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Niels Bohr and Twenty-First Century Physics

A Prospectus for Niels Bohr: Reflections on Subject and Object, Volume 1 of The Theory of Interacting Systems

by
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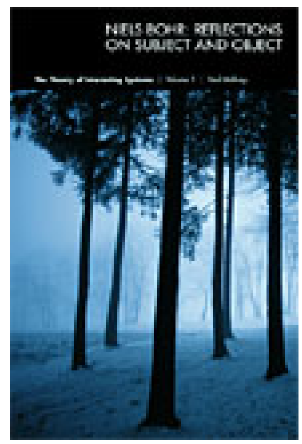

"Whose woods these are I think I know . . ."

The study of the epistemological work of Niels Bohr requires reflection on the sources of knowledge and its manifestations. As Robert Frost's lines remind us, part of the answer lies in understanding what we bring to the relation of the knower to the known. Bohr was the first to realize that disentangling ourselves from what we observe is as much a matter of physics as of philosophy. This distinction between subject and object is necessary for the proper representation of physical systems and our knowledge of them.

Bohr maintained that connections between physics, language, and philosophy lie at the root of what we can know. These connections are examined in the historical context of the concepts he drew on in both physics and philosophy. His epistemological position is tested against recent work in physics and current views on language and knowledge. This inquiry shows that his theory of knowledge can serve as a foundation for twenty-first century physics.

Portions of the text of this Prospectus are excerpted from the Preface, Table of Contents, Chapter 1, and the Back Cover of *The Theory of Interacting Systems, Volume 1, Niels Bohr: Reflections on Subject and Object* published by MicroAnalytix. It is referred to as RSO in this document. Similarly, The Theory of Interacting Systems is referred to as TIS.

1. The Importance of Bohr's Work

The philosophical and scientific work of Niels Bohr are the subjects of RSO. It is the first volume in a 6 volume series published by MicroAnalytix. This series presents the results of an extended inquiry into the relationship between the macroscopic and microscopic descriptions of interacting physical systems. It is fitting to begin with Bohr because he was the first physicist to address deeply the issue of the relation between different descriptions of a given collection of matter. In his work on an adequate foundation for quantum theory in the face of the uncertainty relations and other potential paradoxes, he realized that understanding the philosophical issues connected with the theory of knowledge in this setting were crucial to understanding how to interpret what we have observed and avoiding error. It turns out that his ideas are also needed to reconcile the relation between macroscopic and microscopic descriptions in classical theory.

This series begins with the work of Bohr because his study of the relation between microscopic and macroscopic descriptions in quantum mechanics showed that there is a disjuncture between these two levels of description. In this first volume, Bohr's concern with the relation between microscopic and macroscopic descriptions and his attempt to provide a philosophical foundation for twentieth century physics are analyzed in detail. The issues addressed in the other volumes in this series are discussed below.

Niels Bohr began his work in 1913 at a time in which physics was facing a number of serious crises. By the beginning to the twentieth century, several fundamental aspects of classical physics were under a cloud because of discrepancies between theoretical computations and experiment. Thermodynamics was in question because classical theory had been unable to provide an adequate treatment of the specific heats of substances at low temperatures. The photoelectric effect could not be explained because the classical wave theory of light could not account for how electrons could be emitted immediately by an illuminated piece of metal when the amplitude of the illuminating light was too weak for sufficient energy to accumulate in the area around the emission point before the electron was emitted. Newtonian mechanics was plagued by an anomaly in the orbit of the planet Mercury that it could not explain. Moreover, recent experiments by Rutherford had shown that the atom contains an electrically charged nucleus surrounded by oppositely charged electrons, but it did not seem possible to understand the structure of the atom in terms of these components using classical electrodynamics.

A number of more subtle problems had begun to emerge as well. Thermodynamics was hobbled by persistent paradoxes connected with trying to explain irreversible macroscopic thermodynamic phenomena in terms of the reversible underlying microscopic mechanics. Other paradoxes emerged when thermodynamics was extended to other phenomena. William Thomson, for example, had employed a reversible Carnot cycle to describe the thermodynamic state of a charged current moving around a circuit to derive equations describing thermoelectric phenomena. While this procedure was successful, in that the derived equations agreed with experiment, Thomson had simply ignored the irreversible i^2R Joule heating generated by the current i in a circuit with resistance R when he employed a reversible Carnot cycle for the calculation without giving a justification for doing so.

The entropy was another issue. Computing the value of the entropy of systems at absolute zero had become important because defining it at absolute zero would allow its computation from first principles and give it a definite rather than relative value. A number of unsuccessful attempts were made by well-known physicists to compute the absolute entropy.

Some progress had been made by 1913. Planck had discovered in 1900 a formula that could explain the spectrum of blackbody radiation, but he was forced to introduce an element of discontinuity, later called the quantum of action, as part of his formula. Einstein had explained the photoelectric effect in terms of a quantum of light, but this made no sense in classical electrodynamics. Einstein had also modified mechanics to bring the transformation laws of mechanics and electrodynamics into line with each other, but the inclusion of gravitational forces was still in the future. Einstein had a hand in resolving the problem with specific heats as well. He saw that macroscopic objects could support only a finite set of vibration modes into which energy could be transferred as heat. Each of these discoveries moved physics further from its classical foundations and into unknown territory.

Bohr's discovery of the structure of the hydrogen atom in 1913 made it clear that far-reaching changes in physics were required. The development of a mechanics that could account for the structure of an atom took about 15 years and Bohr played an important role in the process. The success of this quantum mechanics brought new problems, however.

Heisenberg's discovery of the uncertainty relations was the first in a series of theoretical and experimental investigations that established how different the new quantum mechanics was from classical mechanics. As the consequences of these discoveries sunk in, it became clear that the notion of reality and other concepts inherited from the conceptual framework of Newtonian mechanics were incompatible with the new mechanics.

Bohr more than anyone else realized how profound these conceptual differences were and was compelled to address them. He felt that without an adequate replacement for the conceptual framework of mechanical philosophy, it would not be possible to avoid paradoxes and contradictions in the new quantum theory. Beginning in 1927 and lasting until the end of his life in 1962, he devoted a good deal of time and energy investigating how to use quantum mechanics in a way consistent with what is possible to know and observe. He expressed the results of his investigation in the form of brief statements made over many years concerning the principles underlying the consistent employment of the formalism, the interpretation of observations, and the avoidance of contradictions.

Sections 2–4 below are excerpted from the first chapter.

2. Philosophical Issues in Bohr's Work

Thinking about epistemological issues becomes important in science when an existing theory cannot be extended and the theory replacing it cannot be fit within the current conceptual framework. By the early twentieth century, classical physics had been shown to be powerless for computing the emission curves of the full blackbody radiation spectrum as a function of temperature and had been replaced by Planck's theory. Classical theory had also not been successful in explaining the specific heats of substances and had been replaced by the theories of Albert Einstein and Peter Debye. Finally, classical theory was unable to account for atomic spectra, which still awaited a theoretical account. This was the situation in physics when the Danish physicist and philosopher Niels Bohr began his work.

Bohr's concern with putting the physics that he was helping to develop on a proper conceptual footing led him to an analysis of the role of theory and experiment in our scientific endeavors and to propose a theory of knowledge that supports their use. His goal was to find a consistent way to reconcile the apparently contradictory aspects of matter and electromagnetic radiation that the new observations seemed to imply and make the new theories predicting these observations intelligible. Out of this analysis, came a set of philosophical principles that he stated and reiterated over many years. Bohr's contributions, to both physics and epistemology, were central to the development and interpretation of quantum mechanics as it emerged.

Because Bohr was forced to clear a new path into these issues, he came to see more clearly than his colleagues did the inadequacy of the implicit philosophy underlying classical physics as most understood it. He also came to see the central importance to physics of the subject/object distinction in epistemology. Bohr felt his inquiry into epistemology had a much wider philosophical application than just the problems of quantum physics. In the form in which he presented it, however, Bohr's work is more of a prolegomena to an epistemology than a finished whole. He did, in fact, develop a general theory of knowledge based on this inquiry. But the full structure of his theory is implicit in his writings and needs to be pulled together and unpacked. The overall purpose of this volume is to extract that theory, explain it, test it, and extend it.

To understand what Bohr accomplished, I will need to take his theory apart, so to speak, and put the pieces on the shop floor so we can understand what they are and evaluate the validity of his conception of them. In the end, I will propose some modifications before putting the pieces back together. But I believe that the result preserves the spirit and intention of Bohr's work.

In this analysis of Bohr's epistemology we are opening a circle that connects intuition, knowledge, and perception. In rounding this circle, I will follow Bohr's philosophical inquiry into physics, philosophy, language, and biology, and explore the concepts of subject and object, reality, causality, perception, knowledge, and existence, as elements of the epistemology he developed.

3. The Theory of Interacting Systems

This is the first volume of a six volume series. The purpose of the series is to create a theory of the macroscopic world we occupy based on the physics of the microscopic world that underlies it. The formalism for a thermodynamics of local, time-dependent macroscopic physical quantities, which is based successively on the Hamiltonian statistical mechanics of classical, quantum, and relativistic particles, is developed in this series of volumes.

The epistemology presented by Bohr is an appropriate place to begin this work. Bohr was concerned with the relation between levels of experience and dug deeply into the issues that these connections raise. He was the first to recognize the importance of the subject/object distinction in physics and its formal expression in quantum mechanics. He also considered the issues involved when concepts based in ordinary experience are applied to microscopic settings. Bohr's perspective on the quantum state represented an important step away from the view of physical systems based on the conceptual framework of materialist metaphysics. All of these issues play an important role as aspects of physics in the work presented in this series.

The significance of thermodynamics to understanding issues connected with the relation of theories on different levels was hinted at by Bohr [**1930**], who was looking for aspects of classical theory in which complementarity might appear. He proposed at that time a possible complementarity between the 'spacetime coordination' and 'fixed temperature' descriptions of statistical mechanics and thermodynamics, respectively. An examination of the standard accounts of the relationship of thermodynamics to statistical mechanics showed that the equilibrium theories on which these accounts were based are not adequate to test Bohr's ideas. That realization led to the work in this series.

The examination of Bohr's ideas in connection with the relation of thermodynamics to statistical mechanics finally showed that Bohr's epistemological stance has a wider application than the atomic physics from which it emerged. Suitably extended, his epistemology provides a general approach to any pair of theories concerned with describing a system of particles on both macroscopic and microscopic levels.

The general title of this series is the Theory of Interacting Systems, which will be referred to as TIS. Although many of the topics and equations presented in TIS are based closely on work of particular authors, almost all analyses and equations will be expressed within a single TIS framework and notation that is common to all volumes. While this leads to the loss of some historical accuracy, the theoretical unification and the ability to compare work even between disparate theories within one notation far outweigh this disadvantage. An attempt will be made to notify the reader when, for example, a symbol or sign convention is used in a way that is different from that of the author under discussion.

This first volume will be referred to as RSO.[1] The succeeding volumes are primarily works of physics with a strong concern for the historical development of the concepts and their philosophical foundations. The second volume is titled *The Theory of Interacting Systems, Volume 2, Classical Theory.* This volume is referred to as CIS, which stands for the 'classical theory of interacting systems'. The fundamental principles of the Theory of Interacting Systems and the mathematical construction of a spacetime thermodynamics out of the classical Hamiltonian mechanics of systems of microscopic particles are presented in CIS. The third volume is *The Theory of Interacting Systems, Volume 3, Equilibrium Theory,* and is referred to as EIS. This volume specializes the spacetime theory of CIS to the equilibrium case. The equilibrium formalism, equations of state, thermodynamic coefficients, thermodynamic surfaces, phase transitions, asymptotic theory, and thermodynamic approximations are the main subjects of EIS. The fourth volume is called *The Theory of Interacting Systems, Volume 4, Quantum Theory,* or QIS. It contains a presentation of quantum mechanics that is based closely on Bohr's epistemology and his view of the quantum state. The resulting quantum mechanics differs significantly in its conceptual underpinnings from the versions presented by Schrödinger or von Neumann. The last completed volume, as of this date, is the fifth volume, *The Theory of Interacting Systems, Volume 5, Quantum Thermodynamics,* which is designated by QTS. QTS extends TIS thermodynamics to the quantum domain. The specialization of the theory to equilibrium quantum thermodynamics results in a different formalism than the one developed by von Neumann. The sixth volume on relativity theory is called *The Theory of Interacting Systems, Volume 6, Relativity Theory,* or RIS. It is in progress.

4. An Approach to Bohr

There has been a proliferation of books and articles on Bohr in recent years, each offering new insights and a new look at his ideas. Bohr has been viewed in this literature as a positivist, verificationist, idealist, realist,

[1]This volume grew out of work that was first presented in 1971 in my doctoral thesis at MIT entitled "The Philosophy of Niels Bohr".

antirealist, instrumentalist, seer, obscurantist, transcendentalist, visionary, reactionary, a deep thinker, and a shallow thinker, among other things. Few other thinkers have been seen in so many widely diverse ways. This forest of incompatible viewpoints is a testimony to the difficulty in coming to grasp with Bohr's work as well as to the unshakable feeling that there is something important to be found there. In spite of this plethora of books and articles, there are certain essential aspects of Bohr's work that have not been understood properly.

Bohr was driven to develop an epistemological response to the problems of quantum theory because he felt, more than any other physicist of the time, the discrepancy between the conceptual framework of classical physics and the requirements of some new conceptual framework that needed to replace it. Without significant formal philosophical training, Bohr nevertheless had a deep and strong philosophical intuition concerning fundamental physical matters that seemed to guide his thinking along a particular path over many years.

An adequate approach to Bohr must come to terms with his style of expressing himself and with certain core concepts that lie at the center of his thinking. Among these concepts are the subject/object distinction, observation, description, communication, and conceptual frameworks. Each of these concepts has a specific role in his epistemology. In addition, Bohr often used words important to philosophers, such as 'definition' and 'meaning', in the way physicists do and this seems to have caused some confusion in the philosophical literature. Finally, because he developed a novel argument in terms of the requirements of the subject/object distinction and communication to justify his new epistemological viewpoint, the careful analysis of the elements of this argument are central to understanding him.

The various discussions in the literature of the subject/object distinction are illustrative of the problems in understanding Bohr. Bohr expressed the requirement of maintaining a proper boundary between the subject and object as a requirement for the unambiguous definition, in communicable terms, of physical quantities in a measured system. Most authors present this point in the same way Bohr did and analyze it in terms of a philosophical theory of meaning and communication. In these terms, Bohr's argument seems to be an almost self-evident sequence of statements that objective scientific work must be communicable and that successful communication requires unambiguous concepts. This leaves these authors feeling a little uneasy because, as John Honner put it, there is so little to it. By contrast, I will show that the subject/object distinction, and the requirements Bohr imposed on experiments for establishing it, were introduced by Bohr for reasons of physics, not to meet the needs of communication or philosophy. In addition, his introduction of a philosophical argument concerning communication to support his epistemological ideas represents an after the fact justification for the epistemological requirements he had imposed. In a final step, I will argue that his justification in terms of language and communication is not supportable and must be replaced.

One of the recurring points that will be touched on concerning the analysis of Bohr's work and evaluating it is that he must be approached as a physicist and not as a philosopher. This is probably the greatest cause of misunderstanding Bohr and the source of a number of mistakes concerning his views. Another source of error is ignorance. My survey of the literature indicates that many, if not most, of the casual statements of Bohr's views made in passing in the physical and philosophical literatures are caricatures of his beliefs. The problem is pervasive in that statements in this literature of what is called the standard interpretation or the Copenhagen interpretation of quantum mechanics are often very far off the mark. Even those authors who do a better job characterizing standard views on the interpretation of quantum mechanics often attribute to Bohr conceptions that would more properly reflect those of Werner Heisenberg, Wolfgang Pauli, or John von Neumann.

The question of influences on Bohr, which by now has its own literature, will be discussed below. At this point, I will simply state that Bohr drew on nineteenth century conceptions for many of his philosophical ideas. Although Bohr did not make a systematic study of philosophy or other disciplines outside of physics, it is clear that he had absorbed a great deal from the milieu in which he worked and lived. A detailed historical and philosophical study of nineteenth and early twentieth century work in philosophy, physics, biology, language, and psychology, uncovered what I feel are the roots of many of the ideas that Bohr used.

For the most part, the focus in this book is on the parallel physical and philosophical issues underlying Bohr's work. I am less concerned with his scientific achievements or events in his life except as they illuminate his philosophy. A brief historical development of his ideas in the context of their times is used in Part I to show what problems Bohr and others faced in physics and the strategies they used to solve them. As part of this, just enough of the formalism of Bohr's theory of the hydrogen atom, quantum mechanics, the uncertainty relations, and von Neumann's theory of measurement, are introduced to provide a context for the points Bohr was making and the problems under discussion. A detailed examination of the foundations and mathematical representation of the quantum mechanics and quantum thermodynamics of macroscopic interacting systems is pursued in QIS and QTS.

A number of problems make the study and expression of Bohr's philosophy difficult and account for the divergent viewpoints in the literature. First, and foremost, is the well-known fact that Bohr himself never stated a full philosophical position on any of the topics that were central to him. Thus, in spite of having a general conception of the important features of an epistemology, Bohr never worked out the details necessary to fit these philosophical components into a sufficiently explicit epistemological system to support his ideas. In addition, although Bohr used a number of distinctly philosophical terms in his writing—such as individuality, irrationality, wholeness, and subject and object, among others—he did not attempt a deeper analysis from the philosophical perspective of the roles played by these ideas and how they are related to other similar inquiries that are part of the philosophical tradition. It is likely that he did not feel this was necessary, and, as will be discussed further below, he and others around him did not acknowledge any specific philosophical influences on his thought.

The second problem in the study of Bohr's work is that he tended to express his positions in terms of a small set of well turned phrases—almost aphorisms. He used these specific locutions repeatedly with a subtle shift in wording, meaning, and emphasis, as his views developed. In the end, his statements made at different times often have more of a family resemblance than equivalence. To discern the central core of meaning in these phases and statements requires a careful textual analysis and a timeline of the forms of speech he used in the context of his whole theory and the context of the physical problems he was considering over the fifty-year period of his work. Because of this, I have let Bohr and others speak for themselves as much as possible on issues where precision is paramount.

The third problem in Bohr's work is that he left some important things undone. The most significant of these is the incompleteness of his account of how we connect microscopic events, described in terms of probabilities by quantum mechanics, with the world of our macroscopic experience. He developed what I will present as an observation thesis and a description thesis to regulate how experiments should be represented theoretically and the observed results are to be interpreted. He used a communication thesis to place requirements on what an experiment must do to provide unambiguous results and what concepts can appear in statements of experimental results in a given experimental setting. I will also examine his mature concepts of a 'phenomenon', which refers to results obtained within a definite experimental context, and 'closure', which indicates that an experiment has been completed and its results recorded macroscopically. In his mature theory, he required that we refer only to closed phenomena when we are discussing the results of an experiment on the grounds that only closed phenomena are free of the quantum ambiguities associated with superpositions and nonlocalities. But he did not characterize these concepts further in his publications or indicate how they are to be reconciled with quantum mechanics itself.

In spite of these problems and slight shifts as Bohr's ideas developed, there is a consistency is his approach to understanding the issues and a depth of awareness of what is at stake that is not present in the thinking of his contemporaries on epistemological issues in physics. He maintained a close tie to the concrete and practical problems he was facing as a scientist, which has been widely recognized as one source of his strength. It is also the key to understanding him. He did not propound or indicate that he accepted a particular philosophical theory of meaning with regard to the description of physical systems, a particular theory of the truth of physical propositions, or anyone else's philosophical system. Each day he refocused on the physical problem at hand and brought to bear, often with the help of others, the concepts and insights he could for their solution. He approached the epistemological issues he faced in the same way and this close tie to concrete physical problems and examples continually guided him in this difficult terrain.

The evaluation of the validity of the elements Bohr used in the justification of his epistemological argument is of special interest. At the heart of Bohr's epistemology is a claim about the requirements on the communication of information obtained from experiments. This has been viewed variously as a simple statement of objective requirements on communication or as a part of a transcendental argument. Once again we see that there is not even general agreement on what Bohr was trying to do—quite apart from the question of whether he was successful or not. This thesis concerning communication is the linchpin of Bohr's work and I shall present a detailed case that Bohr's focus on the subject/object distinction and communication as the core justifications for his epistemology are translations into philosophical terms of points of physics.

Another issue by contrast, has received little attention recently from philosophers. This is the question of the significance of superposition in quantum mechanics. While this may be viewed as a technical aspect of the formalism, as the 'wave' part of the 'wave-particle duality', allowing superpositions of solutions is a radical innovation from the standpoint of the particle theories that were the precursors of quantum theory. Somehow, the 'either/or' relation of particle mechanics is replaced by the 'both/and' relation of wave mechanics. While this is often viewed by analogy with classical waves in terms of the interference between different microscopic entities, the situation is subtle and requires an understanding of what it implies in terms of the possibilities of observation in the context of a given experimental arrangement.

The subtitle of this book, *Reflections on Subject and Object,* refers to the central role of the subject/object distinction in Bohr's thought. Reflection is also one of the attributes of a knowing subject in almost any epistemological theory. In that spirit, this book will reflect on itself. In short sections entitled Reflections, set apart from the discussion of Bohr's work and its historical flow, I will consider what has been accomplished and what it means.

The book is organized into functional units. In Part I, the development of Bohr's philosophical thinking and work on quantum physics is examined in the context of the work of his contemporaries over his lifetime. The first concern in this historical context is how he fashioned out of the scientific issues he was facing his perspectives on theoretical description, observation, the place of complementarity, perception, language, and communication. As part of this discussion, I will examine briefly his attitude towards reality, causality, the uncertainty relations, the quantum formalism, measurement in quantum mechanics, and much more. A close analysis of his writings in chronological order, along with information on the work of his contemporaries and developments in physics, will be used to pursue the development in time and the proper characterization of these core concepts. Some of the issues, such as the philosophical classification of Bohr's views on reality, have recently acquired a large literature. Bohr's views on the issue of reality depend in part on his epistemological attitude toward quantum theory and experiment and will be taken up in stages throughout the book as the analysis progresses.

In Part II, the concern is with codifying the fundamental elements of Bohr's conceptual scheme. I will bring together his views on empirical observation and theoretical description and begin the process of organizing his philosophical position. This will show that there are a number of distinct philosophical commitments, which were designated above as *theses,* that are implicit in Bohr's work concerning the nature of observation, theoretical descriptions, perception, language, and communication. As part of this inquiry, these theses are stated in an explicit form that can then be evaluated in terms of their value in making sense of the scientific problems and their philosophical cogency. Bohr showed how these elements work together in what I will call his *main argument.* These theses and their links in the main argument are the primary focus of my exposition and subsequent assessment of Bohr's epistemology.

Reconstructing someone's thought in this way is always risky. However, without such a reconstruction, it is impossible to get at the deeper issues or even to see if Bohr's position is coherent in the larger sense. This detailed reconstruction of Bohr's philosophical views is one of the factors that set this work apart from most, but not all, other studies of Bohr. Opposition to an attempt to understand Bohr in this way was voiced by Leon Rosenfeld [**1946**], p. 9. He objected to an enterprise such as this on the grounds that it is a betrayal of the very spirit of Bohr's work, which he characterized as "pragmatic" and "supple". Rosenfeld was making an important point when he warned us that we may destroy Bohr's theory in our very attempt to pin it to the drawing board. Without a systematic approach and a clear idea of Bohr's commitments, however, we cannot really be sure of what he was saying or make a proper evaluation of it. What I will not do is assign Bohr to one or another philosophical position. Those who have categorized Bohr as, say, a positivist or attributed to him a philosophical theory of meaning, have projected a philosophical structure onto him that is unwarranted by his training and inclination. This approach also loses sight of the physical problems that Bohr was addressing with his terminology. Whenever this has been done in the literature on Bohr, it has obscured more than illuminated his views and led to serious errors in understanding him.[2]

Bohr justified his theory of knowledge by providing an account of the role of language, classical physics, and the subject/object distinction. In doing this, he used a vocabulary that is distinctly philosophical. In Part III, the possible sources of Bohr's philosophical ideas are examined. Because he did not make explicit reference to these sources, a circumstantial case must be constructed for the origin of his ideas.

For the sake of the larger perspective, Part III begins with a brief history of epistemological thinking that is focused on the subject and object distinction. Because Bohr was aware that elements of the issues of concern to him were present in what he referred to as "wisdom of the East", the examination of the roots Bohr's ideas begins with ancient Eastern thought concerning existence, causality, reality, and knowledge. This is followed by a discussion of parallel ideas in ancient Greek works. The subsequent expression of these ideas in Roman and Persian thought is touched on briefly followed by a discussion of the reemergence of these ideas in Western thought in the seventeenth and eighteenth centuries.

The influence of Kant on nineteenth century thought in philosophy and science was pervasive. This was still true in most of Europe, and at the University of Copenhagen in particular, at the beginning of the twentieth century. Bohr's thinking also shows some influences, however indirect, of Kant's ideas, so Kant's epistemology is presented in some detail. Both Kant and Bohr were engaged in creating epistemologies, so there is an opportunity to compare their approaches to a number of specific ideas with respect to these issues. The discussion of Kant also provides us with a valuable background for the examination of European thought during the nineteenth century.

The inquiry proceeds with a brief and focused historical account of the development of European thought in the areas of epistemology, biology, physics, and language during the nineteenth century.[3] The objective is to assess just how much Bohr had absorbed from the scientists and philosophers that immediately preceded him in Europe. This account is used to show how ideas such as 'individuality', 'irrationality', and 'wholeness', among others, function in Bohr's thought and why he employed specific terms such as these in his work.

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[2]More than one philosopher writing about Bohr has made this point. John Honner [**1987**] in particular has stressed it.

[3]Catherine Chevalley [**1994**], pp. 50–51, has emphasized the importance of both the history of science and the history of philosophy in developing an appreciation of the context in which the ideas of Bohr and other quantum physicists developed and bemoaned the fact that knowledge of this context is often missing in current writers. She observed that this fact has made Bohr's epistemological vocabulary unintelligible to many modern writers.

As we enter the twentieth century, and the beginning of Bohr's education at the University of Copenhagen, I will give a detailed account of the work of the Danish philosopher Harald Høffding. Høffding's philosophical writings and the ideas of other philosophers discussed in Høffding's books are examined for ideas that Bohr drew on in the development of his philosophical thinking. This is not to say that Høffding himself is a direct influence on either Bohr's scientific thinking or his epistemology, but there is strong evidence I will present that the concepts Bohr chose for his epistemology exhibit the influence of transmitted ideas. Høffding is only one possible source among many that will be presented and that Bohr may have encountered during his education and reading, and in discussions with physicists, philosophers, and others.

The next step is an examination of Bohr's concern with the part that language plays in epistemology. I will collect the statements of his views on language and its role in knowledge and communication. A comparison between Bohr's ideas and those of Ludwig Wittgenstein shows some interesting parallels and differences.

The background provided by this specialized inquiry into the history of European philosophy, language, and science serves as the basis for a philosophical evaluation and critique of Bohr's work. At issue is the way Bohr tied these elements together in his *main argument.* Modern scientific research on language and concept acquisition will be used to evaluate some of Bohr's claims regarding the epistemological primacy of language. This will help in the examination of his perspectives on language and his statement of the need for classical physics and classical concepts to describe measuring instruments and experimental results. These inquiries will also help decide whether his claim that complementarity is a general aspect of epistemology and his applications of it outside of physics are plausible.

Part IV is devoted to reflecting on the epistemological theory that has emerged. As a test of Bohr's ideas, I follow a suggestion he made and look at epistemological issues in classical physics. I have outlined above his feeling that in the relation of classical thermodynamics to statistical mechanics a concept like that of complementarity is required to reconcile the proper application of the concepts of energy and temperature. Bohr's concern with the subject/object distinction also has a parallel in the relation of thermodynamics to statistical mechanics—but not in the form that he had expected it.

A detailed comparison of Bohr's approach to the theory of measurement in quantum mechanics with von Neumann's is the next concern. The notion of a measuring instrument is examined in term of the conditions a physical system must meet in order to qualify as a measuring instrument. The account of Bohr's approach to measurement comes out of the prior discussion of his understanding of the requirements on an observation. Because he allowed only a closed experiment to be subject to quantum analysis, there are significant differences in the ways that Bohr and von Neumann approached measurement in terms of both formalism and their views of the way a measurement works. This includes the reduction of the wavefunction by consciousness at the end of an experiment in von Neumann's approach versus the closure of the experiment in Bohr's approach.

Closure is a key concept in Bohr's theory because it represents the point at which quantum probabilities are converted into macroscopic observations. Because of the important role of the concept of closure, Bohr's speculations concerning how this might come about are examined. His hunch that closure might be explained in terms of an irreversible increase in entropy during an observation is shown not to be adequate. While Bohr would not have accepted an attempt to solve these problems within quantum dynamics, as many have tried with quantum ergodic theories and decoherence theories, I will use some other recent work to provide an epistemological solution to the problem of closure consistent with Bohr's perspective.

The interpretation of quantum mechanics is another area in which Bohr's viewpoint differs significantly from those of others. To contrast the way Bohr thought about these matters with some current approaches such as decoherence theory, some of the more recent work of other authors is reviewed briefly. Bohr's epistemological viewpoint is compared with the attempts of most of these authors to interpret the wavefunction realistically as a physical substance and to use quantum dynamics to provide a resolution of the problems.

A summary of significant epistemological and theoretical problems in quantum mechanics that are outstanding illustrates the conceptual problems that are still faced there. These involve specific issues such as the question of whether a photon interferes only with itself or with other photons. A number of other issues are connected with the relation of microscopic quantum theory to the macroscopic world we inhabit.

The work in this book is completed by returning to the question of the connection of subject and object. I bring together the study of the philosophical themes Bohr used in his work and the discussion of the physical implications of the subject/object distinction for an assessment. The final step is to review the threads in Bohr's work that have been separated during the course of this analysis. I tie them together and re-present Bohr's epistemological work in a form I feel preserves the harmony of his thought and meets the objections I have raised. An Epilogue closes the circle we have opened and echoes the poetry with which we began.

5. Bohr and Twenty-First Century Physics

It has been more than a century since the discrepancies between the predictions of classical theory and experimental results first surfaced. In a relatively short time, these discrepancies led to quantum theory and opened the door on a very different world than the one described by classical materialism. We have been sorting out the consequences of these changes ever since.

Bohr saw that philosophical considerations were essential to understanding where we stand when the very notion of what we are standing on comes into question. He repeatedly returned to simple experiments that exhibited quantum phenomena and compared the theoretical representation with the interpretation of the observations. By staying as close to this connection as he did, he avoided the errors that many physicists fell into when they put a quantum face on a classical worldview.

Bohr felt that his philosophical perspective on physics was not limited to quantum theory. In particular, the disjuncture that Bohr found between the interpretation of certain concepts in one context as opposed to another context, which he characterized as a complementary relationship, has echoes in the classical version of TIS when a system of particles is represented by a general distribution rather than as a collection of precisely defined trajectories.

To support this extension of Bohr's ideas, some of them have been reframed in RSO as a concern with macroscopic versus microscopic representations of the world. Bohr's justifications for his ideas in terms of the implications of the use of language and the requirements of communication were found to be inconsistent with modern views of the epistemological status of language and its role. These elements were shown not to be necessary to Bohr's viewpoint and an alternative justification was proposed.

With the changes outlined in this book, Bohr's viewpoint on the foundations of physics does provide an adequate platform on which to construct a physics in which the context influences the set of concepts that can be used to represent a physical system and no encompassing context that embodies all the significant concepts can be given.

6. Bohr and The Theory of Interacting Systems

As discussed in RSO in detail, thermodynamics was important to Bohr, so it is fitting that his ideas have been used as part of the TIS account of the relation of thermodynamics to statistical mechanics. Moreover, it was mentioned above that a viewpoint expressed by Bohr was the impetus for my work in this area as a way of testing his ideas.

The formalism of the Theory of Interacting Systems and the analysis that underlies it supports the conclusion that Bohr's philosophical approach can serve as the foundation for physics for some time to come. It should be noted that the analysis and discussion of Bohr's work in RSO is independent of TIS except when his thermodynamic examples are considered and in the discussion of his view that entropy changes might give rise to closure in experiments. It is also the case that the majority of the work in TIS on thermodynamics and statistical mechanics is independent of the work Bohr did. However, TIS does provide an extended example of Bohr's ideas in action and shows their worth.

The Theory of Interacting Systems extends Bohr's viewpoint into a specific analysis of the relation of macroscopic knowing subjects to the microscopic substrate of the world. Proceeding from Bohr's perspective on the disjuncture between the quantum representations of physical systems, such as that between coordinate and momentum space, it is shown in TIS that the paradoxes of thermodynamics are consequences of failing to recognize a similar epistemological disjuncture between alternative microscopic representations of a collection of matter as an extended particle distribution or as a collection of exact particle trajectories. While it is usually felt that these are alternative descriptions of matter that have equal validity and applicability, the choice of which to use has thermodynamic implications. It is shown in Volume 2 and later volumes that certain aspects of thermodynamics that are available when an extended particle distribution is used, such as the system entropy, are not available when particle trajectories are used to describe the particle system. Once this is understood, it opens the door to a solution of the conceptual problem of the relation of thermodynamics to statistical mechanics and a resolution of the paradoxes.

Bohr's perspective has significance beyond the confines of either thermodynamics or statistical mechanics in that thermodynamics in its widest sense is the theory of macroscopic mechanics, which includes hydrodynamics, thermodynamics, solid state physics, etc., and statistical mechanics is the theory of microscopic particle mechanics and its representations. Viewed in this sense, it is straightforward to understand thermodynamics in connection with various representations of the underlying mechanics in terms of classical mechanics, quantum mechanics, and relativistic mechanics. Moreover, viewing a general time-dependent classical particle distribution as analogous to a psi function in the quantum mechanical description of a system shows how a nonequilibrium thermodynamics that is consistent with the underlying particle mechanics can emerge naturally.

Bohr's challenge to classical materialist metaphysics was deeper and more far-reaching than his contemporaries realized. The work presented in RSO and the succeeding volumes of this series shows that his ideas are essential, and will continue to be essential, to understanding how physics is to be done and understood in a world represented in terms of part and whole, small and large, particle and wave. In this sense, The Theory of Interacting Systems is a tribute to Bohr's intuition, insight, and prescience.

7. Bibliography

The bibliography of RSO contains more than 700 references that were actively used in the preparation of this book and play a role in it. As indicated at the end of the RSO Table of Contents, presented below in Section 9, the bibliography covers Bohr's writings, his writings with other authors, writings on Bohr, and analyses of his philosophy, his physics, his views on biology, his views on language, and discussion of the related work of many other scientists and philosophers.

8. References for this Prospectus

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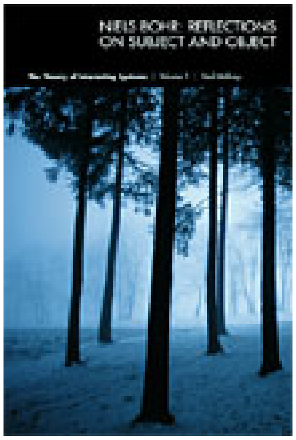
9. Table of Contents

The detailed Table of Contents of RSO appears on the next few pages. It shows the range of issues that are considered in this comprehensive and detailed examination of Bohr's work.

RSO Table of Contents



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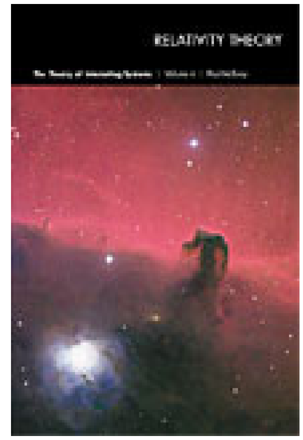

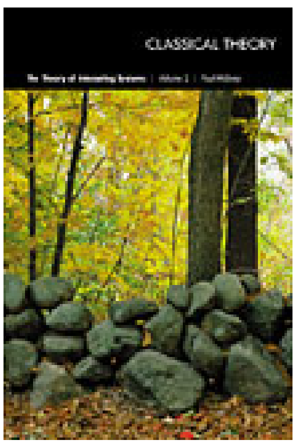

The Theory of Interacting Systems

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