle states at a specified time are *not* composed of exclusively the positive frequency modes identified in the positive-negative frequency decomposition; instead both positive and negative frequency modes are used (Rodríguez-Vázquez et al. 2014, 119-120). The fact that time translations are

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[18] Rodríguez-Vázquez et al. (2014) modify Colosi and Rovelli's construction in order to satisfy the spatial boundary conditions. A consequence of respecting the boundary conditions is that the local modes can only be chosen to be spatially localized at a given time and not for all times.

not needed to uniquely decompose the classical field into positive and negative frequency modes means that local n-particle states at a specified time for a given particle detector can be defined in non-stationary spacetimes. The local n-particle operators are approximations of the global n-particle operators on the Fock space in the sense that the local n-particle operators converge to the global n-particle operators in the weak limit (Colosi and Rovelli 2008).[19] The particulate properties of global Fock space are "an artifact of the simplification taken by approximating a truly observed local particle state with easier-to-deal-with Fock particles" (2).

Colosi and Rovelli pose the question of whether their construction supports an interpretation of QFT according to which particles are fundamental entities. Their own answer to this question is "partially a yes and partially a no," but they do conclude their paper with the statement that "[t]he world is far more subtle than a bunch of particles that interact" (15). The "partially a yes" refers to the interpretive option of regarding local n-particle observables as "complementary," but not in the robust sense of Sec. 2.2 above of providing complementary descriptions of a common underlying ontology with a single set of objects; the observables are complementary in the minimal sense that "there is no reason to select an observable as 'more real' than the others" (15). Colosi and Rovelli provide compelling reasons that the local n-particle operators and states do not support a fundamental particle notion. In essence, the trade-off for dropping the requirement of time translation invariance that went into the construction of global Fock space is that there is no unique basis of local n-particle states. In contrast to the global n-particle states and operators defined on the Fock space, a set of local n-particle states and operators is defined with respect to a detector that makes measurements within some finite region. The Hamiltonians associated with different detectors do not commute. Colosi and Rovelli point out the consequence that "[w]hether a particle exists or not depends on what I decide to measure," which is reminiscent of Davies' operationalist slogan that "particles are what particle detectors detect" (15). However, in the introduction to the paper, Colosi and Rovelli hold up Davies' position as a target for their arguments. This underscores that the main goal of Colosi and Rovelli's paper is not to shed light on the ontology of particles, but to argue that Davies (and Wald) have overlooked mathematically possible representations for curved spacetime that retain some features of Fock space in modified form. For Colosi and Rovelli, whether the mathematical framework of local particle observables latches onto the fundamental ontology is not the most important consideration for determining whether to use this mathematical framework in quantum gravity.

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[19] That is, expectation values of the local n-particle operators for some region R converge to the expectation values of the global n-particle operators as $R \to \infty$.

The approaches of both Halvorson and Clifton and Colosi and Rovelli are best categorized as regarding particle concepts as approximate in Norton's sense. Both approaches establish that the global, non-localized Fock n-particle descriptions are inexact but approximately accurate descriptions of the states identified by each approach as exactly representing the target system. For Halvorson and Clifton, the local observables are measured by particle detectors. Though they do allude to particles being fictions, which sounds like idealization in Norton's sense, their analysis is aimed at establishing the usefulness of talk of particles rather than carving out a role for particles as fictional entities. Colosi and Rovelli take local n-particle states associated with detectors to be exact states, and their primary aim is not to defend particles as fictional entities, but to relate these states to global n-particle Fock states by approximation.

3.3 Particles are an idealization introduced by scattering theory

The development of the notion of particles as an approximation that was traced in the previous sub-section was largely a response to no-go theorems for free systems surveyed in Sec. 2. The no-go results for interacting systems inspire a different approach to regarding particles as non-fundamental entities. Bain (2000) argues that scattering theory supports a variety of particle interpretation at asymptotically early times prior to an interaction and asymptotically late times after an interaction. Essentially, at these asymptotic times, the interacting system tends to a free system and the Hilbert space representation is suitably related to a Fock space representation for a free system in the infinite limit.[20] Bain proposes that "a 'particle' be considered a system that minimally possesses an asymptotic state (i.e., a system that is free for all practical purposes at asymptotic times)" (394). Naturally, this 'particle' can also be regarded as localized for all practical purposes, along the same lines sketched in the preceding section (Bain 2000, 395–396).

This notion of particle is an idealization in Norton's sense. The free system described by the Fock space representation is a fictitious system. In the real world, there are always interactions. In the infinite limits of early and late times, the properties of the fictitious free system provide an inexact description of the real interacting system. In particular, the particulate properties of the free system provide an inexact description of the interacting system. (Additional layer of approximation:

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[20] LSZ and Haag-Ruelle scattering theories establish a suitable relationship to the Fock space representation for a free system in the asymptotic limit without violating Haag's theorem. See Fraser (2006, Sec. 3.1.2) for details.

the properties of the free system are only particulate–i.e., localized–for all practical purposes.) The fictitious system must be posited because, as explained in Sec. 2.4, interacting systems do not admit a quanta interpretation. In Norton's terms, this particle notion is an idealization–a mere approximation is insufficient. Within this approach, particles have the status of fictitious entities.

3.4 Realism: Particles are emergent entities

Another way of fleshing out the non-fundamental status of particles is to regard them as emergent.[21] Wallace (2001) defends this interpretation. The animating idea of his interpretation is that bosons in relativistic QFT have the same ontological status as quasi-particles (e.g., phonons) in non-relativistic condensed matter physics. Phonons are vibrational modes of an atomic crystal. For strongly interacting systems, there are phenomena which are most effectively represented using phonons. For example, heat transport is modeled using localized phonons. Representations involving phonons are useful, but in condensed matter physics it is clear that phonons are not part of the fundamental ontology. The atoms in the crystal lattice are part of the fundamental ontology; the phonons represent collective excitations of the crystal lattice. Wallace argues that phonons are nevertheless real:

> Are quasi-particles real? They can be created and annihilated; they can be scattered off one another; they can be detected (by, for instance, scattering them off "real" particles like neutrons); sometimes we can even measure their time of flight; they play a crucial part in solid-state explanations. We have no more evidence than this that "real" particles exist, and so it seems absurd to deny that quasi-particles exist–and yet, they consist only of a certain pattern within the constituents of the solid-state system in question. (2010, 59)

Following Dennett, Wallace regards patterns as constituting real, emergent entities (or properties) when they prove useful in a theory, especially with respect to explanatory power and predictive reliability (2010, 58).

Wallace reverses the argument in the block quote to support the conclusion that particles in QFT should be classified as emergent. Using quasi-particles as a template, he argues that in order to grant particles emergent status it is only necessary to provide pragmatic definitions; a notion of particle that is approximately localized to an extent that it can be regarded as localized in practice is sufficient. Wallace's

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[21] See Wilson (this volume) for further discussion of emergence.

formal proposal for introducing particle states that are approximately localized is similar to Halvorson and Clifton's,[22] but the interpretation is different. Halvorson and Clifton regard particle states as merely approximations, while Wallace classifies particles as real, emergent entities. Wallace also points out that Haag-Ruelle scattering theory uses a similar formal framework for analyzing the particle content at asymptotically early or late times (2001, 8, 38). However, the physical interpretation again differs from Bain's. Wallace considers particles not as merely idealizations, but as real, emergent entities.

An important source of motivation for regarding particles in particle physics as having the same status as quasi-particles is the effective field theory perspective on QFT. As Wallace stresses in his contribution to this volume, a compelling reason to regard particles as emergent is that particle representations are scale-relative. For example, in QED the interaction between electrons and photons increases in strength as the energy scale gets higher. Different particle representations with different particulate properties (e.g., mass) are required for different scales. A related consequence of the application of renormalization group methods in particle physics is that the fact that the Standard Model has been empirically well-confirmed by experiments at relatively low-energy scales is compatible with the truth of a whole class of models (with different Lagrangians) at much higher energy scales.[23] The Standard Model is effectively valid at relatively low energy scales in the same manner that quasi-particle models in solid state physics are effectively valid at relatively large distance scales. J. Fraser (2017) and Williams (2017) have recently argued that the effective field theory perspective supports a brand of selective scientific realism according to which, if there are features of a model (including particles) valid at a specified lower energy scale that are insensitive to assumptions about the unknown physics of higher energy scales,[24] then it is appropriate to adopt a realist attitude towards these features.

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[22] Wallace identifies a set of states that are approximately localized in a finite region of space O in the sense that expectation values of field operators defined on regions outside O in states approximately localized within O will differ negligibly from the vacuum expectation value. These states are in practice localized in O because outside of O very high energies would be required to distinguish them from the vacuum state.

[23] See Williams (this volume) for a more detailed discussion of renormalization group methods.

[24] For example, how a high energy-momentum cutoff is implemented or which of the possible Lagrangians that satisfies basic constraints (e.g., symmetries) is used.

3.5 Anti-realism: Particles are intuitive pictures that are heuristically useful but do not represent the world

Wallace appeals to quasi-particles to make the methodological point that, when doing metaphysics, pragmatic characterizations that involve approximations and idealizations can be used to pick out emergent entities. However, as Wallace points out, there are strong formal similarities between the mathematical representations of particles in QFT and quasi-particles in solid state physics. There is a long history of frameworks for representing particles being passed back and forth between relativistic QFT and non-relativistic quantum mechanics applied to many-body systems. Dirac's 'hole theory' of the electron was possibly inspired by ionic crystal models of conductors constructed by Frenkel in the 1920s, and Dirac's idea was certainly picked up in solid state physics in the 1930s (Kojevnikov 1999). Renormalization techniques developed for QED in the 1940s and the associated concept of dressed electrons were exported from QED to solid state physics in the 1950s (Blum and Joas 2016). For example, Bohm and Pines' electron gas model for metals introduces an effective heavy electron and plasmons. In the late 1950s and 1960s, spontaneous symmetry breaking (SSB) and associated quasi-particles were developed in models of superconductivity and then exported to particle physics. These analogies inspire another approach to fleshing out a particle interpretation for particle physics: regard quasi-particles as ontological templates for particles in particle physics (i.e., particles have the same (or similar) physical properties as quasi-particles). (In contrast, Wallace argues that quasi-particles and particles have the same ontological status, but does not argue that the entities are physically similar.) For the purposes of assessing the viability of this approach, grant that quasi-particles are real entities. Motivation for this approach can be derived from the thrust of the 'no miracles' argument, that success in science is explained by getting something right about the world. However, analysis of the types of analogies drawn between non-relativistic quantum mechanics of many-body systems and QFT systems reveals that this approach fails to yield a particle interpretation for QFT. The approach is untenable because the analogies are formal analogies, not physical analogies; that is, the analogies map elements of the mathematical frameworks that play similar mathematical roles, but do not map elements with similar physical interpretations. Insofar as intuitions about quasi-particles played a role in the successful development of particle physics, this approach once again leads to a conception of particles as fictions, albeit useful ones.

As an illustration of how this approach to interpretation pans out, consider the role that analogies played in the development of the Higgs model. In this case, what has come to be known as SSB was originally a feature of the Ginzburg-Landau and

Bardeen-Cooper-Schrieffer (BCS) models of superconductivity. Anderson, Higgs, and others noted that a model with a massive Higgs boson and massive W and Z bosons could be constructed by drawing on analogies to these models of superconductivity. The quasi-particle in the superconductivity models that is the analogue of the Higgs boson is the plasmon. Fraser and Koberinski (2016) analyze the intricate pattern of analogical reasoning and conclude that formal analogies are accompanied by substantial physical disanalogies. The analogies map space in superconductor models to spacetime in the Higgs model. The causal structure of the superconductor models is not preserved by the mapping. The mathematical frameworks of the models are similar–and thus support the formal analogies–but the physical interpretations of the mathematical framework differ in these crucial respects. As a result, the physical properties associated with particles and quasi-particles in the superconductivity models (e.g., composition, effective mass, causal-dynamical process of spontaneous symmetry breaking) do not carry over to the analogue 'particles' in the Higgs model. A root cause of these physical disanalogies between the superconductor and Higgs models is that the former are non-relativistic (framed using non-relativistic quantum statistical mechanics) and the latter are relativistic (framed using relativistic QFT). Once again, special relativity gets in the way of a particle interpretation of QFT.

The Higgs model has unquestionably proven to be a success, even if at some point in the future it gets replaced by a successor model. The physical properties of particles and quasi-particles in condensed matter physics were a source of physical intuitions for the physicists who originally developed the Higgs model, and continue to be used in pedagogical presentations of SSB for particle physicists. The situation is similar to that in electromagnetism in the nineteenth century: Thomson, Maxwell, and others successfully used fluid and mechanical models to develop the theory of electromagnetism, even though we now recognize that these models do not accurately represent the world (even approximately). The intuitive physical pictures associated with the fluid and mechanical models were useful fictions. Similarly, the intuitive physical pictures associated with the particles and quasi-particles of superconductivity models (and condensed matter physics models more generally) are useful fictions for the purpose of developing models and theoretical frameworks in QFT.

4 Conclusion

Multiple lines of argument support the conclusion that QFT does not describe a world that contains particles as fundamental entities. These arguments rely on special relativistic or general relativistic premises. However, particles continue to play important roles in the experimental and theoretical practice of particle physics. Different proposals have been made for non-fundamental roles for particles, inspired by different no-go arguments. Davies advocates a minimal operationalist account. Halvorson and Clifton and Colosi and Rovelli defend accounts according to which quanta descriptions afforded by the Fock space for a free system are approximations of exact descriptions of the target system. Halvorson and Clifton are motivated by arguments that quanta are not localized, while Colosi and Rovelli are motivated by these same arguments as well as Wald's argument that non-stationary spacetimes typically undermine the uniqueness that the Fock space representation possesses in Minkowksi spacetime. To address the obstacles to a particle interpretation for interacting systems, Bain argues that particles are idealizations–fictional entities that are associated with interacting systems that asymptotically approach free systems. Wallace acknowledges both the localizability and interaction barriers to a fundamental particle interpretation, but argues that the resulting approximate, idealized notion of particle is a notion that is appropriate for a real, emergent entity. Finally, I have added the proposal that particles be considered fictions in another sense: particles and quasi-particles in condensed matter physics supply physical intuitions that are useful for formulating mathematical frameworks for QFT, but which do not represent the world (even approximately).

These approaches to according particles a non-fundamental status in QFT entail different ontological commitments. The apparent references to particles in experimental and theoretical particle physics do not require an ontology that includes particles as either fictional or real entities. One consideration that could distinguish among these alternatives is which (if any) plays a role in the successful development of new physics. For example, Wald, Colosi and Rovelli, and Rodríguez-Vázquez and collaborators formulate their approximations with an eye towards quantum gravity. Of course, another possibility is that it will be the entities that do have a fundamental status in QFT that turn out to be relevant to developing new physics. Furthermore, the domain of applicability of particle concepts considered here is limited to massive, bosonic QFTs. There is also philosophical and foundational work remaining to be done in investigating other cases. For example, massless bosons in QED (photons) present mathematical and conceptual challenges which may also turn out to be relevant to quantum gravity if massless gravitons are involved.[25]

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[25] For a brief introduction aimed at philosophers see Swanson (2017), for a mathematical physics presentation see Strocchi (2013), and for recent research relating to quantum gravity see `http://perimeterinstitute.ca/conferences/infrared-problems-qed-and-quantum-gravity`.

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