What is a Quantum Field?

Tian Yu Cao

Boston University

Rutgers-Columbia Workshop on Metaphysics of Science:

Quantum Field Theories

Rutgers University, New Brunswick, NJ, May 17-18, 2018

Quantum field theory is the contemporary locus of metaphysical research

Howard Stein : "On the notion of field in Newton, Maxwell and beyond"
in *Historical and Philosophical Perspective of Science (1970),* 264-287

I. Introduction
II. Ontological Approach
III. Ontological Foundations of QFT
IV. Reality of Quantum Fields
V. QFT and Metaphysics

I. Introduction

Two major approaches to interpret QFT

A. Operationalist

-- Physical content (meaning) lies in human operations

B. Ontological

-- What is the meaning of basic (theoretical) ontology?

-- Instrumentalist

-- Realist

I-A: Operationalist Approach:

Rudold Haag's Algebraic QFT:

1. The role of fields as a convenient artifact, i.e., as the coordinates of the algebra of the observable operators, is to implement the principle of locality, and the number and nature of different basic fields needed in the theory are related to the charge structure, but not to the empirical spectrum of particles as the manifestation of the field as a physical entity.
2. The physical interpretation of the quantum fields is not attached to physical entities, such as physical fields or particles, but to local operations, and a local field operator represents nothing but a physical operation, performed on the system within a local region n spacetime.
3. Quantum fields can only be used to associate each region in spacetime with an algebra of observable operators on the Hilbert space, representing physical operations performable within their region.

I-A: Operationalist Approach:

4. Haag argues that this interpretation tells us how to compute collision cross sections, which are the only things that are observable and thus physically real.
5. Thus, it is the algebra of the observable operators but not the system of non-observable fields that constitutes the intrinsic mathematical description of the physical content of QFT

I-A: Operationalist Approach:

6. Operational approach is inconsistent:

   In general, within the framework of AQFT, whatever the representation the algebra of observables chooses to represent physical processes, the representation, as claimed by Haag himself, has to satisfy a selection criterion, that is, elementary systems are localized excitations of the vacuum. Thus the primary existence of the vacuum is presumed by the algebraic approach. (the famous Reeh-Schlieder theorem also requires the existence of a cyclic vacuum)

I-B Ontological Approach

1. Ontology: what exists in the world.
2. Basic ontology in a theory:

   What is postulated in a theory as primary, underlying, autonomous and explanatory, from which all other entities, structures, and their properties and relations can be deduced.
3. The roles of basic ontology: (a) specifying what is to be investigated, (b) dictating the theoretical structures, and (c) directing theory's further evolution thus defining a research program.
4. Popular candidates of basic ontology in QFT

   Processes in SMT

   Mathematical structures in OSR

   Particles and/or fields
5. Two opposing attitudes toward basic ontology in a theory (a theoretical term):

   (a) Instrumentalist: easy and flexible

   (b) Realist: difficult to justify.

II. Ontological Approach

(1) Process ontology:

Chew and Mandelstam: bootstrapping scheme

(2) Structure Ontology:

Redhead’ OSR: Lagrangian/Hamitonian.

(3) Entity ontology

- Particle
- Fields

II. Ontological Approach

(4) Since no process and structure can have free floating existence without being instantiated in entities, they cannot be viewed as ontologically primary. While it is true that entities are always involved in processes, their properties and behaviors patterns can be represented by mathematical structures, they are ontologically primary in the sense that they can be detached from any particular process and particular mathematical representation, while all processes and structures have to be instantiated in entities. So my interpretation of QFT is based on entity ontology

II. Ontological Approach

(5) Redhead's structuralist position has an interesting twist: it heavily relies on: "a complementarity between the specification of a sharp local field amplitude (the field picture) and sharp global quantities representing the total momentum or energy in the field (the particle picture." From this ***ontological indifference between particle and field***, he argues that both fields and particles are merely different representations of the same Lagrangian or Hamiltonian structure and the related equations, neither of them can play the role of the fundamental ontology in QFT, while the mathematical structure (Lagrangian or Hamiltonian) can.

(6) Redhead's ontic SR position rises and falls with the ontological indifference. But in fact, there is a difference.

II. Ontological Approach: Entity Ontology: Particle

Constraint: a candidate should enjoy the same status in all mathematically equivalent formulations (S-matrix formulation, canonical formulation, path-integral formulation)

<A> Particle ontology

The notion of particle in QFT plays extremely important roles, especially in the path-integral formulation

But the path-integral formulation is derivable from the canonical approach based on the field ontology (Weinberg, 1995)

More generally, particle cannot serve as the basic ontology of QFT because of two serious difficulties

(1) It cannot accommodate some important physical content of QFT

(2) It is not well-definable in the mathematical structure of QFT

II. Ontological Approach: Entity Ontology: Particle

(1) It cannot accommodate some important physical content of QFT

-- The vacuum fluctuations and the related renormalization effects and Casimir effect

-- Processes involving the creation and annihilation of particle (and virtual particles)

II. Ontological Approach: Entity Ontology: particle

(2) It is not well-definable in the mathematical structure of QFT

-- The notion of particles is definable (can emerge from) only in the Fock space representation, for free, massive fields in a flat spacetime with the Poicare group as its symmetry group, thus in a curved spacetime or for a massless field, not definable. In the case of interacting fields, the Fock space representation, one among many unitarily inequivalent ones, can only be defined asymptotically, and thus is not generally definable.

-- The famous Unruh effect has shown how a particle detector responds in a given Fock space state depends both on the nature of the detector and its state of motion, and thus has revealed a serious flaw in taking particles as the basic ontology existing independently of our observation.

II. Ontological Approach: Entity Ontology: Field

<B> Field ontology

What is a quantum field?

-- A quantum field is taken to be a dynamical global substratum -- in fact a complicated physical structure with infinite number of degrees of freedom – that is ever fluctuating*, locally excitable**, and quantum in nature***.

II. Ontological Approach: Entity Ontology: Field

<B> Field ontology

* The intrinsic and primitive quantum fluctuations of a field's physical properties over a spacetime reginon is the ontological basis for the copling of physics at different scales, which in turn is a conceptual basis for renormalization group organization of physics

** A field can be locally excited by its intrinsic fluctuation or by external disturbances.

*** Quantum in nature means

(a) that the local excitations of a field obey quantum principles, such as CCRs or C(anti-)CRs and uncertainty relations, and

(b) that their existence and dynamics is probabilistic.

II. Ontological Approach: Entity Ontology: Field

<B> Field ontology

The ontological difference between particle and field can be seen clearly:

--The particles emerge as the quanta of the corresponding field, carrying some of its dynamic properties, as a manifestation and characterization of the excited states of the field in the Fock space representation.

-- The particles are just the possible outcome of conceivable measurement of the field, and thus their contingent existence (meaning creatable and destroyable) and behavior can be empirically investigated and registered, although these do not exhaust the physical content of the field.

-- Thus the concept of particle as a phenomenalogical indicator for the complicated structural features of the ontologically primary field, manifested in carious situations, is an objective though only derivative concept in QFT

III. Ontological Foundations of QFT

In addition to

(1) Quantum fields,

QFT also has

(2) a deeper layer of its foundation, that is, a pregiven background spacetime manifold with a fixed classical chronogeometrical structure*, in which each point has its own identity and thus can serve to index the dynamic degrees of freedom in a field system.

III. Ontological Foundations of QFT

This global but structured background spacetime underlies

(1) A global vacuum state of the field and its excitations.
(2) An infinite number of degrees of freedom of the field, indexed by the spacetime points
(3) The localizability of each and every degree of freedom of the field: thus defined local fields in turn have provided an ontological basis for various kinds of local interactions (local couplings).
(4) The conceptual structure of QFT as it is formulated in Wightman's or Haag's axiom system and more: Poincare invariance, the spectral condition (the vacuum state and mass gap), the causal (light-cone) structure and the quantum structure (CCRs and C[anti-] CRs, uncertainty relations and intrinsic fluctuations controlled thereby, light-cone singularity)

In short, it provids ontological support for both the field and quantum aspects of quantum fields

III. Ontological Foundations of QFT

* A paradigmatic case for such a background manifold is the Makowskian spacetime, which is sufficient for formulating QFT. But it is not necessary. The equivalence principle allows one to extend QFT to non-dynamical curved background manifold (with some restrictions). In cases where gravity is important (but geometries are still static) while quantum gravity is not, such as Hawking radiations (as a limiting case where the initial and final geometries are static [for example, a star before gravitational collapse or a black hole after]), concrete results can be obtained, although in general non-static cases nothing is unproblematic.

IV: Reality of Quantum Fields

I. Structural understanding of entities:

(a) Our conception of an entity is constituted by our knowledge of the structural properties and relations this entity carries in various situations.

(b) Thus the reality of the entity carrying the structural knowledge involving the entity can be inferred from the reality of the structural knowledge (which is empirically accessible), although there is an ambiguity caused by the multiple realizability of structural relations by entities.

II. The reality of quantum fields

The concept of fields is used in two ways:

(a) it is used to produce field equations which describe the relational and structural aspects of these hypothetic entities

(b) it is used to extract the concept of particles, which are the observable manifestations of the same hypothetical entities

IV: Reality of Quantum Fields

II. **The reality of quantum fields**

(c) If the equations and various structural statements (predictions) about the particles are confirmed by empirical investigations, then the reality of the fields is established.

(d) But according to the structural understanding of entities, this claim to reality can only be partial and incomplete, extending only to the structural information that the concept of fields carries with it and has been confirmed so far. That is, the reality of any concept or conceptual structure, quantum fields included, of scientific theories (QFT included) has a historically constitutive character.

(e) This Kantian phenomenal reality should be viewed as a window through which we can have certain access to the noumenal reality, rather than a curtain that separates them.

IV: Reality of Quantum Fields

III The historicity of the reality of quantum fields

The reality of quantum fields constituted by our historically constructed structural knowledge about them, due to its historically constitutive and structurally constructed origin, has a historical character. The true spirit of the historicity of the reality of quantum fields has been revealed most prominently by the development of effective field theories

V. QFT and Metaphysics

Metaphysics: reflections on science, not prescriptions for science.

1. QFT is constrained by the existing metaphysical scheme (conservation laws, etc.) and world's responses to its implications – experimental testings
2. QFT requires revisions in existing metaphysical scheme:

   (a) A new natural kind, quantum field, has to be introduced, which is very different from either particle or field in the old scheme.

   (b) In the case of QCd, the nature of constituents (separable or not) and reality (cognitively accessible in isolation or not) has to be understood differently from traditional ways.

   (c) In the case of the EBH mechanism, which is confirmed recently by the registration of the Higgs boson in CERN, an even newer natural kind is waiting to be introduced into the ontological list in the metaphyscial scheme offered by QFT. Let me explain.

V. QFT and Metaphysics

The EBH Mechanism

Can be properly understood as simply *a set of the scalar field's couplings*:

-- its self-coupling λ responsible for its own broken symmetry solution,

-- its gauge coupling (to the gauge field) g responsible for the broken symmetry solution for the gauge field manifested in massive gauge bosons and

-- its Yukawa couplings η responsible for the broken symmetry solution for spinor fields manifested in massive fermions

V. QFT and Metaphysics

Realism versus instrumentalism

Do the broken symmetry solution of a scalar field and the symmetrical solution of gauge fields exist in the physical world (rather than only in mathematical formulas)?

If yes, then

-- why not observationally- experimentally- empirically accessible in a separate way?

-- why at the experimental ("physical") level, some of them always appear in a redefined (recombined) way (in the unitary gauge) as the massive scalar and vector bosons.

V. QFT and Metaphysics

Instrumentalism

If there is no way to have any experimental access to their *identifiable, separate* existence, then what is the ground for believing in their reality? An *instrumentalist* may thereby deny the reality of the broken symmetry solution of the scalar field and the symmetrical solution of gauge fields, relegating them into the fictitious status of phlogiston and the ether, whose *only function* is to construct the *observable* particles (massive gauge bosons and the Higgs boson) and *measurable* parameters (the weak scale and masses, whose ratios are the relevant couplings), which, according to *the positivist-instrumentalist philosophy*, are *the only reality* in the physical world

V. QFT and Metaphysics

A Realist Response:

Ontological assumption: What exists in reality is *a scalar-vector symbiont (the schwinger-Goldstone symbiont)*, a new primary entity which possesses broken symmetry solutions for its scalar and vector moments, rather than a set of scalar and vector fields.

The *physical foundation* for the EBH mechanism is this *ontologically primary symbiont* -- whose internal dynamics explains the EBH mechanism – rather than *a primary scalar field and its set of couplings (as we previously summarized)*.

V. QFT and Metaphysics

The Schwinger-Goldstone Symbiont

A physically non-decomposable primary entity: the scalar-vector symbiont describable by an analytically separable mathematical structure. Yet,

No mathematical separation of the two moments of the symbiont would have any physical meaning.

V. QFT and Metaphysics

The Schwinger-Goldstone Symbiont

1. The holistic structure of the symbiont is different from, e.g., the structure of a coupled system, (1) whose components (say, electron and photon) in the gauge-less limit can exist separately, and (2) there is no way for the symbiont's components to be recombined in different ways to produce differently structured moment systems, while differently structured component-field systems is possible for a coupled field system.

2. The two moments are dynamically identifiable: each moment has its own *dynamical identity*, namely its *characteristic ways of coupling* to other systems without being affected by those of the other moment.

V. QFT and Metaphysics

A spacetime analogy: a symbiont with two moments

Hermann Minkowski declared:

"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality." "Die grundgleichungen fur die elektromagnetischen vorguge in bewegten korper,"*Goett. Nachr,* (1908): 53-111.

Similarly, we may say: Goldstone's scalar system and Glashow's gauge system are doomed to fade away into mere shadows, and only the symbiotic scalar-vector complex is the non-decomposable independent physical entity in the EW part of the physical world, aside from the fermion system.

V. QFT and Metaphysics

Conceptual difference between the scalar and vector moments:

In the case of spacetime, conceptually, the spatial aspect is different from the temporal aspect, even though the only reality is spacetime.

Similarly, the scalar moment is different from the vector moment of the scalar-vector symbiont, although they are just different manifestations of a single physical entity, having no separate existence.

V. QFT and Metaphysics

Uncertainty in the Ontological Status of the EBH Mechanism

Two puzzles:

A. The transmutation of the identity of the massless modes of the scalar moment.

B. The Fixity in the internal organization of the Symbiont

V. QFT and Metaphysics

Puzzle A: The transmutation of the identity

Weinberg: Through the redefinition, "the Goldstone bosons [here he refers to "fictitious GBs] have no physical coupling." By "physical coupling," surely he meant only *experimentally accessible* coupling, not all its dynamical interactions with other degrees of freedom at experimentally **inaccessible** level.

The massless modes do not disappear through redefinition; they are only to be reorganized into vector moment, being their longitudinal components. Thus, their dynamical capability does not disappear, only gets reappeared in different incarnations.

Thus *the mystery of the transmutation of the dynamical identity of the massless modes of the scalar* moment*:* In their interactions with another mode of the scalar moment, and with fermions, their *original self-coupling and Yukawa coupling have been transmuted into the gauge coupling through the reorganization,* which renders them to be the longitudinal components of the massive bosons.

Puzzle B: The Fixity in the internal organization of the Symbiont

A disanalogy with the spacetime symbiont:

In the spacetime symbiont

The reorganization of its spatial and temporal moments is driven by a relative velocity between two reference frames.

The reorganization through the Lorentz transformations is flexible and variable, depending on the variable velocity involved, and can result in various different configurations of spatial and temporal moments.

In the Schwinger-Goldstone symbiont

No physical ground for flexibility and variability, [similar to the Lorentz transformation in the ST symbioant], has been explored. In fact, there is a rigid fixity in the internal organization of the Symbiont.

If the fixity cannot be dissolved, the symbiont can be nothing but a mental device, and the symbiont-based EBH mechanism threatens to be an *ad hoc* device for obtaining the observable particles and measurable parameters, and thus cannot be taken realistically.

V. QFT and Metaphysics

An impasse?

(1) Instrumentalism is not acceptable: It implies reducing Weinberg's model to Glashow's, in which the put-in masse of gauge bosons destroy GI and thus the renormalizability.

(2) The theory must be GI to ensure the renormalizability; but the gauge bosons must be massive to account the weak interactions. Thus a realist EBH mechanism is imperative.

(3) Realism of the EBH mechanism based on separate existence of a Goldstone sector and a gauge sector has no chance to be true.

(4) Realism of the EBH mechanism based on the reality of the tentative notion of a Goldstone-Schwinger symbiont has two seemingly indissoluble puzzles

How to proceed and get out of the impasse? I don't know. But,

V. QFT and Metaphysics

The above discussions strongly suggest that

(1) a new natural kind, a scalar-vector symbiont, has to be introduced into the ontological list offered by QFT.

(2) But the nature of the symbiont, especially its ontological status, elementary or not, requires further investigations. The difficulty lies in the following dilemma:

According to the traditional understanding of the world picture offered by QFT, what is elementary is what appears in the Lagrangian, but

(a) we cannot assign an elementary status to the symbiont since what appear in the Lagrangian is not the symbiont, but its moments,

(b) We also cannot assign the moments an elementary status, since this would deprive the symbiont of its primary status in the realist understanding of the EBH mechanism, and we will have to face instrumentalist's devastating attacks again.

So I think this is a fascinating research topic for metaphysical investigations of QFT.

Thank you !