Conceptual foundations of quantum field theory

Quantum field theory is a powerful language for the description of the subatomic constituents of the physical world and the laws and principles that govern them. This book contains up-to-date in-depth analyses, by a group of eminent physicists and philosophers of science, of our present understanding of its conceptual foundations, of the reasons why this understanding has to be revised so that the theory can go further, and of possible directions in which revisions may be promising and productive.

These analyses will be of interest to students of physics who want to know about the foundational problems of their subject. The book will also be of interest to professional philosophers, historians and sociologists of science. It contains much material for metaphysical and methodological reflection on the subject; it will also repay historical and cultural analyses of the theories discussed in the book, and sociological analyses of the way in which various factors contribute to the way the foundations are revised. The authors also reflect on the tension between physicists on the one hand and philosophers and historians of science on the other, when revision of the foundations becomes an urgent item on the agenda.

This work will be of value to graduate students and research workers in theoretical physics, and in the history, philosophy and sociology of science, who have an interest in the conceptual foundations of quantum field theory.

For Bob and Sam

Conceptual foundations of quantum field theory

EDITOR

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Preface

This volume is the result of a two-tier conference consisting of a two-day symposium followed by a one-day workshop, which was first conceived by a group of philosophers and historians of physics in the Greater Boston area, the core members of which were Babak Ashirafi of Massachusetts Institute of Technology, Ronald Anderson of Boston College, Tian Yu Cao of Boston University, David Kaiser of Harvard University and Silvan S. Schweber of Brandeis University, and then sponsored by the Center for Philosophy and History of Science, Boston University, and held at Boston University on March 1–3 1996, with financial support provided by the U.S. National Science Foundation and the Boston Philosophy of Science Association.

The intention was to offer an opportunity for a group of leading scholars to present their penetrating and in-depth analysis of various formulations and understandings of the foundations of quantum field theory, and to investigate philosophical and historical issues associated with these formulations, and also to provide a forum for the desirable, mutually beneficial but difficult exchange of views and ideas between physicists and mathematicians on the one side and philosophers and historians on the other. Although the experiment in dialogue was not completely successful, the publication of this volume will make the valuable contributions to this conference as well as interesting material about the tension between two groups of scholars accessible to a much wider audience for further theoretical, philosophical, historical, and sociological analysis.

During the long period of preparation for the conference, in addition to many planning meetings by our group, we also received advice and numerous suggestions from the prospective participants, and also from Professor Gerald Holton of Harvard University and Professor Robert S. Cohen of Boston University. We are grateful for their intellectual and spiritual support. Thanks also to Ms Corinne Yee and Ms Carolyn A. Fahlbeck, without whose effective handling of the complexities that constantly emerged in the process of meetings the conference would have been practically impossible.

Tian Yu Cao
Boston University

Part One. Philosophers' interest in quantum field theory

1. Why are we philosophers interested in quantum field theory?

TIAN YU CAO

This two-tier conference signals a new phase of philosophers' interest in quantum field theory, which has been growing noticeably in the last few years. However, some prominent physicists have shown their deep suspicions against ignorant philosophers' intrusion into their profession, and have expressed their hostility quite openly. In the philosophy community, some prominent philosophers of physics have also expressed their suspicions against the rationale of moving away from the profound foundational problems raised by Einstein and Bohr, Bohm and Bell, such as those concerning the nature of space-time and measurement, possibility and implications of hidden variables and nonlocality, and stepping into the technical complexity of quantum field theory, which is only an application of quantum mechanics in general without intrinsically distinct philosophical questions to be explored. In order to dispel these suspicions, it is desirable to highlight certain aspects of quantum field theory which require philosophical reflections and deserve further investigations. This discussion intends to suggest that philosophers can learn many important lessons from quantum field theory, and may be of some help in clarifying its conceptual foundations. At this stage of crisis that quantum field theory is experiencing now, the clarification may contribute to the radical transformation of our basic concepts in theoretical physics, which is necessary for a happy resolution of the crisis and the emergence of a new promising fundamental physical theory.

Generally speaking, philosophers are interested in the metaphysical assumptions adopted by science and the world picture suggested by science. They are also interested in understanding the successes, failures and significant changes that have happened in science, in terms of its ontology and theoretical structure. Thus it is natural for philosophers to be interested in examining various scientific theories from these angles. But for historical and institutional reasons, many philosophers of physics have for many decades been preoccupied by questions raised by Newton and Leibniz, by Einstein and Bohr, and by Bohm and Bell, without properly appreciating novel features that have occurred in quantum field theory and statistical mechanics. They have ignored the fact that physics, both in terms of richness of its theoretical structure and in terms of the complicated world picture it suggests, has moved far away from Einstein and Bohr, and thus raised many new foundational issues to be clarified. It is true that the old profound puzzles of measurement and nonlocality continue to be a serious challenge to human intellect and deserve our reflections, just as the old puzzle of action-at-a-distance of Newton's gravity remained a serious challenge to the scholars musing during the period between Maxwell's theory of electromagnetic field and Einstein's general theory of relativity. But there is a possibility that serious reflections on the recent developments in contemporary physics may shed new light on the old puzzles, just as Einstein's theory of gravity did resolve the puzzle of Newton's action-at-a-distance. Even if it turns out not to be true for the 20th century puzzles, these recent developments in their own right remain a proper scientific context for our philosophical reflections upon science.

As a representation for describing subatomic entities and as a framework for the hierarchical structure of the microscopic world which can be built from these entities, quantum field theory embodies the reductionist view of science and is taken to be the foundation of fundamental physics: that is, the foundation of particle physics and cosmology. The reductionist pursuit reached its most spectacular success in the standard model of the 1970s, which, in addition to a unified representation of fundamental interactions, has also profoundly influenced the development of contemporary cosmology. Thus to a large extent, our present conception of nature, concerning the ultimate constituents of matter, the laws and principles that govern them, and the origin and evolution of the whole universe, is shaped by quantum field theory.

This explains why some philosophers take quantum field theory as the contemporary locus of metaphysical research[1] when they try to use current physical theory as a guide to detect and resolve metaphysical questions such as the following: 'Is the world ultimately continuous, or discrete, or dual in nature?' 'What is the meaning of the concepts of particle and field in the context of the microscopic world?' 'What is the nature of the vacuum and how should one conceive and understand the vacuum fluctuations in terms of substance that is supposed to obey the law of conservation?' 'What is the physical mechanism underlying cooperative correlations between the fluctuating local quantities at different length scales, which is assumed by quantum field theorists in their multiplicative renormalization procedure?' 'What justifies the idea of scale dependence of physical parameters that underlies the idea and technique of renormalization group in quantum field theory?' 'How does one reconcile global features, such as quanta, the vacuum and gauge conditions, with a local field theoretical framework, and what are their implications for our understanding of causal connections?' 'Is the world homogeneous or hierarchical in nature? If it is hierarchical, then what is the nature of the relationship between different levels in the hierarchy, reducible or not?' These and many other questions will be discussed in the following contributions to this volume.

Quantum field theory also provides rich material for epistemological discussion. Let me give just two examples. One concerns concepts, the other concerns theoretical structure. A persistent question in the philosophy of science is whether we should give theoretical concepts an instrumental interpretation or a realistic interpretation. The instrumentalist has difficulty in explaining the effectiveness, and the realist has difficulty with the elusiveness or underdetermination of the concepts in their relation to empirical data. Now in quantum field theory no one would deny that quantum particles and quantum fields are different from classical particles and classical fields. Thus the terms particle and field, with their inescapable classical connotation, in the context of quantum field theory, can only function as metaphors. But metaphors are useful only when they capture certain structural similarities with the

[1] See Howard Stein (1970): 'On the notion of field in Newton, Maxwell and beyond,' in *Historical and Philosophical Perspectives of Science* (ed. R. Stuewer, University of Minnesota Press), 264–287.

originals. That is, theoretical terms are useful only when they carry certain structural features of the objects they intend to describe. This attitude toward theoretical concepts seems to be accepted by almost all quantum field theorists. For example, the prominent physicist Rudolph Haag suggests that in the context of quantum field theory, the real function of the concept of particle is to indicate the charge structure, and the concept of field is to indicate the local nature of interactions.[2] This kind of understanding certainly supports a structural realistic interpretation of theoretical concepts, which was suggested by Henri Poincaré, Bertrand Russell, Rudolf Carnap and many other philosophers a long time ago, and has been adopted by some philosophers and conceptual historians of science, including myself, in arguing for the continuity and cumulativity of scientific development.[3]

The theoretical structure of the standard model is notoriously complicated, tightly constrained by various general requirements or principles, such as covariance, unitarity and renormalizability. One result of complying with these accepted principles is that, although a counter-example has been declared recently,[4] in most formulations of non-Abelian gauge theories we have to assume the existence of ghosts, even though we can manage to make them permanently unobservable. This has raised a serious interpretive question about the ontological status of the ghosts: should we take them only as a step in our mathematical manipulation, or give them more realistic interpretation, letting them enjoy a status similar to that of quarks, gluons and Higgs particles, if the latter are also permanently elusive to our detection? It has also raised a question about relative weights among the criteria for theory acceptance: should we take parsimony of ontology, or internal consistency and coherence, as the most important criterion for accepting a scientific theory?

Technically, the standard model is highly successful. Yet a proper understanding of its successes remains to be achieved. For example, the standard model would be impossible without the ideas of gauge invariance, spontaneous and anomalous symmetry breakings, asymptotic freedom and renormalizability. While our understanding of the first two ideas is relatively clear, no proper understanding of the other two ideas would be possible without a proper understanding of the idea of renormalization group. Now the question is what physical mechanism justifies the idea of a continuous scale dependence of physical parameters in the context of quantum field theory, without which the idea and technique of renormalization group adopted by quantum field theory would be devoid of their physical content, and thus be incomprehensible.

Besides, the success of the standard model has often been exaggerated. In fact, it has many conceptual difficulties. First, the description of low-energy pion–nucleon interactions by QCD, and the explanation of quark confinement in a four-dimensional space-time, have not been achieved (if they can be achieved at all) within the framework of the standard model. Second, the unification of the electroweak with the strong interactions has been attempted; these attempts, although suggestive, are still open to question. Most notably, the quantization of gravity and its unification with other interactions are generally believed to be unattainable goals within the framework of the standard model.

[2] Rudolph Haag (1992): *Local Quantum Physics* (Springer).
[3] See Tian Yu Cao (1997): *Conceptual Developments of 20th Century Field Theories* (Cambridge University Press).
[4] See Bryce DeWitt's contribution to this volume.

At a more fundamental level, traditionally the consistency of a quantum field theory is taken to be threatened by divergences and saved only by its renormalizability. But a rigorous proof of the renormalizability of a quantum field theory can only be obtained through the renormalization group approach. If a theory has a fixed point for the renormalization group transformations, then the theory is renormalizable, but not otherwise. Yet the proof of the existence of fixed points for the standard model in a four-dimensional space-time has not been achieved mathematically. Moreover, the idea of the renormalization group and the related ideas of decoupling and effective field theories have also suggested the legitimacy of nonrenormalizable interaction terms in a quantum field theory, and this has raised a serious question concerning the place of renormalizability in our understanding of the consistency of quantum field theory, and opened the door for alternative formulations.

Philosophically, the most interesting developments, dictated by the inner logic of the standard model, are a set of concepts, namely symmetry breakings, renormalization group and decoupling, which, ironically, are eroding the very foundation of the standard model: reductionism. A new world picture suggested by these advances is a hierarchy layered into quasi-autonomous domains, which are separated by mass scales associated with spontaneous symmetry breakings. Connections between layers exist and can be expressed by renormalization group equations. Yet the ontology and dynamics of each layer, according to the decoupling theorem, are quasi-stable, almost immune to whatever happens in other layers, and are describable by stable effective theories.

These developments in quantum field theory invite serious philosophical reflections so that their significance can be properly appreciated. Ontologically, the picture of a hierarchy of quasi-autonomous domains has endorsed the existence of objective emergent properties. This in turn has set an intrinsic limit to the reductionist methodology. Thus the development of quantum field theory as a global reductionist pursuit has reached its critical point at which its own conceptual foundation of reductionism has been undermined. Moreover, the historization of the laws of nature, suggested by the notion of spontaneous symmetry breakings and the related idea of cosmic phase transitions, seems to have undermined the idea of immutable fundamental laws of nature, another conceptual foundation of quantum field theory. Furthermore, the occurrence of a tower of quasi-stable effective theories has suggested that we need to revise the way we conceptualize the growth of scientific knowledge.

If we take these interpretations seriously, then some of the conceptual difficulties encountered by the standard model are unlikely to be normal puzzles which can be solved by the established methodology. What is required, it seems to some empiricists, is a drastic change of our conception of fundamental physics itself, a change from aiming at a fundamental theory (as the foundation of physics) to having effective theories valid at various accessible energy scales.

Many theorists have rejected this conception. For David Gross and Steven Weinberg, effective field theories are only the low energy approximations to a deeper theory, and can be obtained from it in a systematic way. However, an interesting point is worth noticing. Although both Gross and Weinberg believe that within the reductionist methodology, ways out of conceptual difficulties of the standard model can be found sooner or later, with the help of more sophisticated mathematics or novel physical ideas, both of them have lost their confidence in quantum field theory as the foundation of physics, and conceived a deeper theory or a final theory not as a field theory, but as a string theory or some other theory radically different from quantum field theory.[5] But string theory, or related speculations such as M-theory, can hardly be taken to be a physical theory at this stage; neither can it be taken as a mathematical theory because, as some mathematicians have argued, there are too many conjectures and too few rigorously proven results.

A question worth discussing is this: from a string theorist's point of view, what kind of defects in the foundations of quantum field theory have deprived it of its status as the foundation of physics? A related question is: should we take strings as a continuation of quantum field theory, or as a revolution, a radical breaking away from quantum field theory? For some more conservative mathematical physicists, these questions are non-existent because, they believe, by more and more mathematical elaborations, a consistent quantum field theory can be established and continue to serve as the foundation of physics. Thus at the present stage, there are essentially three approaches to the questions of the foundations of quantum field theory, of quantum field theory as the foundation of physics, and of the reasons why quantum field theory can no longer be taken as the foundation of physics: (i) an effective theory approach, (ii) a string theory approach, and (iii) a mathematical approach, the most active version of which now, as compared with the original axiomatic approach in the 1950s and 1960s and the constructive approach that was actively pursued from the late 1960s to the 1980s, is the algebraic approach initiated in the early 1960s. The assessment of these three approaches is closely related to the philosophical debate over reductionism versus emergentism.

The three approaches start from different basic presuppositions, give different overall pictures of the progress of physics, and represent different visions about the central issues the present stage of fundamental physics is meant to address, namely, the possibility of a final unified and finite theory which would close the door for any new physics. Guided by different visions, physicists are pursuing different research strategies, adopting different intellectual arguments about fundamental physics, aside from the philosophical argument about reductionism and emergentism, as we heard last time at the workshop held on November 6, 1993, and sponsored by the American Academy of Arts and Sciences. A wonderful example of this sort is provided by Roman Jackiw's paper in this volume. While string theorists try to avoid the concept of a point-like local field and its consequence infinities, and to construct a finite theory, Jackiw finds infinities entailed by the concept of local fields useful for achieving the breakdown of symmetry, which, as he rightly indicates, is central to the present stage of fundamental physics. One of the duties of philosophers is to examine the credentials of basic assumptions adopted by each approach and the fertility of different visions.

In the debate between those who hold a vision of a final theory and those who hold a vision of many effective theories, many philosophers do not really believe in the possibility of a final theory. Nevertheless, some of them still join the physicists of the first category and support the illusory vision with the concept of regulative function.[6] These philosophers argue that the ideal of a final theory is heuristically and regulatively more productive because its esthetic value can ignite physicists

[5] See the contributions to this volume by David Gross and Steven Weinberg.
[6] See, for example, Michael Redhead's contribution to this volume.

with intellectual excitement, whereas pursuing effective theories, though more practical, is intellectually less exciting.

This argument is very popular among string theorists because it justifies their mental state. Yet it can be neutralized with two counter-arguments. First, the vision of effective field theories is not meant to take a purely phenomenological approach. Rather, it is fully compatible with a pluralist view of fundamentality: there can be many fundamental theories of physics, each of which is responsible for a certain level of complexity in the physical world; thus no one can claim to be more fundamental than the others. Yet within their own domain, theorists can still try to discover the ultimate and underlying order, pursue the esthetic value of unification, and enjoy all the intellectual excitement thereby, even though they realize that their unified fundamental theory is only of a limited validity. But this limited applicability is always the case and would not put a damper on their excitement. The reason for this claim is obvious: even the most dedicated final theorist would not imagine any application of his final theory to economics or poetry; and the intellectual excitement enjoyed by theorists working at various levels of complexities has also defied the exclusive privilege of the final theorists for intellectual excitement. Second, the vision of effective theories keeps our mind open to the future, while the vision of a final theory closes our eyes to any new physics, any future development, except for some not so exciting applications. Thus, even in terms of the heuristic or regulative role, the vision of a final theory does not enjoy superiority.

Finally, let me say a few words about this conference. At this stage, both physicists and philosophers feel that there is a tension between them: for physicists, philosophers are ignorant or even dangerous because they don't understand and tend to distort complicated concepts and theories in physics; for philosophers, physicists are naive about their own work, and rely mainly on handwaving arguments. While I agree with Michael Redhead who claims that philosophers can contribute to the clarification of conceptual foundations of quantum field theory, I also agree with Sidney Coleman who advises me that in order to discuss philosophical questions in physics, philosophers should learn physics first. This two-tier conference is an experiment, aiming to promote the desirable, mutually beneficial, yet difficult dialogue between philosophically interested physicists and scientifically informed philosophers. If both sides can throw away unnecessary closed-minded arrogance and hostility, then a productive dialogue may not be an illusion.