Introduction
Conceptual issues in quantum field theory

TIAN YU CAO

Quantum field theory (QFT) is a powerful language for describing the subatomic constituents of the physical world (quarks, leptons, gauge bosons, Higgs scalars, and so on) and the laws and principles that govern them. Not only has it provided a framework for understanding the hierarchical structure that can be built from these constituents, it has also profoundly influenced the development of contemporary cosmology and deeply penetrated into the current conception and imagination of the origin and evolution of the universe. For this reason, it has justifiably long been taken to be the foundation of fundamental physics: elementary particle physics and cosmology.

QFT reached its most spectacular success in the early 1970s in the standard model, which is able to describe the fundamental interactions of nature within a unified theoretical structure: the non-Abelian gauge theory. Ironically enough, however, this success brought about a long period of stagnation in its conceptual development: virtually nothing of physical importance occurred after the construction of the standard model except for its detailed experimental verification. This situation can be assessed in different ways, depending on what perspective we start with. For example, the stagnation could be taken to be an indication that the theoretical development of fundamental physics has come to an end. If we have already discovered all the fundamental laws, concepts and principles and integrated them into a coherent structure of the standard model, how can we find anything fundamentally new? Thus 'No new physics!' is the slogan of the apologist for the standard model.

Other physicists, such as string theorists, disagree. For them the success of the standard model, or even the adequacy of QFT as a framework for describing and understanding the nature and texture of the physical world, is far from perfect. First, there are too many empirical parameters that cannot be derived and understood from first principles. Second, the unification achieved is only partial: the electroweak theory and quantum chromodynamics (QCD) for the quark–gluon interactions are still separate pieces, let alone their unification with gravity. Moreover, the understanding and handling of physically meaningless infinities are far from satisfactory. But most importantly, there is no way to incorporate gravity into the framework of QFT. Thus the stagnation, from a string theorist's perspective, is only a temporary silence before the thunderstorm, i.e. another conceptual revolution, which, though it may not be related to the current pursuit of string theory, will radically revise many basic assumptions and concepts adopted by QFT, such as point excitations and the very basic ideas of space and time.

Still other physicists, mainly mathematical physicists pursuing the algebraic approach to QFT, feel that the stagnation reflects the profound crisis of traditional (Lagrangian and functional integral) approaches to QFT. According to the most critical among this category, the crisis has its roots in the inadequate pursuit of quantization and the unjustifiable neglect of the locality principle, a condensed form of the most important experience of 20th century physics. These led to the occurrence of infinities in the formalism, and to the superficial struggles for circumventing them, which have prevented us from gaining a deep understanding of the intrinsic meaning of local physics.[1]

Different assessments notwithstanding, the stagnation itself has provided physicists, mathematicians, and historians and philosophers of physics an opportunity to examine carefully and reflect thoroughly upon where QFT stands now and how it has evolved into the present situation. Conceptually, this kind of examination and reflection is indispensable for a proper understanding of the true meaning of QFT, and is also necessary for detecting and pursuing new directions in which theoretical physics may develop.

1 Reality, ontology and structural realism

In undertaking a historical and philosophical analysis of conceptual issues in QFT, different people naturally have different concerns. For mathematicians or mathematics-oriented physicists, the major concern is with the precise and rigorous proof of the existence and consistency of the symbolic system adopted by QFT. Thus plausible arguments adopted by practising physicists are far from satisfactory and convincing, and a large part of the conceptual development of QFT, seen from this perspective, seems to be restricted only to the so-called heuristic physics. For physicists who take QFT as part of empirical science, the physical interpretation of the adopted mathematical structure, and its power to provide a unified description of various observed or observable phenomena and make empirical predictions are far more important than the formal concern with existence and consistency, which they see as stifling their creative activities. For conceptual historians and in particular for philosophers, the major concern is with the presuppositions about the world adopted by QFT and the world picture suggested by its conceptual structure. They are also interested in understanding the successes and failures of QFT and the significant changes in QFT in terms of its basic entities and theoretical structure.

Different concerns lead to different opinions on various issues. But the basic dividing line that separates people is a philosophical one. If one takes an instrumentalist attitude towards scientific concepts and theories, then there is no room for any deep conceptual analysis. The only thing one can do is to compare concepts and theories with experience and to see how successful they are in making verifiable predictions. Once the link between theory and the world is cut and removed, the success or empirical adequacy becomes a primitive parameter and can have no explanation.

[1] See B. Schroer (1996): 'Motivations and Physical Aims of Algebraic QFT,' manuscript (July 1996).

Thus no further conceptual analysis of the theoretical structure can be done, or is even desirable.[2]

The realists, in contrast, make (and also try to justify) assumptions about the world in their conceptual structure. That is, they assume that some concepts are the representation of the physical reality, while acknowledging that others may merely be conventions. This entails a complexity in the theoretical structure, which is divided in broad terms into two parts: a representative part and a conventional part. The dividing line in most cases is vague, uncertain and shifting. And this requires a conceptual analysis to clarify the situation in a particular case at a particular moment of the conceptual evolution of a theory. For example, the answer given now to the question 'Are quarks real?' may be quite different from the answer given in 1964 when Gell-Mann first invented the concept of quarks. The situation with the Higgs particle is similar but with more uncertainty at this moment. Still more difficult is the question as to the reality of virtual particles: they can either be dismissed as an artifact of the perturbative expansion in terms of free particle states, or seen as entailed by the basic assumption of quantum fluctuations in QFT.

Another deep question involves the function played by conventions in a theory, and asks why it is possible for them to play such a function. Some realists assume that conventions are not merely conventions but encode within them some structural information about the entities under investigation. Conventions, such as particular ways of fixing the gauge, by definition can be replaced by other conventions. But the structural information encoded in them has to be retained, perhaps in a very complicated way. In short, the whole issue concerning the relationship between formalism and reality has its roots in the realistic attitude towards scientific theory and its ensuing division of a theory into representative and conventional parts.

Further complications in the conceptual analysis of the theoretical structure come from another assumption of the realists about the causal-hierarchical structure of the physical world. Some physicists assume that entities and phenomena of the world are causally connected and layered into quasi-autonomous domains. Usually a relatively upper level domain (or relatively restrictive phenomena) can be understood or derived, sometimes wholly, sometimes only partially, from a relatively deeper level (or relatively universal phenomena), which is assumed to be primitive in the derivation. While the relationship between domains at different levels, which are grasped by theoretical models at distinctive cognitive levels, is very complicated, involving both reducibility and emergence, the causal-hierarchical relationship within each domain in terms of the primitive and the derivative is universally assumed in scientific practice. Without this assumption, no theoretical discourse would be possible.

This assumed causal-hierarchical structure of the world is believed to be embodied in the hierarchy of conceptual structures of scientific theories. For the realists, a very

[2] On the 'divisive rhetoric' of this paragraph, Arthur Fine has made very interesting comments: 'I do not think that the issues you discuss about ontology would simply be dismissed by an instrumentalist, as you suggest. After all, as van Fraassen would say, the instrumentalist is committed to the QFT worldview even if she does not necessarily believe it. So, the instrumentalist too would like to know to what she is committed. I think that it is almost always a mistake when one says that the realist is interested in this or that feature of science but the instrumentalist not.' (Private exchange.) It would be very interesting to have a conceptual analysis of the ontological commitment and theoretical structure of a scientific theory, such as quantum field theory, from an instrumentalist's perspective. This would provide a testing ground for a proper judgment of the two competing philosophical positions: realism and instrumentalism.

important task in conceptual analysis, the so-called foundational analysis, is to analyze the logical relationship between the primitive concepts, which are assumed to be the representation of what are primitive in the domain, and the derivative ones in a conceptual structure. The latter have historically emerged from empirical investigations; and thus their logical relationship with the primitive ones is not explicitly clear.

Some physicists claim that they feel no need for foundations. This does not mean that their scientific reasoning is detached from the logical structure of concepts in their discipline, which represents the causal structure of the domain under investigation. What it means is only that their intuition at the heuristic level, which usually takes the accepted understanding of the foundations for granted, is enough for their daily researches. However, in a situation in which complicated conceptual problems cannot be understood properly at the heuristic level, or in a period of crisis when basic preconceptions have to be radically revised for the further development of the discipline, a clarification of the foundations is badly needed and cannot be avoided without hindering the discipline from going further. Nonetheless, the difficulties in grasping the questions in a mathematically precise way and in the conceptual analysis of the unfamiliar logical and ontological foundations would deter most practising physicists from doing so.

From a realist point of view, the clarification of what the basic ontology is in a given theory is a very important aspect of the foundational discussion. Here the basic ontology of a theory is taken to be the irreducible conceptual element in the logical construction of reality within the theory. In contrast to appearance or epiphenomena, and also opposed to mere heuristic and conventional devices, the basic ontology is concerned with real existence. That is, it is not only objective, but also autonomous in the sense that its existence is not dependent upon anything external, although its existence may be interconnected with other primary entities. As a representation of the deep reality, the basic ontology of a theory enjoys great explanatory power: all appearance or phenomena described by the theory can be derived from it as a result of its behavior.

It is obvious that any talk of a basic ontology involves a reductive connotation. Ontological and epistemological emergence notwithstanding, a reductive pursuit is always productive and fruitful in terms of simplification and unification in a scientific discourse, and thus is always highly desirable. Furthermore, the ontological commitment of a theory specifies the basic entities to be investigated, provides stimulation and guiding principles for further theoretical and experimental researches, and dictates the structure of the theory and its further development, which results in a series of theories, or a distinctive research program.

In order to clarify what the basic ontology of QFT is, we have to realize that any statement about an ontology refers to certain underlying particular entities and their intrinsic properties, mainly through reference to the structural characteristics of these entities. One can even argue that any ontological characterization of a system is always and exclusively structural in nature. That is, part of what an ontology is, is mainly specified or even constituted by the established structural properties and relations of the underlying entities. Moreover, this is the only part of the ontology that is accessible to scientific investigations through the causal chains that relate the structural assertions about the hypothetical entities to observable phenomena. The recognition that structural properties and relations are constitutive of an ontology is crucial in our understanding of the nature of space-time that, arguably, has underlain, or individuated, or at least indexed local fields, which in turn are arguably the basic ontology of the traditional QFT.

Various issues related to the place of space-time in the theoretical structure of QFT have been addressed by authors in this volume, and I will turn to some of them shortly. Here I only want to stress that in any discussion of the basic ontology of QFT, the distinctive theoretical context has to be clearly specified. For example, in various formulations of QFT that are based on the concept of space-time provided by the special theory of relativity (STR), we can find two categories of entities: local fields individuated by space-time points, and non-individual quanta[3] that are global in nature. If we take Kant's position that the individuation and identification of entities are necessary for our conception of the world as consisting of distinct entities,[4] then we may take local fields as the basic ontology and quanta as an appearance derived from the fields. As we shall discuss in the next section, there are good reasons to argue for a particle ontology instead. This position requires a rejection of the Kantian metaphysics, which, however, often cause some confusions that are not unrelated to the conflation of several theoretical contexts at different cognitive levels.

For example, it is legitimate to argue that a conceptual analysis of a complex concept (such as that of a local field) into various elements (such as its substantial stuff, the various properties attached to it, and individuating space-time points) does not generally ensure that these elements have their own existence. However, in the discussion of the ontology of STR-based QFT, this argument itself does not give sufficient grounds to reject the autonomous existence of space-time points, which are presupposed by STR as an irreducible structure underlying a field system. Some scholars argue, mainly by adopting Einstein's argument against the hole argument in the context of general theory of relativity (GTR),[5] that space-time points have no reality because they have to be individuated by the metric field that defines the spatiotemporal relations.[6] It is further argued that the classical metric field, as an agent for individuating space-time points that individuate local fields, itself is not a primitive entity, but only an appearance of some substratum that is quantal in nature: an argument for quantum gravity (QG). These arguments are interesting in their own right. They have improved our understanding of the nature of space-time, and pointed to a new direction for the further development of QFT, which requires a clarification of the inter-theoretical relationship of the concepts involved. But these arguments are irrelevant to the discussion of the ontology of STR-based QFT. In order to claim their relevance to the discussion about the ontology of QFT, we have to have mathematical formulations of GTR-based or QG-based QFT in the first place.

3 For an analysis of why quanta can be regarded as physical entities without individuality, see Steven French and Décio Krause in this volume.
4 This is compatible with the ontological commitment, in fact has provided the metaphysical foundation, of Cantor's set theory and all of classical mathematics.
5 For a detailed historical investigation and insightful conceptual analysis about Einstein's hole argument against the idea of general covariance and his later argument against his own hole argument, see John Stachel (1989): 'Einstein's search for general covariance, 1912–1915,' in *Einstein and the History of General Relativity* (eds. D. Howard and J. Stachel, Birkhauser), 63–100.
6 Although the lack of individuality of space-time points does entail their lack of reality, this entailment is not generally true because some non-individual entities, such as quanta, are also real.

This brings us to another issue of interest: the nature of mathematical concepts and formalisms. In our construction of a physical theory to approximate the structure of reality, we have to use mathematical concepts (such as the continuum, the vacuum, a local field, the bare charge, gauge symmetry, ghosts, etc.) as an idealization and exploit their logical ramifications to the ultimate conclusions, because this is the only window through which we can have access to reality. Then, in view of the shifting line separating representative and conventional parts of a theoretical structure, an important interpretive question arises: what is the criterion for the physical reality or partial reality of a mathematical concept?

Obviously only those mathematical concepts that are indispensable and independent of particular formalisms, or invariant under the transformations between equivalent formalisms, have a chance to claim to be part of reality, either as a basic ontology or as derivative structures. A case in point is the status of ghosts in non-Abelian gauge theories: they have appeared in some, but not in other, empirically equivalent formalisms, and thus cannot claim to be part of physical reality. It is debatable, however, whether gauge invariance should be taken as a criterion for reality, although it is generally accepted to be relevant to observability. A trivial counter-example is the accepted reality of the non-gauge-invariant charged fermion field (such as the electron or proton field). A justification for its reality, from a structural realist point of view, is that this non-gauge-invariant concept has become a universal carrier of structural relations in various experimental situations. The empirical and logical constraints are so tight that the acceptance of its existence becomes mandatory if we do not want to give up what we have achieved, since the scientific revolution in the 16th and 17th centuries, in scientific reasoning and hypothetico-deductive methodology in general. But its claim to reality can only be partial, extending only with respect to the structural information the concept carries with it so far.

2 Particles and fields

Historically, in the physical interpretation of STR-based QFT, particularly in the discussion of the field–particle relationship, the operator formalism of free fields and their Fock space structure has played a central role. The statement that particles are just the quanta of the fields makes sense only within this formalism, and many difficult interpretive questions hiding behind this statement become discernible when we take a closer look at the logical structure of the formalism. In order to address these questions, we have to pause and consider the core concept of the structure: quantization.

With regard to the idea of quantization, physicists as well as philosophers are divided into two camps. The first endorses the idea of active quantization, which presumes the necessity of finding a given classical reality, or a classical structure, or a classical theory, and then tries to establish a procedure to quantize it. The second camp, that of the quantum realist, rejects the two-step strategy and tries to formulate a quantum theory directly without quantizing a classical system.

Initially, the indispensability of classical structures for quantum theories was forcefully argued by Niels Bohr on three related grounds. First, the need for unambiguous communication requires classical concepts. Second, quantum theory makes sense only when the system it describes is measured by classical apparatus. Third, there is the correspondence principle: any quantum system, and thus quantum theory, must have its classical limit.

Bohr's correspondence principle provided the ultimate justification for the idea of active quantization. But it had foundered as early as 1928 when Jordan and Wigner tried to incorporate fermions into the operator formalism and to interpret fermions as quanta of a fermion field: there simply was no classical fermion field available to be quantized and the quantum fermion field they introduced had no classical limit. Thus, the measurement problem notwithstanding, the quantum realist feels confident that the microscopic world is quantum in nature, regardless of the existence of its classical limit, which may or may not exist at a certain level, although ultimately, at the macroscopic level, it should have classical manifestations.

The first attempt to formulate a relativistic quantum framework for the description of particles and free fields without recourse to the idea of active quantization was Wigner's representation theory,[7] which, however, can be shown to be compatible with and equivalent to canonical quantization. This, together with the fact that various formalisms of QFT are constructed upon classical space-time, or classical histories in the case of the path-integral formalism, has raised a question: 'What is the meaning of being quantal, in contrast with being classical, which may or may not have a classical counterpart?'

From its genesis (Planck, Einstein and Bohr), the term 'quantum' was related to the assignment and measurement of physical properties in the microscopic world and their discreteness. The condition for ensuring certain discreteness of the measurable properties was called by Bohr and Sommerfeld the quantization condition. In the context of matrix mechanics, the Bohr–Sommerfeld quantization condition was converted into the canonical commutation relation (CCR). But the function played by CCR remained just the same: to ensure the discreteness of physical properties in measurement.

Deeper implications of the concept of quantum were explored soon after the formulation of CCR, which set the limit for the simultaneous measurements of certain pairs of properties. The most profound consequence was of course Heisenberg's uncertainty relations. On the surface, the uncertainty relations address the epistemological question of measurement. However, for justifying or simply understanding experimentally well-established relations, an ontological presupposition is indispensable: we have to assume the existence of intrinsic (perhaps also primitive) fluctuations in the microscopic world, which are numerically controlled by the uncertainty relations. Fluctuations of what? Physical properties. What the uncertainty relations tell us is just this, no more. In particular, no question as to whose properties are fluctuating is addressed by the implications of the concept of quantum or uncertainty relations. It is a line of thought whose upshot is this: for a system to be quantal, the discreteness of its properties must be assured, the uncertainty relations must be obeyed, and the intrinsic fluctuations must be assumed. Does a quantum system require a classical structure to be its underpinning? Physically, it is not necessary: a system can be intrinsically quantum in nature without a classical substratum. But there is no incompatibility either; STR-based QFT is a case in point.

It should be clear now that the idea of quantum or quantization sheds no light at all on the ontological question as to whether the underlying substratum of QFT consists

[7] E. P. Wigner (1939): *Ann. Math.*, **40**: 149.

of particles or fields. In order to develop the idea of particles as field quanta from the concept of a quantum system, several steps have to be taken. First, a quantum field has to be assumed. It does not matter too much whether this quantum field is intrinsically quantal or is quantal only as a result of quantizing a classical field. The difference only refers to the difference in the existence of a classical limit, but has no impact on the nature of the quantum field whatsoever.

The exact meaning of a quantum field is difficult to specify at this stage. The most we can say is only that there are two constraints on the concept. First, devised as a substratum for generating substantial particles (meaning those that carry or are able to carry energy and momentum), the field itself cannot be merely a probability wave, similar to the Schrödinger wave function, but has to be substantial too. Second, as a quantum system, which by definition is discrete, it is different from a classical field, which is continuous in character.

However, as we shall see, this intrinsically discrete system is not equal to a collection of discrete particles. Thus no particle interpretation of a quantum field is guaranteed. Worse still, even the very existence of discrete particles is not entailed automatically by the concept of a quantum field. Thus a widespread misconception that we can get particles from a field through quantization should be dispelled. In order to extract particles from a quantum field, we have to take other steps. The most important among them is that we have to assume the excitability of the field as a substratum; the source of excitation can be the intrinsic fluctuations of the field, or external disturbances; and what is to be excited, just as what is to be fluctuating, is the property of the field, which characterizes the state of the field.

Before specifying the further conditions for extracting particles from a quantum field, let us look at the arguments against taking the field as the basic ontology of QFT. These arguments are interesting because otherwise it would be so natural to take the field ontology for granted, considering the fact that in this line of reasoning the field is taken to be the primary entity from which particles are extracted.

A strong case can be made that empirically only particles are observed, and fields, except for the classical fields, are not observable.[8] This suggests relegating the concept of the field to the status of a convention, a device for generating particles and mediating their interactions. The case becomes even stronger when physicists realize that from the viewpoint of particle interactions, as the theory of collision suggests, what matters is the asymptotic state of particles but not the interpolating field. Besides, as Borchers's theory shows, the S-matrix does not distinguish a particular interpolating field within an equivalent class. In the same spirit, the point-like local fields in the algebraic approach to QFT were only allowed to have a function similar to that of coordinates for the local algebra of observables.

However, in order to develop a particle interpretation of QFT, two steps have to be taken. First, conditions under which the notion of particle emerges from that of the field have to be specified. Second, it has to be shown that the physical content of QFT is in fact exhausted by the notion of particles. The first challenge is met by the construction of the Fock space representation, which permits a number operator and a unique vacuum state with an eigenvalue zero of the number operator. However, some inherent difficulties have already been built in. First, in order to define the number operator, a notion of energy gap between the vacuum and the first particle

8 See remarks by Sam Treiman and Fritz Rohrlich in this volume.

state has to be presumed, which however is not applicable to massless particles. Second, in specifying the spectral condition, particularly in picking up a preferred vacuum state, the Poincaré group has played a key role, but this is only a symmetry group of a flat space-time. The recognition that space-time is in fact not flat has cast deep doubts upon the whole Fock space approach, although this would go beyond the context of STR-based QFT.

Thus, within and only within the Fock space representation, particles can be taken as associated with excited states of the field, or as the quanta of the fields, and the structure of Green's functions and the S-matrix can be analyzed in terms of particles. But the Fock space representation can only be defined for free fields. In the case of interacting fields, there are many unitarily inequivalent representations, among which only one equivalence class involves the Fock representation. The latter, however, can only be defined asymptotically, and thus is not generally definable.

Even within the Fock space representation of free fields, the notion of particles as quanta is difficult to define. In addition to the well-known lack-of-identity problem, which, as Steven French and Décio Krause suggest in this volume, requires a radically new formal framework for understanding the notion of quanta and its underlying metaphysics, there is the famous Unruh effect that has shaken the foundation of the very notion of particles: a uniformly accelerating observer in flat space-time feels himself to be immersed in a thermal bath of particles when the quantum field is in its vacuum state. This shows that how a particle detector responds in a given Fock space state depends both on the nature of the detector and on its state of motion. In general, the particle interpretation emerges only when the field is coupled to a simple system (a particle detector) and the effects of the interaction are investigated in flat space-time or in a curved but stationary space-time.[9]

The ontological primacy of particles is challenged by another consideration. In a system of relativistic particles in interaction, measurements of the position and momentum of individual particles can be made only in asymptotic regions. This suggests to some positivism-oriented scholars that only the S-matrix describing a physical process deals with reality, and that the notion of particles as part of the process emerges only in the asymptotic regions, and thus does not itself designate a basic ontology.

An advocate of the particle ontology may retort that this argument presupposes a direct linkage between reality and observation; but the linkage may be indirect and, in this case, the argument collapses. It can be further argued that in the path-integral formalism, which is empirically equivalent to the operator formalism, the notion of particles enters *ab initio*, thus enjoying an ontologically primary status. But even in this case, the physical content of QFT cannot be exhausted by the notion of particles. Here the key concept situated at the center of the ontological discussion of QFT is the concept of the vacuum.

If we take particles as the primary entities, then the vacuum can only mean a state of nothingness. Dirac's concept of the vacuum as filled with unobservable zero energy photons and negative energy electrons was dismissed as early as the 1930s as an unnecessary complication, and thus cannot claim to be physically real. On the other hand, if we take the fields as the primary entities, then the vacuum, as a

[9] See Robert M. Wald (1994): *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*, p. 3 (University of Chicago Press).

ground state of a quantum field, designates a state of a substantial substratum. As a state of a substantial substratum, the vacuum can be conceived, as Bryce DeWitt argues in this volume, as a cauldron of interacting virtual particles arising from fluctuations, and as carrying a blueprint for the whole field dynamics. Such a fluctuating vacuum was taken to be the physical basis for the calculations of renormalization effects in the 1930s and 1940s. More direct indication for the substantiality of the vacuum state was provided by the Casimir effect first observed in the late 1940s, which shows that the energy density of the vacuum is not zero, but negative.[10]

An advocate of the particle ontology may argue that the physical content of the vacuum conceived as the ground state of the field actually can only be captured in terms of particles, even if only in terms of virtual but not real particles. But this argument is inconsistent and cannot stand by itself. It is untenable not because of the unobservability and the lack of necessity (as artifacts of perturbation calculations) of virtual particles, but mainly because the very idea of fluctuations can only be applied to some state of some entities, or some substance, or some substratum, but not to the state of nothingness. The properties of something may be fluctuating, but 'nothing' cannot be fluctuating. The incompatibility between the concepts of fluctuations and the vacuum state within the framework of the particle ontology has removed the conceptual basis for the notion of virtual particles in that same framework; and the concept of a fluctuating vacuum, even though it still remains within the Fock space framework, goes in fact beyond the framework of a particle ontology.

Moreover, in the field ontology framework, the number of particles is only a parameter characterizing the state of a free field. Thus the appearance of virtual particles as a result of the fluctuating changes of the field state, and the physical effects (such as renormalization effects) they cause, are conceivable. Even the creation and annihilation of real particles are conceivable if enough changes can be brought in from external disturbances. But in the particle ontology framework, particles are themselves entities. Thus, considering the primacy and fundamentality of ontology, the fluctuations of the properties of particles, or any external disturbances, cannot be conceived as the cause for the creation of real or even virtual particles. On top of all these difficulties, there are two more persistent difficulties which have further weakened the particle's candidacy for the basic ontology of QFT. First, the particle as a global concept is not spatially localizable. And second, in the case of interactions, it is not well defined.

A consistent interpretation of QFT, suggested by the operator formalism, seems to be this. The basic ontology is the quantum field. The particles, or the quanta, as the manifestation of the excited states of the field, characterize the states of the field. They can be empirically investigated and registered, but they do not exhaust the physical content of the field. In a very deep sense, the concept of quanta, as objective but not primitive entities, as phenomenological indicators for the complicated structural features of the primitive field (or substratum) manifested in various situations, has well embodied the idea of structural realism.

[10] Although a different interpretation of the Casimir effect, not based on the notion of fluctuating vacuum and operator formalism in general, but based on, for example, Schwinger's source theory, is possible. See Svend E. Rugh, Henrik Zinkernagel and Tian Yu Cao: 'The Casimir Effect and the Interpretation of the Vacuum,' forthcoming in *Studies in History and Philosophy of Modern Physics*.