CONCEPTUAL DEVELOPMENTS OF 20TH CENTURY FIELD THEORIES

This new edition of *Conceptual Developments of 20th Century Field Theories* explores the conceptual foundations and historical roots of fundamental field theories. It also uncovers the underlying issues, logic, and dynamics in fundamental physics. In response to new advances in the field over the past twenty years, the sections on gauge theory and quantum field theory have been thoroughly revised and elaborated. The chapter on ontological synthesis and scientific realism has also been reconsidered, now suggesting a new approach that goes beyond structuralism and historicism. Providing an integrated picture of the physical world, it is a valuable resource for theoretical physicists and philosophers of science with an interest in the development of 20th century mathematical physics. It also provides professional historians and sociologists of science with a basis for further historical, cultural, and sociological analysis of the theories discussed.

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Reviews of the first edition

'Tian Yu Cao's timely book provides a broad overview of twentieth-century field theories … it is an up-to-date, well informed and detailed historical account.'

Ian Aitchison, Nature

"his work is accurate ansd well documented, containing a full description of the tortuous development of gauge theory … this is a spellbinding book, with a wealth of information. As Gordon Fraser, editor of the CERN Courier, told me: 'This book is not leaving my office!'.'

Martinus Veltman, Physics World

Pre-publication reviews of the first edition

In this profound but readable treatise, Professor Cao observes that a consistent description of all observed phenomena of the microworld is at hand. This so-called standard model emerged from a complex interplay between experiment and theory. In all confrontations with experiment, the standard model emerges triumphant. And yet, too many questions remain unaddressed for it to be the last word.

In the course of these developments, the conceptual basis of the present theory has become obscure. Cao argues persuasively that we must first understand where we are and how we got here before we can build a better theory or even comprehend the true meaning of the standard model. His lucid account of the development and interpretation of both classical and quantum field theories, culminating in the creation of a gauge field theory of all the forces of nature, will enable both physicists and philosophers to address the questions of what science is and how it evolves.

Sheldon Lee Glashow, Harvard University

Tian Yu Cao's book confronts an essential problem of physics today: field theory is no longer advancing our understanding of Nature at its fundamental workings. At this critical point in the development of our discipline, the book provides a welcome overview of field theory, clearly recording the path taken to the present, conflicting positions. Cao belongs to the new breed of historians/philosophers of physics who are thoroughly familiar with the technical complexities of the modern material. His discussion is accurate and rich in detail and insight.

Roman Jackiw, Massachusetts Institute of Technology

The work is an impressive tour de force, combining masterly understanding of the many technical details of modern field theories, including general relativity, quantum field theory and gauge theory, together with a spirited philosophical defence of the rationality and objectivity of theoretical physics as captured in Cao's espousal of a structural realist position. The book provides a powerful antidote to the postmodern fashion in contemporary history and philosophy of science.

Michael Redhead, Cambridge University

It is a profound critical inquiry into the metaphysical, philosophical and technical assumptions that underlie the physical theories that so impressively and accurately describe nature in the domains thus far accessible to experimental probing. As with Mach, Cao's exposition demonstrates how a philosophical inquiry that is sensitive to history can illuminate physical theories, and his book may well prove to be a valuable guidepost in helping chart the future path of theorizing in fundamental physics.

Silvan S. Schweber, Brandeis University

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For Rosa

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Preface to the Revised Edition

There are two main changes from the first edition. First, Part III (The Gauge Field Programme for Fundamental Interactions) has been radically revised. Historiographically, the rise of nonabelian gauge theory, the emergence of the EBH mechanism, and the construction of QCD are reanalyzed and reassessed. Conceptually, ontological synthesis realizable in a background-independent theory of quantum gravity is treated separately (by adding Section 11.3) from the conceptual synthesis achieved in the gauge theory programme (as the synthesis of the geometrical programme and quantum field programme). The latter can be understood in two ways. Mathematically or formally, if the gauge field is revealed to have a geometrical interpretation in the language of the fiber bundle theory, then a conceptual synthesis is arguably achieved. But this sense of synthesis is much weaker than the ontological synthesis mentioned above. More substantially, if unification of gravity and other forms of fundamental interactions can be successfully described in a mathematical-conceptual scheme of the Kaluza–Klein theory or a nontrivial fiber bundle theory, then a conceptual synthesis much stronger than the ontological synthesis is also achieved.

Second, Chapter 12 (Ontological Synthesis and Scientific Realism) has also been radically revised, and a structural, historically constitutive, and historically constructive approach to scientific realism has been elaborated. This is necessary because my philosophical position (structural realism), which underlies the organization and argument of the book, has been misunderstood. On publication of the book, my position was taken by many philosophers of science as an ontic version of structural realism. As I have rejected this reading, I have been accused of being an antistructural realist. Thus a clarification of my position is in order. The more so as, in the past two decades, there is a new trend in the philosophy of science, the neo-Kantian trend, which tries to strengthen T. S. Kuhn's positions – the major target of my book– in a philosophically more sophisticated way.

Further important improvements have been made in the analysis of the conceptual foundations of quantum field theory: (1) the historical role of second quantization in the discovery of a new natural kind, quantum field, is stressed in the revised Section 7.1, along with its importance in the evolution of quantum field theory as a conceptual framework for particle physics; (2) the local and global aspects of the quantum field are articulated in the newly added Section 7.2.

The first edition has been criticized for having not treated many important topics, such as the path integral formalism, BRST symmetry, Haag's theorem and the Reeh–Schlieder theorem, mentioning them and some others only casually. The new edition is still open to these criticisms. Technically, path integral formalism and BRST symmetry are extremely sophisticated and impressive. But conceptually, the former is equivalent to the canonical formalism, and the latter does not touch the foundations with which this book is concerned. The situation for Haag's theorem and the Reeh–Schlieder theorem is different. Conceptually, they are deep and important. Haag's theorem challenges the legitimacy of the interaction picture that grounds perturbative calculations, without which quantum field theory (QFT) becomes impotent and useless. But perturbative QFT works extremely well. Although the reason that perturbative QFT can evade Haag's theory remains unknown, it is not part of the actual history of QFT and plays no role in the conceptual development of QFT. The Reeh–Schlieder theorem challenged the localizability of local excitations in local operator field theory, but the challenge can be practically evaded by the cluster properties of the Wightman functions. So it is clear that this theorem also plays no role in the conceptual development of QFT. These two theorems deserve serious research by axiomatic field theorists, but they are beyond the scope of this book.

Preface to the First Edition

The aim of this volume is to give a broad synthetic overview of 20th century field theories, from the general theory of relativity to quantum field theory and gauge theory. These theories are treated primarily as conceptual schemes, in terms of which our conceptions of the physical world are formed. The intent of the book is to give a historico-critical exposition of the conceptual foundations of the theories, and thereby detect a pattern and direction in the evolution of these conceptions.

As an important component of culture, a conception of the physical world involves a model of the constitution and workings of nature, and includes assumptions about the mechanisms for fundamental interactions among the ultimate constituents of matter, and an interpretation of the nature of space and time. That is, the conception involves what philosophers usually call metaphysical assumptions. Talking about metaphysics is out of fashion these days. This is particularly so in the profession of science studies, where the primary concern now is with local and empirical successes, social interests, and power relations. Who would care for the ontological status of curved spacetime or virtual quanta when even the objective status of observed facts is challenged by the social constructivists? However, as we shall see in the text, metaphysical considerations are of crucial importance for path-breaking physicists in their investigations. One reason for this is that these considerations constitute essential ingredients of their conceptual frameworks. Yet the cultural importance of metaphysics goes much deeper and wider than its contribution to professional research. My own experience might be illuminating.

When I began to study theoretical physics after reading the philosophical writings of Descartes, Kant, Hegel, Russell, Einstein, Heisenberg, and David Bohm, I was attracted to physics purely by cultural curiosity, trying to obtain a picture of the physical world endorsed by the most recent developments in physics. I was told that the Newtonian picture was not a proper one, that in the 19th century the mechanical worldview was replaced by the electromagnetic one, essentially a field-theoretical picture of the world. I also learnt that the 20th century had witnessed two profound conceptual revolutions in the physical sciences, which were brought about by relativity theories and quantum theories. As a result, we are equipped with new conceptual frameworks for probing the foundations of the physical world. But what about an integrated picture of the world suggested by these revolutionary theories? When I began doing research in the history and philosophy of science twelve years ago in Cambridge, England, I tried in vain to find such a picture in works by physicists, or by the philosophers and historians of 20th century physics.

Of course I have learnt a lot from Ernst Cassirer, Moritz Schlick, Hans Reichenbach, Karl Popper, Gerald Holton, Adolf Grünbaum, Howard Stein, John Earman, John Stachel, Martin Klein, Thomas Kuhn, John Bell, Abner Shimony, Arthur Fine, Michael Redhead, and many other scholars. For example, I have learnt that some metaphysical presuppositions, such as the principles of universality and correspondence, played an important heuristic role in theory construction by the founders of the revolutionary theories. I have also learnt that for most educated people, some of the metaphysical implications of these theories, such as the absence of the mechanical ether, the removal of the flatness of spacetime, and the impossibility of causal and spatio-temporal descriptions of individual events in the microscopic world have been accepted as important parts of our picture of the world. Yet nowhere could I find an integrated picture, let alone a cogent exposition of its evolution and of the pattern and direction of the evolution. I decided to fill this gap, and the result is this volume.

The book is written primarily for students of theoretical physics who are interested in the foundational problems of their discipline and are struggling to grasp the internal logic and dynamics of their subject from a historical perspective. But I have also done my best to make the text accessible to general readers with a basic scientific education who feel that their cultural curiosity concerning the contemporary conception of nature cannot be satisfied by popular writings. The last audience I have in mind are mainstream historians and philosophers of science. Although the book has provided a basis for further cultural and sociological analyses of these theories, and contains much material for philosophical reflection, the project pursued in this volume under present circumstances is unlikely to be interesting or even acceptable to these scholars. The disagreement comes from different conceptions of science. Detailed arguments against current positions will be given in the introductory and concluding chapters. Here I just want to highlight a few points at issue.

For many science studies scholars, any discussion of a world picture in terms of the ultimate constituents and hidden mechanisms posited by a scientific theory as underlying empirical laws seems equal to presupposing a naive realist position on the unobservable entities and structures of the theory, and this is simply unacceptable. This antirealist position has a long tradition. For the classical positivists, any statements about unobservables, such as atoms or fields, that go beyond the scope of empirical evidence or logical inference are meaningless and have to be expelled from scientific discourse; thus the world picture problem is a pseudoproblem. For constructive empiricists or sophisticated instrumentalists living in the postempiricist period, theoretical terms for describing hypothetical unobservables are permitted but accorded no existent status, because these terms are merely tools for saving phenomena and making predictions, or a kind of shorthand for observables. Then a question facing them is what the sources are of the effectiveness of these tools.

To answer this question requires a clarification of the relationship between the tools and the external world. No such clarification has ever been provided by the instrumentalists.

Nevertheless, they have tried to discredit the realist interpretation of theoretical terms by appealing to the so-called Duhem–Quine thesis of underdetermination, according to which no theoretical terms can be uniquely determined by empirical data. The convincing power of the thesis, however, entirely rests on taking empirical data as the single criterion for determining the acceptability of theoretical terms posited by a theory. Once empirical data are deprived of such a privileged status, the simplistic view of scientific theory as consisting only of the empirical, logico-mathematical, and conventional components is replaced by a more tenable one, in which a metaphysical component (e.g. the intelligibility and plausibility of a conceptual framework) is also included and taken to be a criterion for the acceptability of a theory, thus putting scientific theories in a wider network of entrenched presuppositions of the times and in a pervasive cultural climate, then the Duhem–Quine thesis alone is not powerful enough to discredit the realist interpretation of theoretical terms.

More radical is Kuhn's position. If the Duhem–Quine thesis accepts the existence of a multiplicity of conflicting theoretical ontologies, all of which are compatible with a given set of data, and thus nullifies the debate on which ontology should be taken as the real one, Kuhn (1970) rejects the reality of any theoretical ontology. He asks, since whatever ontology posited by a scientific theory is always replaced by another different and often incompatible ontology posited by a later theory, as the history of science seems to have shown us, and there is no coherent direction of ontological development, how can we take any theoretical ontology as the real ontology of the world? Yet a historical fact is that explicitly or implicitly some hypothetical ontologies are always posited in the theoretical sciences. Thus a problem facing Kuhn is why a theoretical ontology is so indispensable in the theoretical structure of science.

Kuhn's work has produced some resonances. Unlike the logical empiricists, who are preoccupied exclusively by abstract logical and semantical analyses of scientific theories, Kuhn has tried to develop his view of science on the basis of the historical examination of actually existing theories. However, some of his followers are not so happy with his limiting scientific practice solely to conceptual aspects. They passionately cry out for the importance of experiments and institutions, social interests and power relations, and so on. In my opinion, however, Kuhn is essentially right in this regard: the core of scientific practice lies in theory construction and theoretical debates. Experiments are important, but their importance would be incomprehensible without being put in a theoretical context. All external factors would be interesting and valuable for our understanding of science, but only if they had some bearing on a theory, on the genesis, construction, acceptance, use, and consequences of a theory. Otherwise they would be irrelevant to our understanding of science. In this regard, Paul Forman's work (1971) is important because it describes the cultural climate in Germany that helped the acceptance of the notion of acausality developed in quantum mechanics, although it does not touch upon the question whether the cultural climate had played any constitutive role in the formation of the notion of acausality.

Questions similar to this are taken up and answered affirmatively by the advocates of the strong programme in the sociology of science, who uphold that science is a social construction (see Bloor, 1976; Barnes, 1977; Pickering, 1984). In a trivial sense few people at present would dispute with them the socio-constructive character of science. Yet the really interesting point at issue is their special position concerning nature. If nature is assumed to play no role in the construction of science, then the social constructivists would have no theoretical resources to address questions concerning the truth status and objectivity of scientific theories, and relativism and skepticism would be inescapable. Yet if nature is allowed to have a role to play in the construction of science, then science is more than a social construction, and the social constructivists would have achieved little in illuminating the nature of science as knowledge of nature.

The latest fashion in science studies follows a radical version of social constructivism that has absorbed much of its rhetoric from the cultural fad of postmodernism. The faddists take science only as an art of rhetoric for persuasion, manipulation, and manufacture of facts and knowledge; knowledge only as a power move, having nothing to do with truth or objectivity; and objectivity only as an ideology, having nothing to do with how scientific knowledge is actually made. They argue that the important tasks for science studies scholars are not to find out who discovered facts and who constructed concepts and theories, but rather who controlled laboratories; not to explain why science works in the sense that the redshift predicted by the general theory of relativity really can be observed, but rather to question who benefitted from science. A problem for the faddists is that they can only talk to each other, and will never be able to talk to scientists seriously about their major practice, that is, about their theoretical activities.

Another influential position is Putnam's (1981) internal realism. This allows us to talk about abstract entities, truths, and reality, but only within a theoretical framework. Since any talking is always conducted within a certain framework, it seems impossible to escape from this position. It should be noticed that this position has a close kinship with Carnap's position on linguistic frameworks (1956). Both reject the external question concerning the objective reality of theoretical entities independent of our linguistic frameworks, thus having denied any objective and rational criteria for choosing between linguistic frameworks. The justification for the position, as Putnam puts it, lies in the claim that we have no access to metaphysical reality if it exists at all. Assuming that the ontologies posited by successive theories can be shown to have no connection to each other, then this position is indistinguishable from Kuhn's position. But what if there is a coherent direction of the evolution of ontological commitments in successive theories? Then Putnam will have to face the old question raised by the realists: what is the noumenal basis for the coherent direction?

Thus to justify a conceptual history of physics focusing on the underlying assumptions about the ultimate constitution and workings of nature, we have to answer two questions. First, why are these metaphysical assumptions indispensable for physics? Second, do we have any access to metaphysical reality? An affirmative answer to the second question will be given in the last chapter. Here is a brief outline of my position on the first question.

As is well known (see Burtt, 1925; Koyré, 1965), at the end of the medieval period there was a decline of Aristotelian philosophy and a revival of Neoplatonism with a Pythagorean cast. The latter took mathematics as the foundation of reality and the universe as fundamentally mathematical in its structure. It was assumed that observable phenomena must conform to the mathematical structures, and that the mathematical structures should have implications for further observations and for counterfactual inferences which went beyond what were given. Since then there has been a strong tendency, particularly among mathematical physicists, to take mathematical structures as conceptual frameworks for describing the elementary entities of the physical world and their behaviors.

Another aspect of the changing metaphysics in the same period was a replacement of the final cause by the efficient cause in the conception of causality, which was concomitant with the replacement of the power of authority by the power of rational, i.e. causal, reasoning, that is, with the rise of scientific rationality itself. Thus forces, instead of the Aristotelian telos, as agents of causality were taken to be the metaphysical foundations of natural phenomena. In some sense, all subsequent developments in physics can be regarded as being driven by searching for a model, mechanical or otherwise, for describing forces, understood as causal agents.

The concurrence of these changes led to a rise, in the 17th century, of a hypothetico-deductive method in physics, as developed by Descartes, Boyle, and, to some extent, Newton, for explanation and prediction. It is in this particular structure of physical theory that we can find a deep root for the indispensability of ontological assumptions. Forces, fields, the ether, rigid or dynamical spacetime, virtual quanta, confined quarks, gauge potentials, all these hypothetical (at certain stages of development, they were called metaphysical) entities are indispensable for theoretical physics because they are required by the historically emergent hypothetico-deductive method that is inherent in the discipline. The assumption of some ultimate ontology in a theory provides the basis for reducing some set of entities to another simpler set, thus endowing the theory with a unifying power. No proper understanding of theoretical physics and its power would be possible without paying enough attention to this characteristic of its theoretical structure. In this regard, I think Meyerson (1908) is right when he holds that modern science as an institution which emerged since the time of Copernicus is only a further stage of a natural metaphysics, whereby commonsense assumes the existence of permanent substance underlying observable phenomena.

The treatment of field theories in this volume is highly selective. Considering the rich content of the subject it could not be otherwise. The selection is guided by my view of scientific theory in general and my understanding of field theories in particular. These have provided perspectives from which various topics are examined and interpreted, and thus have determined, to a large extent, the significance of the topics in the evolution of the subject. The general framework in which material is selected and interpreted relies heavily on some organizing concepts, such as those of metaphysics, ontology, substance, reality, causality, explanation, progress, and so on. These concepts, however, are often vague and ambiguous in the literature. To clear the air, I devote chapter 1 to spelling out my usage of these concepts and to addressing some topics of methodological importance. The departure point of the story, namely the rise and crisis of classical field theories up to Lorentz's work, is outlined in chapter 2. The main body of the text, in accord with my understanding of the structure of the developments that I wish to elaborate, is divided into three parts: the geometrical programme, the quantum field programme, and the gauge field programme. Each part consists of three chapters: prehistory, the formation of conceptual foundations, and further developments and assessment. The philosophical implications of the developments, especially those for realism and rationality, are explored in the concluding chapter.

A remark about the Bibliography. Only those works that have actually been used in the preparation of this volume are listed in the Bibliography. In addition to original contributions of crucial importance, recent scholarly works that provide interpretations of the original works are also listed in the Bibliography. Yet no effort has been made to offer an exhaustive bibliography of the secondary literature; only those works having direct bearing on my interpretation of the subject are included. As to the general background of the intellectual history of modern times, to which the first two chapters frequently refer, I simply invite readers to consult a few of the outstanding historiographical works instead of giving out detailed references to the original texts, which in fact can be found in the books suggested.

My work on this project proceeded in two phases. During the first phase (from 1983 to 1988 at the University of Cambridge, England) I benefitted importantly from many discussions with Mary Hesse and Michael Redhead, my supervisors, and with Jeremy Butterfield, my closest friend in Cambridge. Each of them read several earlier versions of the manuscript and made numerous remarks and suggestions for revision. I express my deep gratitude for their invaluable criticisms, help, and, most importantly, encouragement. I am also grateful to Henry K. Moffatt for his concern, encouragement, and help, and to David Wood for friendship and help.

The second phase began with my moving from Cambridge, England, to Cambridge, Massachusetts, USA, in 1988. During the last seven years, I have been fortunate to have numerous opportunities to discuss matters with Silvan S. Schweber and Robert S. Cohen, to both of whom I owe a considerable debt; I have also had some detailed discussions with John Stachel and Abner Shimony. I have been deeply impressed by their knowledge and understanding of contemporary physics and philosophy, and greatly appreciate their significant criticisms and suggestions about all or part of the manuscript. Since the mid-1980s I have benefitted from a long-term friendship with Laurie Brown and James T. Cushing, and I am indebted to them. I am grateful to Peter Harman for stimulation and encouragement. I am also grateful to many physicists for clarifying conversations, among them Stephen Adler, William Bardeen, Sidney Coleman, Michael Fisher, Howard Georgi, Sheldon Glashow, David Gross, Roman Jackiw, Kenneth Johnson, Leo Kadanoff, Francis Low, Yoichiro Nambu, Joseph Polchinski, Gerardus't Hooft, Martinus Veltman, Steven Weinberg, Arthur Wightman, Kenneth Wilson, Tai Tsun Wu, and Chen Ning Yang.

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