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STRUCTURAL REALISM AND THE INTERPRETATION OF QUANTUM FIELD THEORY[1]

1. MOTIVATION

When I started working on the history and philosophy of science at Cambridge, under the guidance of Mary Hesse and Michael Redhead, my major concern was with Kuhn's revolutionary view of the history of science. In particular, I tried to address Kuhn's claim that "I can see no coherent direction of ontological development" in the history of science (Kuhn, 1970). If Kuhn was right, then in our conception of the history of science, there would be no room for cognitive progress, in the sense of the accumulation of our objective knowledge of what exists and happens in the world, although a kind of instrumental progress, in terms of our ability to solve puzzles, would still be imaginable. The anti-realist implication of Kuhn's view can be best seen through Hilary Putnam's meta-induction thesis: if no theory in the history can be taken as true from the viewpoint of later theories, then there is no reason to believe that our present theories would enjoy any privilege over their predecessors.[2]

In order to address Kuhn's claim, or more generally to develop a realist conception of science and a cognitively progressive conception of history of science, a mere appeal to formal logic or empiricism is not of great help. According to Carnap (1950, 1956), formal logic is unable to address what he calls the external questions that are related to radical changes of conceptual framework. And it is a truism that empiricism has no theoretical resource to deal with the underdetermination thesis, which challenges the status of empirical evidence as a bridge connecting theoretical entities and physical reality. Taking the history of 20th century physics as an example, what was required, it seemed to me, was a conceptual analysis of its theoretical structures and their evolution, which aimed at a clarification of what the basic ontology is for the discipline and its replacement. Then, with a structural understanding of ontology and a realist understanding of structural knowledge, we would be able to, first, make a realist claim that

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we could have objective knowledge of even the non-observable ontology; second, understand the radical changes of ontology in the development of science in terms of the accumulation and reconfiguration of recognizable, cumulative and modifiable structural statements that are constitutive of our conception of an ontology; and third, recognize a pattern in some cluster of scientific revolutions in terms of ontological synthesis. (Cao, 1997).

2. THE CENTRAL PLACE OF ONTOLOGY IN SCIENCE

It is characteristic of anti-realists to reject the concept of ontology in their analysis of science. I have just mentioned Kuhn's denial of the coherent direction of ontological development in the history of science. Bas van Fraassen (1997), among other modest anti-realists, such as some advocates and followers of the semantic approach to science or certain versions of structuralism, who reject or take an agnostic attitude toward the existence of non-observable ontology, claims that different ontologies make no difference to science.

But if we look at the history of science closely, we will find it undeniable that the concept of ontology occupies a central place in science: a clear ontological commitment of a scientific theory tells us what the basic existence is in the domain that is investigated by the theory. Moreover, this ontological commitment is not a pregiven prejudice, which can be chosen at will. Rather, in normal cases, it emerges, often quite unexpectedly, from scientific endeavor. We may make an even stronger claim that it is forced upon us by the internal logic of scientific investigations. Let us look at quantum field theory as an example for illustration.

As a theory of interactions, which are supposed to be realized through the exchange of quanta, real as well as virtual, quantum field theory takes the violently fluctuating vacuum field as its basic ontology,[3] whose excitations result in real and virtual quanta, subject to various conservation laws and the uncertainty relations. But quantum field theory did not make this ontological commitment until the mid-1930s, a decade after its birth, and the commitment did not take a firm hold in the community until the late 1940s when the success of renormalization and the implications of the Casimir effect were assimilated into the conceptual structure of quantum field theory.[4]

At the early stage of quantum field theory, in Jordan's work from 1925 to 1928, or Dirac's work on radiation in 1927, or in Pauli and Heisenberg's work of 1929, the major endeavor was to actively quantize a classical field, either the substantial classical electromagnetic field, or a fermion wave function which was unjustifiably taken as a classical entity. No attention was paid to the vacuum. An exception was Dirac's picture of the vacuum as the infinite sea of negative energy electrons. However, it was introduced in 1928, not in the context of quantum field theory, but of his relativistic theory of the electron. It was not necessary in the conceptual structure of quantum field theory, and was soon abandoned by Oppenheimer and Furry, Pauli and Weisskopf in 1934, and subsequently by many active players in quantum field theory, from Wentzel to Schwinger to Weinberg.

An important development was brought out in 1932-33 by Heisenberg in his work on the compound model of the neutron, in which he developed the idea that the nuclear force consisted in the exchange of pseudo electrons. The idea was taken over and further developed by Majorana. Then a crucial step was taken by Fermi in his work on the beta decay of 1933, in which interactions were conceptualized, not in terms of the exchange of existing particles, but in terms of the couplings of fields, or the creation and annihilation of the relevant quanta at the interacting point. The tacitly assumed conceptual foundation of Fermi's theory was the vacuum fluctuations, which under certain constraints result in the creations and annihilation of real and virtual quanta. A crucial step in laying down this foundation was taken by Niels Bohr and Leon Rosenfeld in 1933 when they investigated the measurability of the field, which brought the idea of field fluctuations into the physics community. This, combined with Heisenberg's uncertainty relations, paved the way for the idea of local fluctuations of the field, no matter it is in the vacuum state or in excited states.

But local fluctuations, according to the uncertainty relations, entail the divergence difficulty, which reveals the inconsistency of quantum field theory. Thus in the 1930s and 1940s no firm ontological commitment was made by physicists, and quantum field theory was in a dubious status. However, there was no other framework for dealing with electrodynamics in the atomic world. Thus intensive investigations were still conducted by many physicists, such as Weisskopf, Kramers, Stueckelberg and Dancoff in the 1930s and Bethe, Lewis, Tomonaga, Schwinger, Feynman and Dyson in the 1940s, to find a way out of this difficulty. The result was, as Schwinger, among many others, argued convincingly that the concept of a fluctuating vacuum seemed to be a viable one if it was combined with the renormalization scheme developed in the late 1940s. More positively, the Casimir effect discovered in 1948 suggested that the fluctuating vacuum even had an observable effect.[5] Only then, that is only at the end of 1940s, a firm ontological commitment to the fluctuating vacuum was made which signaled the maturity of the discipline.

It is not very difficult to show (Cao 1997), although I will not do it here, that an ontological commitment made in a scientific discipline, also dictates its theoretical structure and the direction of its evolution. Even the very idea of a scientific revolution, or a radical shift in perspective, can be characterized as a change of ontological commitment.

Then what is meant in my discussion when I use the word "ontology" or "the basic ontology" in a scientific theory? Generally speaking, ontology refers to what exists in the world. And the basic ontology of a scientific theory refers to the irreducible conceptual element in the logical construction of what is assumed to really exist in the domain under investigation. In contrast with appearance, and also opposed to mere heuristic and conventional devices in a theory, the concept of the basic ontology is concerned with a real and autonomous existence. Although the basic ontology of a theory may be interrelated with other primary existence, its existence is not dependent on anything external to it. As a representation of deep reality, the basic ontology enjoys a great explanatory power. That is, all appearances can be derived from it as a result of its behavior.

Then what is, or should be, the exact metaphysical nature of an ontology in a science? It can be individuals, such as mass points in Newtonian mechanics, or non-individual entities, such as quantum objects; it can also be some non-entities, such as processes, e.g., currents or transition amplitudes in particle physics, or some patterns or structures of processes, e.g., current algebra structures and Regge pole structures. The exact nature of the basic theoretical ontology is an empirical question; what is important in the realism–anti-realism debate is its existential status and its causal efficacy in producing all the derivative entities, appearances and epiphenomena the theory is dealing with.

It is obvious that the notion of the basic ontology has a reductive connotation. Ontological emergence notwithstanding, reductive pursuit within a specific domain (without which no theoretical science would be possible) is highly desirable and productive. In this reductive pursuit, the assumption about the basic ontology plays a crucial role. It is also discernible that in my structural approach to ontology, there is a tension between the reductive analysis of science based on the idea of ontology, and the holistic and phenomenological understanding of science, which characterizes many versions of the structuralist approach.

3. STRUCTURE AND ITS CONSTITUENTS

In order to address this tension, let us start with the notion of structure. A structure is a stable system of relations among a set of constituents. Typically, although not necessarily, in the discussion of basic theoretical ontology in physics, the non-observable constituents are assumed to be entities, with or without individuality, depending on particular situations. Of course, a physical structure, such as a molecule, itself can be taken as an entity. What interests us here, however, is not the entity at this level, which is observable (in physicists' sense, not in constructive empiricists' sense) and is called by many philosophers just as a structure, but the entity at the constituent level, or the basic ontology.

Concerning the relationship between a structure and its constituents, theoretically there are two options. We can take a structure as a primary existence, ontologically subsistent, characterized by some invariance, and its constituents only as place-holders. Or we can take a structure as a structure of its constituents, supported or realized by its constituents, and characterized by its structuring laws, which govern the behavior of the constituents and hold them together to be a structure.

If we take the first position, then the meaning of the constituents should be understood as being constituted by the structure. According to this holistic conception of structure, the assumption of the non-observable entity can only play a heuristic role in allowing the introduction of the structure. It is interesting to note that this metaphysical position concerning the parts-whole relationship was actually taken by some prominent physicists as the conceptual foundation of their methodology. For example, Murry Gell-Mann (1964), when he first introduced the idea of quarks, took the idea of quarks only as a conceptual device for generating the observable structures, namely the currents in physical processes, which would obey the structural relations of his current algebra. The epistemological implication of this methodology was that we should be content with the investigations about the currents, and should not cherish the unreasonable ambition of exploring deeper into the very existence of quarks and their behavior.

If we take the second position, however, then the structure should be taken as being constructed from, and understandable only in terms of, ontologically primary constituents. According to this componential conception of the structure, the structure may enjoy some epistemic primacy because it has provided us with epistemic access to the non-observable constituents. Ontologically, however, it enjoys only a derivative existence. It is interesting to note that this metaphysical position was taken by many particle physicists in the 1960s as the conceptual foundation of their methodology. Guided by this understanding of structure, these physicists tried to understand the behavior of the currents by investigating the properties and dynamics of their quark constituents. This led to the resurgence of quantum field theory as the major theoretical resource in particle physics in the late 1960s, first initiated by Steven Adler in his field theoretical investigations of currents, which resulted in one of a few of the most profound and most consequential discoveries in the history of 20th century physics, namely, the anomalous breakdown of symmetry.[6]

The typical, and also the philosophically interesting, case in the discussion of the structure-constituents relationship, is the case in which the structure is observable but the constituents are not. In this case we still have some knowledge about the non-observable constituents. But then, as widely recognized, this knowledge is structural in nature.[7] Or more precisely, we may have some relational knowledge concerning the places the constituents occupy and the functions they play in the structure, but we can never have precise knowledge about their intrinsic properties. Or, can we?

Here is the place where controversy looms large. According to Immanuel Kant (1783), although "the object in itself always remains unknown, but when, by the concepts of the understanding, the connection of the representations of the object, which are given by the object to our sensibility, is determined as universally valid, the object is determined by this relation, and the judgement is objective". Many realists believe that with the improvement of our experimental tools and methods, most if not all non-observables will sooner or later turn to be observables. But there are many pessimists who argue that while our structural knowledge is reliable and objective, these structural statements can be interpreted with many different ontologies, which may have conflicting intrinsic properties; thus we can never have knowledge about the underlying constituents, which often function in a scientific theory as its basic ontology, with any certainty. This multiple realizability of a structure by its supporting elements, together with the related but differently inspired underdetermination thesis, have posed a formidable challenge to the realist regarding non-observable theoretical entities: can we find a unique way to pick up, from our structural knowledge about the non-observable elements, a set of such elements that underlie the structure? Perhaps it is the almost impossibility to meet this challenge that has prompted the contemporary interest in structuralism. But before moving into the discussion of structuralism, I wish to dispel some confusion. This, it seems to me, may be of some help in the discussion.

Some scholars argue that there is nothing (e.g., an entity at the constituent level, with respect to a structure in which it is involved, with some intrinsic properties, or an ontology) that is over and above the structural relations, that is mathematically expressible and empirically accessible. According to them, the word ontology is only a metaphor of our language; its real content does not go beyond the structural constraints. For example, Steven French asks: what are quantum objects except for the structural constraints such as commutation relations? What are bosons and fermions except for the constraints posed by the permutation group? More affirmatively, he claims with confidence that the reality of spacetime lies only in its geometric structure without being supervenient on the existence of underlying points. (Private correspondence).

The last claim is supported by Einstein's so-called point coincidence argument against his own hole argument, and seems difficult to reject. Here, the ontological primacy of the spacetime structure over its supporting elements (physical events) as place-holders is indisputable. But even in this case, a purely mathematical understanding of the spacetime structure, in the sense that it has no ontological underpinning in terms of physical entities, is undermined by the fact that the geometric structure of spacetime itself is constituted, not by the underlying spacetime points, but by another physical entity, namely the metric or gravitational field, through its universal couplings to all other physical entities. As to the bosons and fermions, their properties such as mass, spin, charge, etc. are expressible in terms of relevant groups; but to identify a physical entity with the sum of its group-theoretical, or more generally mathematical, or even more generally structural properties, which I shall call the Identity Thesis, is a big mistake for the following reasons.

First, as a physical entity, a boson or a fermion has its own intrinsic and measurable properties: the rest mass, charge, spin and others. Although these properties can be defined in mathematical terms, the mathematical structure, as a structure of relational statements, is neutral to the nature of relata and thus cannot exhaust the content of the relata. For example, classical mechanics and quantum mechanics share many mathematical structures, and thus these structures can tell us nothing about the classical or quantum nature of the physical entities under investigation. A permutation group can tell a boson from a fermion, but it cannot tell the difference between a scalar and a vector. Of course, we can use further mathematical means to pin down subtle differences, and this may be the only way to go. Still, we are facing two philosophical options: either we can dissolve a physical entity into a net of mathematical relations, as Howard Stein (1989) and other mathematics-oriented structuralists or Platonists would try to do; or we can take a net of more and more refined mathematical relations as a means to know the physical entity, as realists would surely try to do. I am in favor of the latter option.

Second, the Identity Thesis entails that we have to change our conception of an entity or ontology all the time whenever there is a change of its mathematical description or our structural knowledge of it. Then, considering the central place of ontology in science, together with the fact that our structural knowledge is subject to constant change (accumulation and modifications), we would have to deal with constant or permanent revolutions in science. This is of course absurd.

In this regard, perhaps we have to come back to the very old idea of essential properties of an entity. That is, an entity is defined by its essential properties, not by the total sum of its properties and relations. Otherwise we would not be able to conceptualize the world in terms of conceptually stable entities. Of course, our conception of an entity or ontology is subject to change because what should be taken as an essential property changes with the change of our theory, or more precisely with the expansion and reconfiguration of our structural knowledge of the entity and other entities in the domain under investigation, which may result in the change of the ontological status (primary or derivative) of the entity; that is, result in a conceptual revolution. But this is quite different from the idea of permanent revolutions in science.

A consequence of rejecting the Identity Thesis is that we have to distinguish clearly between a mathematical structure, which is always a purely relational existence, and a physical structure, which, in the case of a substantial structure, can be described by a set of structural statements (most of them are mathematical) about its constituents and their structuring, and thus itself exists as a physical entity; or, in the case of a purely relational structure, such as the spacetime structure, can be shown to be constituted by physical entities (e.g., metric tensors), or, more precisely, can be described by a set of structural statements about relations between physical events, which are constituted by physical entities and dictated by their universal interactions with all physical entities. In my version of structural realism, the appeal is restricted to the structural knowledge of non-observable entities, which is different from mathematical structures, the favorite subject of Bas van Fraassen or Steven French, and also different from the structure of a theory as a whole, as advocated by Sneed (1979) and Stegmuller (1979). In my opinion, it is only the structural knowledge of the non-observable entities, but not mathematical structures themselves (groups, etc.) or the structure of a theory as a whole, that can give us epistemic access to non-observable entities, and to the basic ontology of scientific theories in particular. This is of crucial importance to ontological realism and to the realist conceptualization of the history of science, according to which the history of science proceeds in the form of accumulation that is interrupted by disruptive changes in the form of ontological synthesis, which itself, however, is only another form of progressive accumulation.

4. STRUCTURAL REALISM

Structuralism as an influential intellectual movement of the 20th century has been advocated by Ernst Cassirer, Bertrand Russell, Rudolf Carnap, Nicholas Bourbaki, Noam Chomsky, Talcott Parsons, Claude Leve-Strauss, Jean Piaget, Louis Althusser and Bas van Fraassen, among many others, and developed in various disciplines such as linguistics, mathematics, psychology, anthropology, sociology and philosophy. As a method of inquiry, it takes a structure as a whole rather than its elements as the only legitimate subject for investigations. Here, a structure is defined either as a system of stable relations among a set of elements (such as a physical structure of an atom), or as a self-regulated whole under transformations (such as a mathematical structure of a group), depending on the special subject under consideration. The structuralist maintains that the character or even the reality of a whole is mainly determined by its structuring laws, and cannot be reduced to its parts; rather, the existence and essence of a part in the whole can only be defined through its place in the whole and its relations with other parts.

In the epistemically interesting cases involving non-observable entities, the structuralist usually argues that it is only the structure and the structural relations of its elements, rather than the elements themselves, that are empirically accessible to us. It is obvious that such an anti-reductionist holistic stance has lent some support to phenomenalism. However, as an effort to combat compartmentalization, an urge that is particularly strong in mathematics, linguistics and anthropology, the structuralist also tries to uncover the unity among various appearances through isomorphism, in addition to invariance or stable correlation under transformations, which can help discover the deep reality embodied in deep structures. Furthermore, if we accept the attribution of reality to structures, then the anti-realist implications of the underdetermination thesis is somewhat neutralized, because then we can talk about the realism of structures, or the reality of the structural features of entities exhibited in evidence, although we cannot directly talk about the reality of the entities themselves that support the structural relations. In fact, this realist implication of structuralism was one of the starting points of contemporary interests in structural realism.

The aim of structural realism in the history and philosophy of science, as John Worrall (1989) conceives it, against the general background of the Kuhnian view of ontological discontinuity in scientific development, is to address inter-theoretical relations directly in terms of mathematical structures, rather than physical structures, without any physical entity or ontology as a medium. The realist urge of this position is manifested in the attempt to establish a cognitive continuity in scientific development through a referential continuity or correspondence between mathematical structures used by physical theories at different historical stages, such as those used by Newton and Einstein. The holistic spirit of this version of structuralism is most clearly exhibited in the semantic approach, which, according to Bas van Fraassen (1997), is the current form of the general idea of structuralism. This approach, adopted and developed here in the United Kingdom by Steven French and his collaborators, uses the idea of isomorphism or partial isomorphism to address the semantic relationship between the mathematical structure of a theory and the structure of the data model of the physical system under investigation, and to address the inter-theoretical relationship exclusively in terms of its mathematical structures.

In the materials kindly sent to me by Steven French and James Ladyman just before I came here, they claim that there are two versions of structural realism, a metaphysical or ontic version, which they prefer, and an epistemological one, which they are not happy with. According to the ontic version, the world consists of relations and structures only, and thus there is no sense at all in talking about entity ontology or object ontology, at least in the world described by modern physics. This metaphysical view of the world justifies the representational role of a mathematical structure, which, as an extra-linguistic entity, is what a physical theory is all about, and can bear a partial isomorphism relationship with the structure of the world.

As I have just shown with the example of Gell-Mann's ideas about current algebra and quarks, however, this metaphysical structuralism underlies a methodological holism, and thus has an unproductive implication of giving up exploring deeper than the level of structures available to us now. This unproductive implication of the holistic approach explains the decline of S-matrix theory, which focused exclusively on the analytic structure of the overall amplitudes of hadronic physical processes. Just as the other side of the same coin, the different methodological merits of metaphysical holism versus componential analysis also explain the resurgence of quantum field theory, which paid closer attention to quark dynamics in the same processes, in the late 1960s when the theoretical and experimental conditions were ready for the exploration of quark level physics (Cao 1997), and why physicists usually prefer entity-based models for exploring new features and ideas, such as gauge invariance and supersymmetry. This exploration would be impossible if they simply stared at the existing mathematical structures.

But Ladyman (1998) complains that most structural realists still stick to the epistemological version: they accept the existence of non-observable entities and take the structural nature of our knowledge of them only as an epistemic constraint. This is not acceptable, Ladyman argues, because if we take the structural as purely formal, as in the original case of Russell's structural realism (Russell 1927) which was rightly criticized by Newman (1928), then there would be no empirical content; or if we try to incorporate empirical content by adopting the Ramsey sentence approach (Maxwell 1970), then it will collapse into a version of phenomenalism.

Another possibility opened up by epistemic structural realism that would lead back to traditional realism on the basis of a sructuralist conception of non-observable entities, is dismissed by Ladyman as "quite misleading" for two reasons: first, the underdetermination of an entity by its structural relations; and second, the impossibility of determining the fundamental ontological characteristics and metaphysical status (such as being individuals or not) of the ever-hidden entities. It is not obvious, at least to me, however, why these two reasons are sufficient to dismiss the claim that we may have reliable, though incomplete, fallible and thus historically revisable, knowledge of non- observable entities. Arguably the claim is tenable because, first, the knowledge of hypothetical entities constructed from our structural knowledge about these entities is itself reliable, although with the reconfiguration of our structural knowledge, it has to be revised accordingly. Second, as I mentioned above, the question concerning the exact nature and metaphysical characteristics (such as with or without entanglement) of the hidden entity can only be answered empirically. But whatever the answer is, it has nothing to do with the existential status of the entity and our ability to know many of its other properties, such as mass, spin, charge, etc., which are enough to specify the entity as such. I will discuss the underdetermination thesis shortly.

The ontic version of structural realism is attractive to some people for two reasons. First, it has bypassed the underdetermination thesis by dismissing the very existence of non-observable entities, which, if they existed, were assumed to be underdetermined by structural relations. Second, it has provided a new ground of arguing for the continuity and progressiveness of scientific development. If the very idea of entity ontology is taken as only a metaphor of our language or a heuristic device for the introduction of structures, the ontological discontinuity that appeared in the scientific development can be easily dismissed as irrelevant; and it is not too difficult to argue for continuity in terms of mathematical structures. But the price for this success is to give up the very idea of having an entity ontology, or to call mathematical structures an ontology while dismissing the possibility of having non-observable physical entities as the basic ontology of scientific theories to ground their conceptual structures. Since the idea of ontology, as I have argued earlier, occupies a central place in science, this is not a small price to pay, certainly not a trivial one, and thus deserves serious discussion.

An interesting question concerns the way in which the structuralists give empirical content to their structure. Since this was argued by Newman (1928) to be impossible in the formal logical version of structuralism, the Kuhnian anti-realists Joseph Sneed (1971) and Wolfgang Stegmuller (1979) adopted an informal set-theoretical approach, in which structure referred to the structure of the whole theory, which includes mathematical formalism, models, intended applications and pragmatics, and thus has plenty of room for empirical content. But what this meaning-holism based structuralism lends support to is not scientific realism and the related conception of continuous scientific development, but Kuhnian anti-realism and the disruptive view of scientific development. For French and his realist friends, the notion of structure has been narrowed down to mathematical structures only, and the empirical content is smuggled into structural knowledge through data models, the structure of which is targeted by the mathematical structure of the theory.

When I look at Bas van Fraassen (1997), the situation is quite interesting. On the one hand, he claims that no ontological interpretation of structure would be possible. If you insist on doing it anyway, then different ontological interpretations would make no difference to science. In this way he complies with the holistic stance of structuralism, in which the empirical content lies in general correspondence at the structural level without reference to the non-observable entities. On the other hand, he tries to go beyond structures and reach the level of entity by appealing to the pragmatics of our actual language in use, with a not so effective reservation (which says that the perspective of our language is only one among many perspectives, the privilege of our language in use is historically conditioned and contingent, it bestows no security and no guarantee of empirical adequacy, and thus cannot function as the foundation of science and of knowledge in general). But within the framework of our language in use, van Fraassen is perfectly willing to talk about the truth of our knowledge about unobservable entities in the sense of correspondence with facts. For example, he claims that " 'Electrons always have a precise position' is true if and only if electrons always have a precise position".

Thus one way or the other, in order for mathematical structures to have empirical content, they have to be interpreted by a language in a specified domain, either directly by means of semantic postulates to specify the meaning of their components, or by means of the pragmatics of our actual language in use; or indirectly through the introduction of data models. But once language enters, the old troubles of incommensurability and underdetermination come back again. Are different languages commensurable? Can we pick up entities satisfying the structural constraints in a unique way? The two difficulties are closely interrelated. If we can find a unique and universal language, from which all theoretical languages for scientific discourses can be constructed and to which all theoretical languages can be reduced, then both difficulties can be solved in principle.

The question now is whether we can argue, in a philosophically acceptable way, for such a universal language, or even actually find such a language. Van Fraassen flirted with the idea of our language in use, but shied away from taking it as the unique and universal language. But I would argue that if we accept that, first, our linguistic and representational intelligence has its roots in the prelinguistic sensori-motor intelligence, namely continuous relating which is related with logic, setting up of correspondences, which is related with the sense of objectivity, and establishing functional connections, which is related with the sense of causality; and second, the source of prelinguistic intelligence is the process of assimilation (which is common to all human beings, and by which we fit our environment to the requirements of our physico-chemical structures while at the same time we accommodate ourselves to it), and this process is regulated by equilibration dictated by biological necessity, then we will also have to accept that biologically salient features of the world are somewhat translated into a natural hierarchy of our perceptions and thus of our language, concepts and logic. That is, we will have to assume that all human beings are genetically endowed with the same perceptual and conceptual predispositions for biological reasons, which have provided us with a universal, or human species-wide, deep structure for our language in use or for our daily discourse language.

Of course, it is incontestable that in addition to the biologically given hierarchy of perceptual and conceptual saliency there is a cultural saliency that may radically change the biological hierarchy. But cultural relativity cannot even be expressed without a biological universality: each culture cannot arbitrarily structure the world in a way so its members can find meaning and value; rather, it can only make a very constrained set of choices within a universal and deeply structured system of similarities and distinctions of the world, which the human species is naturally but not socially heir to in its normal maturation. That is, we cannot genuinely understand cultural interventions except within the context of a universal natural human endowment; its linguistic manifestation is the universal language of daily discourse.

If the above argument for a universal language is acceptable, then a non-agnostic version of epistemic structural realism is tenable. The structural nature of this position lies only in its claim that our knowledge of non-observable underlying entities in science is mainly constructed and frequently reconstructed through our structural knowledge of these entities.

Thus if we take structural realism in general as a position between instrumentalism and traditional realism, then my version of structural realism is a position between other versions of structural realism and traditional realism. That is, first, I take structural knowledge as an epistemic access to non-observable entities. Thus, in contrast with the agnostic attitude toward non-observable entities, I claim that both the reality of entities and the objective knowledge of them are warranted by our objective knowledge of the structure and structural relations involving these entities. On the other hand, I also accept that this may be the only warranty. This means that the door to any direct access to non-observable entities may be closed, and any conception of entities has to be constructed and reconstructed by using our ever-increasing structural knowledge. Second, the construction of non-observable entities through our structural knowledge, although reliable, is fallible and subject to revisions. Thus, the attainment of objective knowledge at the level of underlying ontology can only be realized through a historical process of negotiation among empirical investigators, theoretical reasoners and metaphysical interpreters. When should the process come to an end for a particular science? This is an empirical question and cannot be answered a priori.

5. THE INTERPRETATION OF QUANTUM FIELD THEORY

For a metaphysical realist, the primary task of interpreting quantum field theory, or any other fundamental mathematical physics for that matter, is to clarify the meaning of its mathematical formalism: what is the basic entity in the causally organized hierarchy of entities it describes, and what is the relationship of these entities with physical reality. Of course, no realist would take every element of a formalism as having a correspondent in reality. For example, it is very difficult to take the wave functions in non-relativistic quantum mechanics as real waves, or to take interpolating fields in quantum field theory as real fields. Some elements of a mathematical structure are representational; others are just conceptual devices or conventions. Within the representational part, we have to distinguish the ontologically primary entity or entities (the basic ontology) from those that are derivative (epiphenomena), and try to read a metaphysical structure of the world from the conceptual structure of the theory. Or we may go the other way around, try to construct and readjust the conceptual structure of the theory by consulting the entrenched metaphysical picture of the world.

But for Steven French and his fellow structuralists, who have reduced physical theories to their mathematical structures, no interpretation in terms of physical entities would be possible, or even desirable. Thus, for them, wave mechanics and matrix mechanics are just different representations of the same structure, quantum mechanics. Or, in the context of quantum field theory, they claim that particles or fields are merely different representations of the same Lagrangian or Hamiltonian structure and the related equations. You can take a particle ontology, or a field ontology if you like, this difference will make no cognitive difference to the physics physicists are doing, although a different degree of convenience may be involved. In the same spirit, we may claim that both quantized gauge field theory and the general theory of relativity are just different representations of the same mathematical structure, the fiber bundle.

This way of reasoning may seem attractive to some worshipers of mathematics. But, as the last example has shown, it is not very informative. In particular, the ontological difference, which underlies a conceptual revolution separating classical from quantum field theory, becomes invisible in this kind of structural reasoning. Then if we try to reconstruct the revolution, the existence of which is an undeniable fact, we have to find other conceptual resources than the notion of mathematical structure. And a suitable candidate for this purpose is, obviously, the notion of the basic ontology of a theory. The difficulty that comes with this notion is the ontological replacement, which is also an undeniable fact in the history of science, and thus the discontinuity of the history of science. This difficulty, however, can be addressed by the idea of ontological synthesis (see Cao 1997), but this is not the topic for today.

Come back to quantum field theory. Can we really talk about field-particle duality or complementarity? From a structuralist point of view, we can. As Michael Redhead (1999) indicated, there is "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)".

But this ontological indifference can be challenged, in two ways, by ontological realists. There are arguments for taking particles rather than fields as the basic ontology of quantum field theory, although mathematically the field has to be taken as the primary construction from which the concept of particles can be extracted. A strong case can be made that empirically only particles are observed, and fields, except for the classical fields, are not observable. This suggests relegating the concept of the field to the status of convention, a device for generating particles and mediating their interactions. The case becomes stronger when physicists realize that from the viewpoint of particle interactions, as the theory of collision suggests, what matters are the asymptotic states of particles, but not the interpolating fields. As Borchers 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 algebraic quantum field theory were only allowed to have a function similar to that of coordinates for the local algebra of observables. (See Haag (1992)).

The difficulty with the particle interpretation is twofold. Empirically, the physical content of quantum field theory is not exhausted by the notion of particles. Here I am referring to various effects related with the fluctuations of the vacuum, such as renormalization effects and the Casimir effect. Also, as I have shown in other places (e.g., Cao 1999), the very idea of virtual particles and the idea of creation and annihilation of real particles, which are crucial for understanding the physical content of quantum field theory, cannot be accommodated within the particle ontology framework.

Theoretically, in the mathematical structure of quantum field theory, the concept of particles is not well definable. Within and only within the Fock space representation, the notion of particles can emerge from that of the field, as its quanta associated with its excited states. But the Fock space representation can only be defined for free massive fields in a flat space-time with the Poicare group as its symmetry group. Thus in a curved space-time or for a massless field, the notion of particles is not definable. More seriously, in the case of interacting fields, there are many unitarily inequivalent representations, among which only one equivalence class involves the Fock space representation. The latter, however, can only be defined asymptotically, and thus is not generally definable. Even within the Fock space representation of free fields, sometimes the notion of particles as quanta is difficult to define. As is well known, a uniformly accelerating observer in a flat space-time feels himself to be immersed in a thermal bath of particles when the quantum field is in its vacuum state. This famous Unruh effect has shown that 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.

If we take the operator formalism seriously, then the basic ontology of quantum field theory seemed to be the quantum field, from which the particles emerge as its quanta, as a manifestation and characterization of the excited states of the field. The quanta, carrying some dynamical properties of the field, as manifestations of the field in the Fock space representation, cannot be taken as equivalent to the field, nor can they be thought of as being possessed by the field. Rather, they are just the possible outcome of conceivable measurement of the field, and their contingent existence and behavior can be empirically investigated and registered, although these do not exhaust the physical content of the field. Thus the concept of particles as a phenomenological indicator for the complicated structural features of the primary field, manifested in various situations, is an objective though only derivative concept in quantum field theory.

Having established the conceptual primacy of the field over the particle, we can turn to the second step and argue for the reality of the concept of fields, or to explain in what sense and to what extent this mental construction can be taken as an objective representation of the physical reality. This is not a trivial task. In fact, the algebraic quantum field theorist Rudolf Haag (1992) in recent years has raised an argument against the realist interpretation of the concept of fields.

According to Haag, the role of fields as a convenient artifact, or more precisely 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. Thus the physical interpretation of the quantum fields is not attached to physical entities such as physical fields or their manifestation particles, but to local operations, and a local field operator represents nothing but a physical operation performed on the system within a local region in space-time. According to this operationalist interpretation, the basic quantum fields are only used to associate each region in space-time with an algebra of observable operators on the Hilbert space, representing physical operations performable within their region. 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. For this reason, Haag argues, 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 quantum field theory.

However, as some commentator pointed out, few quantum field theorists would follow Haag in believing that the field operators or their observable combinations only describe the detectors placed in a collider rather than physical fields themselves, or that a particle is only the result of the operation of a particle detector, mathematically represented by a positive element of operator algebra, which is almost localized in a spacetime region. But this kind of realist intuition cherished by physicists has to be supported by philosophical arguments. Now let me try to provide some arguments from the standpoint of my version of structural realism.

In our construction of a theory in mathematical physics such as quantum field theory, we have to use mathematical concepts or constructions, such as manifolds, Hilbert space, local fields, ghosts, strings, or even ultraparticles and ultrasymmetries, because this is the only window through which we may have an access to the deep reality. But how can we tell which concepts are objective representations of the reality and which are not? What are the criteria for the physical reality of a mathematical concept? Some scholars suggest that invariance is a necessary condition for a mathematical concept to be objective (Auyang 1995). In my opinion, this suggestion is not tenable. In significant ways, physical reality is not described by invariant constructions, but by constructions in which the invariance is spontaneously or anomalously broken. Another counterexample is provided by the non-gauge invariant fermion field. The reality of the fermion field is supported by numerous structural statements about fermions as its manifestation, which has survived empirical testing, and thus is hard to deny.

The last example has suggested a general philosophical point. This is that the verifiable aspect or perhaps the only verifiable aspect of reality is the net of relations linking its events. Thus, although the reality per se may not be directly knowable, the structural features of the reality can be approached by our concepts. Surely it is difficult to judge the reality of a single concept. But when a concept is incorporated into a network of concepts, and is used to produce structural statements about the reality, usually in a form of a mathematical equation, then the reality of this conceptual structure is subject to empirical investigations and can be confirmed or refuted.

If we recognize that our conception of an entity or an ontology is constituted by our knowledge of the structural properties and relations this entity carries in various situations, then conceptually from the recognition of the reality of a structure to the recognition of the reality of the entity carrying the structure is only a small step, although in history or in practice, due to the difficulty of multiple realizability of a structure by entities, it may take a long period of time to reach a consensus through negotiation within a scientific community. Checking with the history, we find that this is the way in which the reality of quarks was recognized through the empirical investigations about the structure of the light cone current algebra in the late 1960s and early 1970s, and in which quarks as we conceive now were uniquely picked up from other candidates that initially also supported the same net of structural constraints as the quarks did (Cao 1997).

Then what about the reality of our constructed concept of quantum fields? If we apply the above idea to this question, then the answer is not difficult to obtain. The concept of fields is used in two ways. First, it is used to produce field equations, which describe the relational and structural aspects of these hypothetical entities; second, it is used to extract the concept of the particle, which is the observable manifestation of the same hypothetical entity. If the equations and various structural statements about the particles are confirmed by empirical investigations, then the reality of the fields is established. But notice that according to structural understanding of entities, this claim to reality can only be partial, but not total or complete, extending only to the structural information that the concept of fields carries with it and has been confirmed so far. That is, structural realism attributes a constructive and historical character to the objectivity of concepts or the conceptual structure of scientific theories.

It is impossible to over-emphasize the important implications of the last statement for the understanding of quantum physics. Many philosophers have legitimately argued that as a special version of quantum mechanics, quantum field theory has inherited all the difficulties related with measurement and entanglement in interpreting its formalism realistically. That is, if we try to interpret the formalism of quantum field theory as an objective description of what exists and happens in the world, independent of our measurement, then we will be in the same trouble of contradicting observations as in the case of non-relativistic quantum mechanics. The most we could claim is that the formalism describes what could appear to us in various experimental situations. As Bernard d'Espagnat (1995) once commented, what quantum physics teaches us is that we may have some probabilistic knowledge of the phenomenal reality or appearance, but we can rarely get any knowledge about the independent reality or reality per se, which is possible only within the context of classical physics.

But the question is, can we really separate the phenomenal reality and the noumenal reality? In the context of human knowledge, no reality exists independently of human knowing activities. But why should we take our knowing activities only as a curtain to separate the noumenal world from us, rather than as a window through which we can have access to it? Of course, our knowledge of the phenomenal world is always constructed under various human constraints. But since the phenomenal world is only a manifestation of the noumenal world in the context of our experience, not totally detached from the noumenal world, this construction must have its roots in the noumenal world. To be sure that even for the phenomenal reality there can be many conflicting constructions, as is claimed by the underdetermination thesis, which seems to have undermined the objectivity of our knowledge of the phenomenal reality. But the common structure of these empirically equivalent but ontologically conflicting constructions must be objective, which means that under given conditions, this common structure will not subject to any subjective influences. Thus it would be inappropriate to insist that we cannot acquire objective knowledge about the relational and structural aspects of the noumenal reality through the accumulation of structural knowledge of phenomena, which is a manifestation of the noumenal reality in various situations.

Once the objectivity of structural knowledge is established, conceptually, as I argued earlier, it is only one more step to establish the objectivity of our knowledge about entities. In the case of quantum field theory, if we have known that the entity described by its formalism is the field, if we have known the relational and structural properties of the field through the field equations, and if we have very precise knowledge about the appearances of the field in various empirical situations, then we must acknowledge that we have some objective knowledge of the field as a reality independently existing out there, although this knowledge is acquired through our construction, appears as knowledge of its empirical manifestations involving human activities, and is of a structural character.

But with the refinement of our constructions through an open feedback process between conceptual constructions and empirical investigations, with the accumulation of our structural knowledge of the quantum entity being investigated in the process of refinement, the veil of the quantum reality will be gradually lifted in this progressive process. This is the objectivity of our historically constructed knowledge of the quantum reality. On the other hand, the constructive nature and the structural character of our objective knowledge of the quantum reality would prevent the historical process from ending. And this historicity of objectivity, together with the above-mentioned objectivity of historically constructed knowledge, may be the greatest lesson we could learn form interpreting quantum field theory, in particular from the interpretation in the spirit of effective field theory (Cao 1999).

NOTES

[1] The paper was first presented at a Sigma Club meeting at LSE, 3 June 1999.

[2] Putnam, 1978; see also Laudan, 1981.

[3] More discussion on this topic is given in the Appendix.

[4] For detailed references mentioned in this and following three paragraphs, see part II of Cao, 1997.

[5] For possible alternative interpretation of the Casimir effect, see Rugh et al. (1999).

[6] Adler (1969). See also Bell and Jackiw (1969).

[7] See, e.g., Schilick (1918); Russell (1927); Carnap (1929); Maxwell (1970); and Worral (1989).

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