CHAPTER 2

Disciplinarity and Radicality: Quantum Theory and Nonclassical Thought at the Fin de Siècle, and as Philosophy of the Future

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> [T]he necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality . . . provides room for new physical laws, the coexistence of which might at first sight appear irreconcilable with the basic principles of science.
>
> *Niels Bohr*

"The Quantum of Action"

Quantum physics was inaugurated in 1900 by Max Planck's discovery that radiation, previously believed to be a continuous (wave-like) phenomenon in all circumstances, can, under certain conditions, have a quantum or discontinuous (particle-like) character. Planck made his discovery, widely seen as the single greatest discovery in twentieth-century physics, in the course of his attempt to formulate and then interpret the radiation law for the so-called black body (the usual model of the black body is a heated piece of metal with a cavity).[1] The limit where this discontinuity appears is defined by the specific frequency of the radiation of the body and a universal constant of a very small magnitude, h, now known as Planck's constant, which Planck himself termed "the quantum of action" and which turned out to be one of the most fundamental constants of all physics. The indivisible (energy) *quantum* (i.e., quantity) of radiation in each case is the product of h and the frequency ν, $E = h\nu$.

Eventually quantum phenomena proved to have a far more complex character, of which discontinuity is only an approximation. First of all, as became apparent around 1923, whether the phenomenon in question is radiation, such as light, wave-like according to the classical view, or what were classically seen as particles, such as electrons, all quantum objects may manifest their existence (if not themselves) in both wave-like and particle-like phenomena under different circumstances. Crucially, however, one can never observe both types of phenomena together. This duality signaled the epistemological complications that continued to multiply throughout the history of quantum physics.

The very use of the term "phenomena" requires qualification regarding the relationships between quantum objects and what is observable in experiments involving them, a controversial question to this day. Niels Bohr gave the term a rigorous sense as part of his interpretation of quantum mechanics, known as complementarity. (I shall explain the latter term presently.) He defined "phenomena" as referring to the macroscopic and, in terms of the physics of their description, classical (rather than quantum) experimental arrangements where such quantum effects as those associated with "waves" or "particles" manifest themselves, but only as *macroscopic* effects, rather than as properties of quantum objects themselves. These effects include those properties that we classically associate with "particles" or "waves," but only insofar as these properties pertain to certain parts of measuring instruments, as opposed to quantum objects themselves.[2] Classical physics, however, cannot account for the sum total of these effects, which necessitates a deployment of a very different mathematical formalism. This formalism was introduced around 1925 and has ever since been known as quantum mechanics. According to Bohr's interpretation of this formalism, it may not be possible to attribute the properties of particles and waves or any classical physical (or perhaps any) properties to quantum objects themselves. Nor, in Bohr's interpretation, are quantum objects described by this formalism, which instead refers to the effects of the interaction between these objects and measuring instruments upon the latter. These effects define phenomena in Bohr's sense. Quantum objects themselves must, thus, be seen as "entities" different from either particles or waves, while giving rise to one or the other type of phenomena (but never both types together) by virtue of their interaction with measuring instruments. Each type of phenomena (but never both together) appears (in either sense) as the effect of these interactions. Each phenomenon also appears in specific and always mutually exclusive circumstances, which can be rigorously defined and, whenever necessary, set up experimentally. In other words, the appearance of the particle-like or the wave-like phenomena uniquely depends on a particular type of experimental setup; and we can always arrange for such a setup and expect the appearance of the corresponding type of phenomena. We can, however, never combine both types of phenomena so as to ascertain, even in principle, all characteristic phenomenal properties in question, or construct any experimental setup that would enable us to do so (in the way it can always be done, at least in principle, in classical physics). We can observe either the wave-like effects or the particle-like effects of the interaction between quantum objects and measuring instruments, but never both simultaneously.

Thus, we can neither avoid phenomena of either type—either with wave-like effects or with particle-like effects—nor combine the phenomena of both types at any point. In some respects, the latter is true in classical physics as well. There, however, these two descriptions apply (directly) to the distinct and rigorously separable types of *objects*: particles are always particles, waves are always waves. A difference in the experimental setup would not change the nature of either type of object. By contrast, in quantum physics it is the difference in the experimental setup that defines the different—the wave-like or the particle-like—character of the observable phenomena for the same *type* of "objects," while the objects themselves are, ultimately, unobservable as such. While of the same type (electrons, photons, and so forth), two observed "objects" may not be the *same* as objects, and may not even be objects to begin with.[3] We can neither observe a proper fusion of phenomena of different types nor conceive of a single underlying quantum configuration that (even though unobservable and ultimately inconceivable) would itself possess both attributes as its coexisting aspects or effects. It follows that the concept of "underlying quantum configuration" or even such terms as "configuration" and "quantum" (or, it follows, attributing to this configuration any properties) is rigorously inapplicable in Bohr's interpretation. Thus, while always mutually exclusive, the two types of phenomena in question, those with "wave effects" and with "particle effects," are both necessary for a comprehensive overall quantum-theoretical description. Bohr calls such phenomena complementary.

Far from being restricted to the wave-particle pair, complementary phenomena are common in, and are peculiar to, quantum physics. Indeed, they may be seen as defining it, especially in Bohr's interpretation, which he, accordingly, called "complementarity." Bohr realized that the mutual exclusivity of complementary phenomena is an advantage, since it allows one to avoid combining mutually exclusive attributes in the same phenomena. Arguably, the most significant complementary phenomena are those related to the measurement of physical variables, analogous or, in Bohr's view, symbolically analogous, to those of classical physics, such as position and momentum, or time and energy.

Such variables were seen by Bohr as symbolic for the following reason. Even though we sometimes (by convention) ascribe them to quantum objects, in actuality we can only measure the corresponding physical quantities (for example, either position or momentum, but never both together) pertaining to the classically described measuring arrangements. That is, we measure classical physical variables pertaining to certain parts of such arrangements, rather than to the quantum objects themselves. "Allegorical" may even be a better term here, especially if we follow Paul de Man's view of allegory. His formulation in "Pascal's Allegory of Persuasion" is particularly fitting: "[T]he difficulty of allegory is rather that this emphatic clarity of representation does not stand in the service of something that can be represented."[4] Indeed, this clarity may be said to stand in the service of that which cannot be represented by any means, allegorical or not. De Man's formulation is also fitting in that quantum mechanics is defined by its extraordinary clarity and lucidity that rivals that of the best classical theories. Quantum mechanics has nothing to do with vagueness or indeterminacy (except in the specific and precise sense of uncertainty relations, on which I shall comment presently), either in terms of its theoretical structure or in terms of its claims concerning the ultimate constituents of nature as such. Instead, it tells us—rigorously, clearly, lucidly—that it makes no claims of any kind in this latter respect and, in Bohr's interpretation, more radically that no such claims are possible. Quantum epistemology (again, at least in Bohr's version of it) ultimately may never allow us to speak of any properties of quantum objects and their behavior as such, but only of the effects of their interaction with the classically described measuring instruments. Accordingly, any physical description of quantum objects or their behavior based on conventional physical attributes can only be "allegorical" in the sense just defined. Classical physics can offer us only incomplete and partial—and specifically complementary—allegories of the quantum world, both in general conceptual terms and as specifically applied to the measuring instruments involved in a particular (and always unique) situation of quantum measurement. While, as I said, the relevant behavior of these instruments is described fully in classic terms, the (complementary) sum total of the effects of their interaction with quantum objects is rigorously unaccountable by means of classical physics. Indeed, nothing appears to be able to offer us more than, in this sense, partial and, specifically, complementary allegories of the quantum world, which cannot even be assumed to add up to a classical whole, even if an unrepresentable one. As a result of the circumstances just sketched, such (complementary) variables become subject to Heisenberg's uncertainty relations. Uncertainty relations express most immediately the strict quantitative limits absent in classical physics, on the simultaneous joint measurement of "position" or "coordinate" (q) and "momentum" (p), as expressed by the famous formula $\Delta q \Delta p \cong h$, where h is Planck's constant, and Δ designates the precision of measurement. (The same type of formula holds for time and energy.) In Bohr's interpretation, however, the uncertainty relations manifest the impossibility of not only simultaneous measurement but also the simultaneous determination or unambiguous definition of both such variables at any point.

Planck's discovery emerged from the investigation of the nature of energy, entropy, and chance (the concepts developed throughout the nineteenth century) at the level of the ultimate constituents of matter, which modern physics has defined as quantum ever since. The situation may have been imperfectly understood initially. Eventually, however, Planck's law and related developments, and our attempts to interpret them, radically transformed our understanding of physics and of the limits of our knowledge, scientific and philosophical, and its claims upon nature, technology, and mind. The transformation took a while, as did a more adequate interpretation of quantum phenomena themselves—more or less in the wake of quantum mechanics, introduced by Werner Heisenberg and Erwin Schrödinger in 1925–26.[5] It was not easy to develop an understanding of the strange and even mysterious character of the data in question. Nor was it easy to develop quantum theory itself—to work out a comprehensive mathematical formalism for it and to understand the nature of the physical and philosophical problems involved or (equally as difficult) of the solutions it offered. We are hardly finished with sorting these complexities out even now, in the year 2001, at least insofar as the debate concerning quantum physics continues. And no end appears to be in sight.[6] Thus, quantum physics and its radical implications frame two instances of the fin de siècle, that of the nineteenth and that of the twentieth century, or of the beginning of a new century. Indeed, along with radical theories in other fields and the debates they have continuously engendered, quantum physics and the debates concerning it (as those in other fields), gave the twentieth century the character of an incessant philosophical fin de siècle, and have taken us into the twenty-first century. They have made it the scene of what Nietzsche called a "philosophy of the future"—a philosophy that is always and forever yet to come.

"The Epistemological Lesson of Quantum Mechanics"

The epigraph to this essay comes from Niels Bohr's reply, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" to Einstein, Podolsky, and Rosen's (EPR) famous article, by the same title, questioning the completeness of quantum mechanics as a physical theory.[7] These two propositions, which, respectively, open and close Bohr's argument, may be read together: "[T]he necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality . . . provides room for new physical laws, the coexistence of which might at first sight appear irreconcilable with the basic principles of science."

In accordance with the first statement, I shall designate as nonclassical or radical those theories, in any domain, that entail "the necessity of a final renunciation of the classical ideal of causality" and, in particular, "a radical revision of our attitude towards the problem of physical reality." Bohr argues for both in the case of quantum mechanics. At least, the latter can be interpreted consistently with the experimental data in question and the formalism of quantum mechanics, and this interpretation ensures the completeness of quantum mechanics as a physical theory within the proper limits of its application. I shall, accordingly, call classical those theories that are both causal and realist. Ultimately, a final renunciation of the classical ideal of reality may be at stake in Bohr's interpretation of quantum mechanics as well. Indeed, it is conceivable that no concept of reality that is, or even ever will be, available to us may be applicable to our description of the quantum world, assuming that the latter expression or such terms and concepts as "quantum" or "world" themselves could apply.[8]

My argument accords with the second proposition of my epigraph: the nonclassical or radical nature of certain theories or their interpretation in physics and elsewhere provides room for new laws, that is, rigorous propositions accounting for "regularities" in the behavior of objects or phenomena under investigation in these theories.[9] These laws may at first sight appear irreconcilable with the basic principles of science or other disciplines in question. In fact, however, such is not the case. On the contrary, such theories are not only compatible with the basic principles of the disciplines where they emerge, but in view of other aspects of those theories (such as the experimental data in question in quantum physics) they also become necessary at certain points in order to maintain these principles. Radicality becomes the condition of disciplinarity rather than, as it may appear at first sight and as it is often argued by the proponents of classical theories, being in conflict with it. Naturally, this circumstance may also entail a reconsideration of what constitutes the basic principles of science or other disciplines, including the functioning of classical theories—a reconsideration, that is, of what is decisive in enabling the practice of these disciplines.

First, I would like to explain further the terms just introduced. I call the theories in question nonclassical, rather than, say, postclassical for the following reason. It is true that their most radical forms may be argued to be relatively recent. In science, we find them in quantum physics or modern biology and genetics, and in certain areas of modern mathematics and mathematical logic. In the humanities, we encounter these theories beginning more or less with Nietzsche and then extending to, in particular, Heidegger, Bataille, Levinas, Blanchot, Lacan, Foucault, Deleuze, de Man, and Derrida. Certain key elements of such theories can, however, be traced in the earlier history of theoretical thinking in mathematics, science, and philosophy, beginning with some pre-Socratics. This tracing sometimes appears to allow for nonclassical interpretations of some among such earlier theories as a whole, rather than merely arguing that some of their elements can be used in nonclassical theories elsewhere. Such interpretations (whatever the degree of their viability) pose, first, the question of a more rigorous genealogy of nonclassical thought. Secondly, they also pose the question of whether such earlier theories are best read classically or nonclassically. Both are complex issues, which I shall not address here. At the same time, even as the tracing just indicated takes place, at its radical limits, nonclassical theoretical thinking is hardly more accepted by, or acceptable to, a large majority of the contemporary intellectual (including scientific) community than it has ever been.[10] It is this resistance that is primarily responsible for the continuing application of the characterization "radical" to nonclassical theories, by their proponents and critics alike. This resistance can be easily exemplified by recent debates, particularly those involving responses to the thought of the figures just mentioned.

A few further general qualifications and disclaimers are in order. My subject here is the implication of the state of affairs just described—the possibility, if not necessity, of a rigorous suspension of both causality and reality in interpreting the quantum-mechanical data and formalism, and their interrelationships—for the status of quantum mechanics as a physical theory. This is one of the central questions at stake in the Bohr-Einstein debate concerning "epistemological problems in atomic [that is, quantum] physics," to use the subtitle of Bohr's "Discussion with Einstein." Many key concepts and even specific formulations offered above are, however, of a general philosophical nature and, hence, are applicable to other fields of inquiry, in particular to the work of the representative nonclassical thinkers listed previously. An immediate example would be Bohr's extraordinary formulation to be discussed later: "In fact, in quantum physics, we are presented not with intricacies of this kind, but with the inability of the classical frame of concepts to comprise the peculiar feature of indivisibility, or 'individuality,' characterizing the elementary processes."[11] As will be seen, the intricacies in question concern the nature of probability in classical physics. Bohr's proposition, however, extends well beyond the question of causality (or even that of reality) and may be read as defining the essence of nonclassical thought in quantum mechanics and elsewhere. It may be useful to adjust the statement a bit to stress my point: "In these theories we are presented not with usual, if complex, intricacies of the classical kind, but with the inability of the classical frame of concepts to comprise the peculiar features characterizing the processes in question in nonclassical theories."

Accordingly, my argument, although it will deal primarily with quantum physics and Bohr, can be extrapolated to other areas and specifically to the work of the figures in the humanities whom I mentioned earlier. One can also consider the question of *interdisciplinarity* in this context—the question of how the introduction of nonclassical theories affects the relationships between different disciplines and the debates concerning these relationships, specifically at the fin de siècle, or over the course of the twentieth century, in its perpetual fin de siècle. Except by implication, this question cannot be addressed without extending this essay well beyond its intended scope.[12] An invocation of the currently fashionable and (in part by virtue of being fashionable) risky term "interdisciplinarity" may be misleading. I refer to the specific—nonclassical—epistemological configurations rigorously shared by different fields, where they may have different roles to play (for example, in physics versus certain areas of philosophy), rather than interactions between such fields themselves, be they more or less rigorous, or more or less loose. Such interactions and our views of them have sometimes been way too loose and superficial or, one might say, lacking in discipline (in either sense) in certain recent cases in the humanities, often in the name of interdisciplinarity. It may instead be appropriate and opportune to cite Bohr in introducing the second volume of his collected philosophical essays: "The following articles present the essential aspects of the situation in quantum physics and, at the same time, stress the points of similarity it exhibits to our position in other fields of knowledge beyond the scope of the mechanical nature. We are not dealing here with more or less vague analogies, but with an investigation of the conditions for the proper use of our conceptual means of expression. Such considerations not only aim at making us familiar with the novel situation in physical science, but might on the account of the comparatively simple character of atomic problems be helpful in clarifying the conditions for objective description in wider fields."[13] Bohr did, however, sometimes also speak more ambitiously (but not in print) of his "dream of great interconnections."

In part for the reasons just explained, no disciplinary knowledge of physics is required for understanding my argument, though I would stand by my claims concerning physics (and I think we must always try to be as accurate as possible in this respect). Indeed, to the degree that physics qua physics is involved, all my claims will be supported by arguments that are, in fact, Bohr's, if not quotations from Bohr. My main argument, moreover, concerns primarily Bohr's view of the relationships between disciplinarity and radicality (that is, nonclassical epistemology as, at a certain point, a necessary condition for maintaining the disciplinarity of physics). This argument would apply whether or not one agrees with his interpretation of quantum physics or his view of the basic principles of science. Although I argue that both are at the very least effective, for some they are epistemologically difficult to accept, as was the case for Einstein, who ultimately found quantum mechanics, and specifically Bohr's interpretation, consistent and effective but epistemologically unpalatable.

I am, it is true, also concerned with a certain philosophical generalization of Bohr's conceptuality. For the arguments similar to the one offered here concerning Bohr may, I would argue, be developed for thinkers in areas outside of mathematics or science. My claims, however, are also historically specific, whether they concern quantum physics or other fields. First of all, they are restricted to thinkers especially prominent in recent debates. Many of these figures are, in addition, often seen as responsible for the unproductive undermining of disciplinary stability and theoretical, scholarly, and intellectual norms and rigor. I would argue that this view is mistaken, or at least lacking in discrimination.

One could not deny differences among the work and attitudes of the thinkers themselves. In the work of some of them—specifically (in addition to Bohr) Heidegger, Levinas, Blanchot, de Man, and Derrida—radicality is, or at a certain point becomes, the condition of the continuity of disciplinarity and discipline (as both a field of study and a system of governing rules) in their fields. In these cases, one finds what may even be called, strange as it may sound in relation to these thinkers, an extreme disciplinary conservatism. I use this expression in the following sense. A departure from a given preceding (classical) configuration of thought is enacted, first, after exhausting the possibilities it offers for a new configuration, which may in fact arise in part from within the old one. Secondly, this departure is enacted under the extreme pressure of maintaining and perhaps conserving significant and even defining disciplinary aspects of the old configuration. In the case of new physics (relativity and quantum mechanics), Heisenberg, who was close to the events in question (in 1934), argued as follows: "Modern theories did not arise from revolutionary ideas which have been, so to speak, introduced in the exact sciences from without. On the contrary they have forced their way into research which was attempting consistently to carry out the programme of classical physics—they arise out of its very nature. It is for this reason that the beginning of modern [twentieth-century] physics cannot be compared with the great upheavals of previous periods like the achievements of Copernicus."[14]

The point concerning the time of Copernicus may require further qualification. However, it does suggest that there are other configurations, other views, and other effects of theoretical practice in whatever field one considers. Thus, one does find more manifestly or (it may be difficult to be certain) perhaps more manifest radical "moves," more pronounced and "speedier" departures from particular forms of disciplinarity. One can think, for example, of the cases of Nietzsche, Bataille, Deleuze, and Lacan as different from those of Bohr, Heisenberg, Heidegger, Levinas, Blanchot, de Man, and Derrida. In these cases, however, one might still argue for analogues, if not equivalents, of disciplinary conservatism, and indeed arguments to that effect. Thus, for Nietzsche and Deleuze, although in different ways, one's sense of the "discipline" (in either sense) and of theoretical rigor in fact requires an enactment of a much broader and deeper transformation, and indeed a redefinition, of a given disciplinary configuration or field. In the process, a given disciplinary history—such as that of philosophy, or, especially in Lacan's case, psychoanalysis—becomes refigured as well.[15] Bataille's is a still different and somewhat more complex case. His strong sense of philosophical or even, in a certain sense, scientific rigor is pronounced in spite and sometimes because of the strange shapes that his texts assume. There is, in the cases of all these figures, still a question as to the degree of manifestation, in their available texts, of the working through the preceding configuration before entering new theoretical territories. This type of question, however, would especially require extended treatments of each case just mentioned, which cannot be done within my limits here. A proper treatment of Lacan's case would, in addition, require a much more sustained engagement with psychoanalysis than is possible here.[16] In these cases, one also confronts more complex disciplinary and interdisciplinary configurations than in the case of mathematics or science, which are hardly free from these complexities either. The spectrum of disciplinary and interdisciplinary configurations in the cases in question is much broader, however, and, accordingly, one cannot avoid specificity and limitations in making the kind of argument I am making here. I would also argue, however, that the cases in question and, accordingly, the present argument concerning the relationships between disciplinarity and radicality, have a broader intellectual and political significance, especially in the context of recent debates. This matter will be considered later, although my argument concerning developments in the humanities will remain more provisional and will proceed primarily by analogy with my argument concerning Bohr, while keeping the differences in mind, in particular the specificity of mathematics and science.

This specificity remains crucial, first of all, in terms of the conceptual and historical, or, one might say, disciplinary rigor of the argument. It is also crucial, especially for the present analysis, for yet another reason. The case of mathematics and science, or, again, specific cases such as that of Bohr's work, may be disciplinarily (and interdisciplinarily) less complex than those of figures in the humanities, such as those previously mentioned. Or at least this type of complexity may be kept at bay somewhat more easily in the disciplinary practice of mathematics and science, rather than, say, in fully understanding Bohr's work. This specificity, however, also allows one to make a stronger, perhaps the strongest possible, overarching argument: in certain circumstances, extreme epistemological radicality is the condition of the continuation of disciplinarity and even arises as the outcome of extreme disciplinary conservatism. It is primarily in order to make the strongest possible case that the present analysis to some degree bypasses certain extra-scientific complexities of Bohr's work and focuses on the relationships between the radical epistemology of quantum mechanics and the disciplinary specificity of physics there.[17]

Now, in physics the difference between classical and nonclassical theories may be defined (at least initially) without appealing to a priori ontological and epistemological claims upon the objects of investigation or the nature of the theory. Instead it may be defined in terms of physics itself (that is, in terms of the constitution of the data in question and the structure of the theories accounting for these data), as the difference between classical, sometimes also called Newtonian, and quantum physics.[18] The first, however, is indeed causal and realist, or at least it may be and commonly is interpreted as such consistently with the data and mathematical formalism of classical physics. The second is neither, at least in Bohr's interpretation. Nor, more crucially, would this interpretation allow one to assume it as either causal or realist. In other words, Bohr's interpretation of quantum mechanics does not merely (in a positivist vein) renounce realism and causality in interpreting quantum data, but instead rigorously *interprets* these data, as accounted for by the formalism of quantum mechanics, as disallowing for both causality and realism. The preceding formulations are asymmetrical. As I have indicated, there are arguments for classical-like interpretations of quantum mechanics, and Bohmian mechanics is classical-like, causal, and realist, although nonlocal. This question has always had much urgency in the debate concerning quantum physics and, to a considerable degree, has defined this debate. As I said, it is also, in principle, possible to interpret classical physics in epistemologically nonclassical terms. This possibility is actually more intriguing, although it has had rather less, if any, urgency. The classical ideal has always dominated modern physics and largely motivated the search for classical-like interpretations and versions of quantum theory as well. These questions do not affect my main argument here, for which the possibility of a rigorous nonclassical interpretation of quantum mechanics, such as that of Bohr, suffices. Beyond its immense philosophical significance, however, this possibility is also crucial in terms of physics, since, as Einstein was first to note, short of a nonclassical interpretation quantum mechanics could be shown to be nonlocal, that is, to be in conflict with relativity. Bohr's interpretation is also a response to this argument. I shall return to these considerations in my discussion of the EPR argument.[19]

Classical physics, such as Newtonian mechanics, is or may be interpreted as, ontologically, realist because it can be seen as fully describing all the (independent) physical properties of its objects necessary to explain their behavior. (At least, such is the case for idealized systems, when the properties in question are abstracted from other properties of the objects comprising a given system for the purposes of such a description.) It is or may be interpreted as, ontologically, causal because the state of the systems it considers (these systems may, again, be idealized) at any given point is assumed to determine its behavior at all other points. It is also, epistemologically, deterministic insofar as our knowledge of the state of a classical system at any point allows us to know, at least in principle and in ideal cases, its state at any other point. Not all causal theories are deterministic in this sense. Classical statistical physics and chaos theory (which is, in most of its forms, classical and is sometimes a direct extension of Newtonian mechanics) are causal or at least are assumed to be. They are, however, not deterministic even in ideal cases, in view of the great structural complexity of the systems they consider. This complexity blocks our ability to predict the behavior of such systems, either exactly or at all, even though we can write equations that describe them and assume their behavior to be causal. (Indeed the latter assumption is often necessary in these cases.) For similar reasons, it would be difficult to speak of Newtonian mechanics as truly deterministic (or even realist) in most actual cases, which need to be suitably idealized for Newtonian mechanics to do its job. In principle, however, as an idealization, it is a causal and deterministic theory, or can be interpreted as such, while classical statistical theory and chaos theory, are (while causal) not deterministic even as idealizations. In general, it does not follow that either causal or even deterministic theories are realist, since the actual behavior of a system may not be mapped by our description of it, even though we can make exact predictions concerning that behavior. Classical mechanics and chaos theory are, however, also realist insofar as such a mapping is assumed to take place, at least as a good approximation. By contrast, classical statistical physics, or at least the part of it that enables *statistical* predictions concerning the behavior of the systems it describes, is not realist insofar as its equations do not describe the behavior of its ultimate objects, such as molecules of a gas. It is, however, based on the realist assumption of an underlying nonstatistical multiplicity, whose individual members in principle conform to the strictly causal laws of Newtonian physics. The latter assumption becomes no longer possible in quantum mechanics in Bohr's interpretation.

We may expand the denomination "realist" to theories that are approximate in this sense, or further to theories that presuppose an independent reality that cannot be mapped or even approximated but that possess structure and attributes, or properties, in the usual sense. Indeed, realist theories may be described most generally by the presupposition that their objects in principle possess independently existing attributes (such as those conceived by analogy with classical physics) whether we can, in practice or in principle, ever describe or approximate them. Some, understandably, see this latter presupposition as a hallmark of realism.[20]

By contrast, Bohr's interpretation of quantum mechanics is irreducibly nonclassical. It is neither causal, nor deterministic, nor realist in any of the senses described above. The reasons for this are as follows. It is not only that the state of the system at a given point gives us no help in predicting its behavior or in allowing us to assume it to be causally determined, if unpredictable at later points (radical indeterminism and noncausality), but even this state itself cannot, at any point, be unambiguously defined on the model of classical physics (radical nonrealism). That is, the classical or classical-like concept of physical state cannot unambiguously apply.[21] This impossibility arises due to Heisenberg's uncertainty or indeterminacy relations, arguably the defining law of quantum physics, which, accordingly, have, in this interpretation, as much to do with the impossibility of realism as with the lack of causality.

It may be helpful to explain uncertainty relations in Bohr's interpretation, since there is so much confusion about them, especially in the humanities but sometimes even in specialized literature (in part because their meaning is interpretation dependent). In classical physics, the determination of the state of the system at any point—on the basis of our knowledge of it at a given point—is possible for the following reason. We always can, at least in principle, determine both locations and velocities or momenta (including their direction) for objects comprising this system at this point. The equations of classical physics allow us to do the rest. By contrast, in quantum mechanics (now in any interpretation), in view of uncertainty relations, we can measure with unlimited precision (that is, defined by the capacity of our instruments, rather than the nature of quantum physics), or indeed (at least in Bohr's interpretation) determine or unambiguously define either the position or the momentum of a quantum object. In Bohr's interpretation we need to speak, more accurately, of certain parts of a measuring instrument properly correlated with the object in question. We can never simultaneously determine both of these, as they are called, conjugate (the term retained from classical physics) variables. Instead such variables become rigorously complementary in Bohr's sense.

As follows from the above qualifications (concerning the necessity of always considering the measuring instruments correlated with the quantum objects), the situation is actually more complicated even in the case of a single variable. For we cannot, at least in Bohr's interpretation, unambiguously ascribe independent classical-like (or perhaps any) physical attributes to quantum objects. Accordingly, as Bohr argues, uncertainty relations "cannot . . . be interpreted in terms of attributes of objects referring to classical pictures."[22] Thus, uncertainty relations meaningfully apply to the data obtained in measurements resulting from the interactions between the quantum objects and the measuring instruments. They apply to the "indivisible" and always unique or, in Bohr's terms, (irreducibly) "individual" phenomena (using the latter term in the specific sense defined above). According to Bohr, "under [the] circumstances [of quantum mechanics] an essential element of ambiguity is [always] involved in ascribing conventional [and conceivably any] physical attributes to [quantum] objects."[23] This formulation ultimately applies even in the case of a single such attribute under all conditions, rather than only in the case of the joint attribution of complementary variables, more immediately forbidden by uncertainty relations.[24] This is arguably the most radical conception of nonrealism in quantum physics, which at the same time allows and, in Bohr's view, indeed enables one to maintain the rigorously scientific status of quantum theory. The main reason for this situation is, in Bohr's words (recurring throughout his writings), "the *impossibility of any sharp separation between the behavior of atomic [quantum] objects and the interaction with measuring instruments which serve to define the conditions under which the phenomena [i.e. what we actually observe] appear* [Bohr's emphasis]."[25]

From this perspective a more accurate explanation of the meaning of uncertainty relations is as follows. The *data* recorded in certain parts of our measuring instruments, as a result of their interactions with quantum objects, is of the same type as the data resulting from the measurement of classical objects in their interaction with measuring instruments. (In this sense, this macro-level data is "objective" or "realist.") In classical physics, however, we can, at least in principle, always measure both variables in question simultaneously, and indeed disregard or compensate for the interaction between the objects in question and measuring instruments. By contrast, in quantum mechanics we can only measure or, again, unambiguously define either one or the other *variable of that type*, but never both simultaneously. Hence, classical-like determinism is not possible even at this macro-level of measurement, while the *effects* of the interactions between quantum objects and measuring instruments upon the latter can be described in the realist manner. (Any single variable of either type by itself can always be predicted with the probability equal to unity, which, as will be seen, led Einstein to think, and to argue, that something is amiss in quantum theory, that it is perhaps incomplete. Not so, Bohr countered!) In Bohr's view, one can speak only of "variables of that type," rather than attributing them to the quantum object under investigation. Rigorously, such variables can be seen only as defining (in the classical manner) either the positional coordinates of the point registered in some part of the measuring instruments involved or, conversely, a change in momentum of another such part, under the impact of its interaction with the object under investigation. Hence, Bohr argues, in quantum mechanics the interactions between quantum objects and the measuring instruments can never be neglected or compensated for so as to allow us to attribute physical properties to quantum objects themselves in the way this can, at least in principle, be done in classical physics. As Bohr writes, "these circumstances find quantitative expression in Heisenberg's indeterminacy relations which specify the reciprocal latitude for the fixation, in quantum mechanics, of kinematical [position] and dynamical [momentum] variables required for the definition of the state of a system in classical mechanics." He adds a rather striking sentence: "[I]n this context, we are of course not concerned with a restriction as to the accuracy of measurement, but with a limitation of the well-defined application of space-time concepts and dynamical conservation laws, entailed by the necessary distinction between [classical] measuring instruments and atomic [quantum] objects."[26] In this interpretation, there is no presupposition that the quantum-mechanical formalism in any way describes the ("undisturbed") quantum process before the measurement interference takes place, or between instances of such interference. Accordingly, the formalism of quantum mechanics describes only these interactions and their impact on the measuring instruments, rather than the properties, even single properties (if one can still speak of properties here) or the behavior of quantum objects as such. In terms of the corresponding variables of the measuring instruments involved, both variables can never be simultaneously defined. By itself not even a single variable can ever be defined. Even in epistemologically less radical interpretations, the uncertainty relations prevent us, in practice and in principle, from determining or even defining the state of the system in the way we do in classical physics.

"The Typical Quantum Effects"

Arguably the best-known manifestation of complementarity is that associated with the wave and the particle aspects of quantum phenomena. Once properly considered (that is, once we establish what we specifically observe as waves or particles, in what particular circumstances, and so forth), this aspect of quantum physics can be connected to the uncertainty relations, and both to the statistical character of quantum mechanics. These connections are described in most standard accounts of quantum physics, including Bohr's writings cited here. It may be useful to recall the key features of the double-slit experiment—the "archetypal" quantum-mechanical experiment.

The arrangement consists of a source; a diaphragm with a slit (A); at a sufficient distance from it a second diaphragm with two slits (B and C), widely separated; and finally, at a sufficient distance from the second diaphragm a screen (say, a silver bromide photographic plate). A sufficient number (for a full effect it must be very large, say, a million) of elementary particles, such as electrons or photons, are emitted from the source and allowed to pass through both diaphragms and leave their traces on the screen. (I am provisionally speaking for the moment in terms of quantum objects themselves.) A wave-like interference pattern will emerge on the screen, or more accurately, a pattern analogous to the traces that would be left by classical waves in a corresponding media, say, water waves on the sand. That is, the pattern will emerge unless we install particle-counters or make other arrangements that would allow us to check through which of the two slits the particles that hit the screen pass. This pattern is the actual manifestation and, according to Bohr's interpretation, the only possible manifestation of the "wave" character of the quantum world. The pattern would appear whether we deal with what would prior to the advent of quantum physics classically be seen as wave-like phenomena, such as light, or particle-like phenomena, such as electrons. In this interpretation, at least, one can speak of "wave propagation" or of any attributes of the classical-like phenomenon of wave-propagation (either associated with individual particles or with their behavior as a multiplicity) prior to the time when these registered marks appeared only by convention or symbolically, or, again, allegorically. (The same, however, is also true concerning the attributes of classical particle motion, in particular trajectories.) It is also worth keeping in mind that, in accordance with the overall scheme here presented, we see on the screen only classically manifested traces of quantum objects. The objects themselves are destroyed in the process of what Bohr called the "irreversible amplification" of all our encounters with quantum objects to the classical level.[27]

If, however, there are devices allowing us to check through which slit particles pass, the interference pattern inevitably disappears. Its appearance entails the lack of knowledge as to through which slit particles pass. Thus, ironically (such ironies are characteristic of quantum mechanics), the irreducible lack of knowledge, the impossibility of knowing, is associated with the appearance of a pattern and, hence, with a higher rather than lower degree of order, as would be the case in, say, classical statistical physics. (Chaos theory is something else again.) Indeed, this fact of the disappearance of the interference pattern—once we can (even if only in principle) know through which slit each particle passes—can be shown to be strictly correlative to uncertainty relations.

The behavior just described, sometimes also known as the quantum measurement paradox, is indeed remarkable. Other standard characterizations include strange, puzzling, mysterious, and incomprehensible. The reason for this reaction is that, if one speaks in terms of particles themselves (this appears to be the main source of trouble) in the interference picture, the behavior of each particle appears to be "influenced" by the location of the slits. Or, even more radically, the particle appears somehow to "know" whether both slits are or are not open, or whether counting devices are installed or not. The first possibility may appear to imply that each particle would spread into a volume larger than the slit separation or would somehow divide into two and then relocalize or reunite so as to produce a single effect, a point-like trace on the plate. (The distance between slits can be very large relative to the "size" of the particles, thousands of times as large.) This type of view is sometimes found in literature on the subject. However, whether or not one subscribes to the particular interpretation under discussion here, the standard view is more or less as follows. Although having both routes open always leads to the interference effect, once a sufficient number of particles accumulates, any given particle passing through the slits should be seen as an indivisible whole (or, in Bohr's interpretation, the corresponding effects upon the measuring devices are individualized accordingly). There is no evidence that would compel us to conclude otherwise. Placing a detector in the experiment would always confirm this—at the cost of losing the interference pattern, a circumstance that can, as I said, be shown to be equivalent to uncertainty relations. In the so-called delayed choice experiment, we can make alternative arrangements, revealing either the particle-like or the interference pattern, long after the event, while we can never observe any "spreading" or "division" of single particles.

The situation can also be given a statistical interpretation, equally manifesting this apparently inescapable strangeness of the quantum world. I shall follow Anthony J. Leggett's elegant exposition, describing a different but equivalent experiment, in which instead of slits we consider the initial state A, two intermediate states B and C, and then a final state E. (The latter is analogous to the state of a "particle" at the point of its interaction with the screen in the double-slit experiment.) First, we arrange to block the path via state C, but leave the path via state B open. (In this case, we do not attempt to install any additional devices to check directly whether the object has in fact passed through state B.) In a large number (say, again, a million) of trials, we record the number of particles reaching state E. Then we repeat the same number of runs of the experiment, this time blocking the path via B, and leaving the path via C open. Finally, we repeat the experiment again with the same number of runs, now with both paths open. In Leggett's words, "[T]he striking feature of the experimentally observed results is, of course, summarized in the statement that . . . the number reaching E via 'either B or C' appears to be unequal to the sum of the numbers reaching E 'via B' or 'via C.' "[28] The probabilities of the outcomes of individual experiments will be affected accordingly. (In Bohr's interpretation, quantum mechanics predicts these probabilities, and only these probabilities, rather than accounts for the motion of quantum objects themselves in the way classical mechanics does for classical objects.) The situation is equivalent to the emergence of the interference pattern when both slits are open in the double-slit experiment. In particular, in the absence of counters, or in any situation when the interference pattern is found, one cannot assign probabilities to the two alternative "histories" of a "particle" passing through either B or C on its way to the screen. If we do, the above probability sum law would not be obeyed and the conflict with the interference pattern will inevitably emerge, as Bohr stressed on many occasions.[29] One may also put it as follows: we must take into account the possibility of a particle passing through both states B and C (and through both slits in the double-slit experiment), when both are open to it, in calculating the probabilities of the outcomes of such experiments. We cannot, however, assume that either such an event or self-interference physically occurs for any single particle. Leggett concludes,

> In the light of this result, it is difficult to avoid the conclusion that each microsystem [i.e., particle] in some sense samples *both* intermediate states B and C. (The only obvious alternative would be to postulate that the ensemble as a whole possesses properties in this respect that are not possessed by its individual members—a postulate which would seem to require a radical revision of assumptions we are accustomed to regard as basic.)
>
> On the other hand, it is perfectly possible to set up a "measurement apparatus" to detect which of the intermediate states (B or C) any particular microsystem [particle] passed through. If we do so, then as we know we will always find a definite result, i.e., each particular microsystem is found to have passed *either* B *or* C; we never find both possibilities simultaneously represented. (Needless to say, under these [different] physical conditions we no longer see any interference between the two processes.) . . . (Clearly, we can read off the result of the measurement only when it has been amplified to a macroscopic [classical] level, e.g. in the form of a pointer position [of measuring instruments].)[30]

The first possibility corresponds to more familiar questions, such as "How do particles know that both slits are open or, conversely, that counters are installed, and modify their behavior accordingly?" The alternative proposed by Leggett would be as remarkable (or intriguing) as any "explanation" of the mysterious behavior of quantum objects. And it is always mysterious and, indeed, impossible, if one tries to think of such objects and their behavior as independent of their interaction with the measuring devices. In sum, any attempt to picture or conceive of this behavior (leading to the effects in question) in the way we do it in classical physics appears to lead to a logical contradiction; or be incompatible with one aspect of experimental evidence or the other; or entail (by classical or any conceivable criteria) strange or mysterious behavior; or require more or less difficult assumptions, as the one described by Leggett; or, as Einstein argued, imply nonlocality, forbidden by relativity. One finds the latter in David Bohm's and other interpretations based on hidden variables.

Bohr, by contrast, sees the situation as revealing the essential ambiguity in ascribing conventional (and perhaps any) physical attributes, such as wave-like or particle-like behavior, to quantum objects themselves or in referring to their independent behavior. As he writes, "To my mind, there is no other alternative than to admit that, in this field of experience, we are dealing with individual [interactive] phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study."[31] At least, this interpretation allows one to avoid the difficulties and paradoxes just discussed.

In fact, eventually these individual (interactive) phenomena, rather than indivisible quantum objects, the ultimate atoms of nature, become Bohr's interpretation of the quantum "atomicity" (in the original Greek sense of being indivisible any further) of matter, discovered by Planck. By contrast, quantum "objects" themselves are not assigned and, it is argued, cannot be assigned atomicity any more than any other features, properties, and images—such as "wave-like." The phenomena in question are indivisible, first, in the sense that, in the situation of quantum measurement (or any interactions we may have with the quantum world), they are all that we can in principle have and the existence of which can be assigned a classical-like reality. This "invidivisibility" makes it impossible to isolate quantum objects rigorously. Bohr's phenomena are further indivisible in the sense of being unsubdividable. For any attempt at a subdivision of a phenomenon can only produce another indivisible phenomenon or a set of phenomena of the same nature; hence, such an attempt will always retain or reinstate complementarity (rather than allowing a reconstitution of it into a classical-like wholeness). Planck's or, now, Bohr's quantum postulate itself becomes a technological concept, the concept defined through the role of measuring instruments. As Bohr says, "the individuality of the typical quantum effects finds its proper expression in the circumstances that any attempt of subdividing the phenomena will demand a change in the experimental arrangements introducing new possibilities of interaction between [quantum] objects and measuring instruments."[32] Accordingly, in Bohr's interpretation, every event in question in quantum physics is individual in the sense of being unique, singular, unrepeatable, and, in itself, not predictable or, more generally, not comprehended by law, which in quantum mechanics applies only to collective regularities (such as the interference pattern in the double-slit experiment). Quantum atomicity (indivisibility) becomes quantum *individuality* in the ultimate sense of uniqueness of individual quantum events. Quantum "atomicity" appears at the level of the interaction between quantum (micro) objects and classical measuring (macro) instruments, rather than that of quantum objects themselves. From this perspective, the only "atoms" that can be rigorously described by quantum theory are "techno-atoms"—certain indivisible configurations of experimental technology. This circumstance prevents any possibility for quantum objects to appear independently, outside of, in this sense, techno-phenomenological enclosures of specific experiments. We only have access to certain effects of the interaction between quantum objects and measuring instruments upon such enclosures, of which the particular character is determined by these effects. In Bohr's interpretation, quantum mechanics describes such "closed phenomena" and only them, rather than the behavior of quantum objects themselves as the ultimate constituents of nature.[33]

At the (classical) level of phenomena, thus defined, all proper references to the data become "objective," that is, unambiguously defined and unambiguously reportable, and hence not subjective. One may even use the concept of reality (although not causality) in relation to this data, since one deals with the classical physics of measuring instruments. It also follows that "in complementary description all subjectivity is avoided by proper attention to the circumstances [of complementary measurement] required for the well-defined use of elementary concepts."[34]

"Probabilities for the Occurrence of the Individual Processes"

Due to complementarity (mutual exclusivity), "in this situation, there could be no question of attempting a causal analysis of [quantum] radiative phenomena [or any phenomena in question in quantum physics], but only, by a combined use of the contrasting [complementary] pictures, to estimate probabilities for the occurrence of the individual radiation processes." Bohr adds,

> However, it is most important to realize that the recourse to probability laws under such circumstances is essentially different in aim from the familiar application of statistical considerations as a practical means of accounting for the properties of mechanical systems of great structural complexity [as in classical statistical physics]. In fact, in quantum physics, we are presented not with intricacies of this kind, but with the inability of the classical frame of concepts to comprise the peculiar feature of indivisibility, or "individuality," characterizing the elementary processes.[35]

I cannot consider the history of the concepts of chance and probability in mathematics, science, and philosophy from the seventeenth century on, even though this and the earlier history of chance (from Democritus on) as well as the history of materiality (in particular atomism) are crucial here, as Bohr points out.[36] Instead, using this history as a background, I shall outline the *nonclassical* character of the quantum-mechanical concept of chance. Although not without its earlier predecessors, this character defines twentieth-century thinking about chance, whether mathematical-scientific (for example, not only in quantum physics but also in post-Darwinian biology and genetics) or philosophical (specifically in Nietzsche, Bataille, Blanchot, Lacan, Deleuze, de Man, and Derrida). It is worthwhile, however, to revisit the *classical* understanding of chance first.

Classically, chance or, more accurately, the appearance of chance is seen as arising from our insufficient (and perhaps, in practice, unavailable) knowledge of a total configuration of forces involved and, hence, of the lawful necessity that is always postulated behind a lawless chance event. If this configuration becomes available, or if it could be made available in principle (it may, again, not ever be available in practice), the chance character of the event would disappear. Chance would reveal itself to be a product of the play of forces that is, in principle, calculable by humans, or at least by God or Geist, as in, among others (but in an especially complex and interesting way), the thinkers Leibniz and Hegel. Most classical mathematical or scientific theories and the classical philosophical view of probability are based on this idea: in practice, we have only partially available, incomplete information about chance events, which are nonetheless determined by, in principle, a complete architecture of necessity behind them. This architecture itself may or may not be seen as ever accessible in full (or even partial) measure. The *presupposition* of its existence is, however, essential for and defines the classical view as causal and, on the definition given earlier, realist. On precisely this point classical reality and classical causality come together; or rather this point (the assumption of the ultimate underlying causal architecture of reality) brings them together.[37]

For example, if we cannot fully (rather than only in terms of probabilities) predict how the dice will fall, or fully explain why a particular outcome has occurred, it is because the sum total of all the factors responsible is, in practice, unavailable to us. These factors may extend from a particular movement of a human (or perhaps divine) hand to minute irregularities in the material makeup of the dice themselves. In principle, however, a throw of dice obeys the laws of classical, Newtonian physics (or else chaos theory, which would change the essence of the point in question). If we knew all such factors, we could predict and explain the outcome exactly by using these laws, which would describe both individual and collective behavior, and correlate them, in accordance with classical physical (or philosophical) laws.[38]

Subtle and complex as they may be, all scientific theories of chance and probability prior to quantum theory and many beyond it, such as chaos theory, and most philosophical theories of chance from the earliest to the latest are of the type just described. They are *classical* or, in the sense explained above, causal. Most of them are also, and, as was just pointed out, often interactively, realist. Combined, two of Alexander Pope's famous utterances, the closing of the Epistle 1 of *An Essay on Man* and his "Proposed Epitaph for Isaac Newton," encapsulate the classical view of chance and law, even though they are not without a few ironies. (Some of them can hardly be seen as unintended on Pope's part.) Pope writes,

> All Nature is but art, unknown to thee;
> All chance, direction, which thou canst not see;
> All discord, harmony not understood;
> All partial evil, universal good:
> And, spite of pride, in erring reason's spite,
> One truth is clear: Whatever IS, is RIGHT.
>
> (*An Essay on Man*, 289–94)

Nature and Nature's laws lay hid in night;
God said, let Newton be! and all was light.
("Proposed Epitaph for Isaac Newton, who died in 1727")

The *nonclassical* understanding of chance is fundamentally different, as should be clear from Bohr's formulation, cited above.[39] Nonclassically, chance, or (classical-like configurations are also allowed within nonclassical theories) nonclassical chance, is irreducible not only in practice (which may be the case classically as well) but also, and most fundamentally, in principle. There is no knowledge, in practice or in principle, that is or ever will be, or could in principle be, available to us and would allow us to eliminate chance and replace it with the picture of necessity behind it. Nor, however, can one postulate such a causal/lawful economy as unknowable (to any being, individual or collective, human or even divine) but existing, in and by itself, outside our engagement with it. This qualification (which, in Bohr's interpretation, entails and results from the suspension of realism at the ultimate level of description) is crucial. For, as I explained above, some forms of the classical understanding of chance allow for and are, indeed, defined by this type of realist assumption. By contrast, nonclassical chance, such as that which we encounter in quantum physics, is not only unexplainable in practice and in principle but is also irreducible in practice and in principle. It is irreducible to any necessity, knowable or unknowable. It is, in David Bohm's words, *irreducibly* lawless.[40]

Quantum theory requires, and depends on, the concept of the individual physical event. The individuality of such events is essential, in the strict sense of being irreducible. It is, in part, this concept that defines quantum mechanics as quantum, even though it has, Bohr argues, to be given a complex (and in particular nonrealist) architecture. This is what Bohr specifically achieves by configuring such events as indissociable from the irreducible interactions between quantum objects and measuring instruments. That is, even this individuality or/as uniqueness appears (in either sense) at the level of phenomena rather than of quantum objects themselves or, more accurately, as it may be called (in opposition to causality) the "efficacity" of individual (or any other) phenomenal effects. This efficacity itself may not tolerate the attribute of individuality, or for that matter chance, any more than any other attribute. While (and in part by virtue of) ultimately suspending the individual identity of quantum objects themselves, the individuality of each quantum phenomenon (in Bohr's sense) remains crucial. At the same time and by the same token, quantum mechanics offers us no laws that would enable us to predict with certainty the outcome of such individual events, or when some of them might occur. In contrast to classical statistical physics, the laws of quantum mechanics rigorously allow for the irreducible individuality, the irreducible "unlawfulness" or "lawlessness" of individual quantum events, even as, similarly (but not identically) to classical statistical physics, they provide a rigorous (statistical) account of the behavior of quantum collectivities. This is why Bohr says that "the recourse to probability laws under such circumstances is essentially different in aim from the familiar application of statistical considerations as practical means of accounting for the properties of mechanical systems of great structural complexity."

"An Essential Ambiguity"

It is, however, in confronting the question of reality that quantum mechanics reaches its most radical nonclassical limits (those of Bohr's interpretation) and becomes the site of the greatest epistemological debate in modern science. As we have seen, Heisenberg's uncertainty relations, arguably the defining quantitative manifestation of the nonclassical nature of quantum mechanics, may be even more about the lack of realism than causality and determinism in quantum physics.[41] The term "unknowability relations" has been suggested as reflecting the situation more accurately.[42] Quantum nonrealism, however, manifests itself across the spectrum of our encounters with the quantum world and the range of quantum theory.

In their famous article arguing for the incompleteness of quantum mechanics, to which Bohr's propositions cited in my epigraph reply, Einstein, Podolsky, and Rosen (EPR) propose the following, apparently rather natural and minimal, criterion of physical reality: "If, *without in any way disturbing a system* [emphasis added], we can predict with certainty the value of a [single] physical quantity [say, the momentum or the position of a "particle"], then there exists an [independent] element of physical reality corresponding to this physical quantity."[43] It may appear that this criterion applies to quantum mechanics as well. Recall that, in view of uncertainty relations, it is only a joint simultaneous determination of two variables involved in the quantum-mechanical physical description, such as "position" and "momentum," that is impossible in quantum mechanics. A determination or prediction of the value of a single variable is always possible, with any degree of precision. Some adjustment of the earlier argument is necessary. For, in contrast to the way the situation was described earlier, such a determination must now take place without "disturbing" the quantum system under investigation by measurement, that is, without first performing a measurement upon it, which is how quantum-mechanical predictions are made in more standard cases. More accurately, one should speak, as Bohr does, of not interfering with this system, since, as we have seen, there is no classical-like or otherwise specifiable (undisturbed) configuration that is disturbed in the process. This can indeed be done for *a single variable* in quantum mechanics in certain cases, such as that considered by EPR. (The fact that this can be done only for a single such variable remains crucial, as it indicates that uncertainty relations still apply in this case.) It is achieved by means of performing measurements on other systems (for example, as in the EPR argument, another particle) that have previously been in an interaction with the system (such as a particle) under investigation. (Here I am speaking conventionally of "particles" rather than, as would be more appropriate and as Bohr does, of "variables involved in the quantum-mechanical physical description.") Indeed, as Bohr argues in his commentaries on the EPR argument, in a certain sense, this is always the case in quantum-mechanical predictions. In any standard situation of quantum measurement, we can predict (in accordance with the uncertainty relations), say, the position of a particle after a preceding measurement took place (and on the basis of this measurement) and hence without interfering with the particle in question. In the EPR situation, which involves two particles, we have a slightly, but not fundamentally, more complicated case. Predictions (limited by uncertainty relations) concerning a given particle are possible on the basis of measurements performed on another particle that has previously been in an interaction with the first particle, but that, at the time of measurement, is in a region spatially separated from the latter. Hence, at the time of determination in question, there is no physical interaction either between the two particles or between any measuring apparatus and one of the two particles in question. This circumstance led some, beginning with Einstein, to conclude that there are some nonlocal connections involved. Einstein famously called them "spooky action at a distance." Bohr did not think that such connections are implied by the circumstances of measurement just described, in part because he saw them as correlative to the EPR criterion of reality, which he argued to be, in fact, inapplicable in quantum mechanics. "According to their criterion," Bohr wrote in his reply, "the authors therefore want to ascribe an element of reality to each of the quantities represented by such variables. Since, moreover, it is a well-known feature of the present formalism of quantum mechanics that it is never possible, in the description of the state of a [quantum-] mechanical system, to attach definite values to both of two canonically conjugate variables, they consequently deem this formalism to be incomplete, and express the belief that a more satisfactory theory can be developed."[44]

I shall not here present EPR's subtle argument and Bohr's equally subtle reply.[45] The key point is this. If one accepts the EPR criterion of reality as applicable in quantum physics, quantum mechanics can indeed be shown to be incomplete, or more accurately (this is, in fact or in effect, what EPR argue) either incomplete or nonlocal, that is, entailing an instantaneous action-at-a-distance, as just indicated.[46] The latter would be in conflict with relativity, which prohibits all such actions and which is an experimentally fully confirmed theory. Accordingly, perhaps the only effective counterargument would be to show that the EPR criterion is ultimately inapplicable in the situation in question in quantum mechanics. Epistemologically this would mean that quantum physics rigorously disallows even the minimal form of realism entailed by the EPR criterion. This is what Bohr argues. Or, again, at least he argues that one can interpret quantum mechanics accordingly, which is sufficient for my purposes here, since it makes a nonclassical view of quantum theory at least viable, even if not inevitable. It is a separate question whether other interpretations of quantum mechanics also allow one to handle these difficulties, which is beyond my scope here. At the very least, it may be argued that Bohr's was the first such interpretation. In any event, in Bohr's view, one cannot unambiguously ascribe, as EPR do in accordance with their criterion of reality, even a single physical attribute (or ultimately even identity) to a quantum object as such—that is, as considered independently of measurement and hence of our interaction with it by means of experimental technologies. As Bohr states at least three times in "Discussion with Einstein," in "the analysis of typical quantum effects," we are faced precisely with "the impossibility" of drawing "any sharp separation between an independent behavior of [quantum] objects and [their] interaction with the measuring instruments."[47] We cannot do so even though we can, in quantum mechanics, predict the outcome of such measurements on the basis of earlier measurements performed on the object in question or on the basis of contemporaneous measurements performed on other objects, which have previously been in interaction with the object in question, as indicated above. Hence, such measurements would not involve the object in question at the time of determination of the variables concerned, which is crucial to EPR.

It is worth keeping in mind the following circumstances of quantum measurements and the following aspects of Bohr's interpretation. Measuring instruments and the observable effects of their interaction with quantum objects are described classically (and thus also in the realist way), although the sum total of these effects cannot be accounted for by means of classical physics, and therefore requires quantum theory. The ultimate nature of this interaction is quantum, however, which makes it in practice uncontrollable (thus disabling the simultaneous exact measurement of both conjugate variables) and, in its quantum aspects, theoretically indescribable. In this latter respect, this interaction is no different from any quantum process, which, in Bohr's interpretation, is never theoretically describable as such; only its effects (upon measuring instruments) are, as Bohr says in the statement just cited. Bohr's customary caution and precision are especially crucial here: "quantum effects" are all that is available to us, never quantum causes. It is the irreducible interaction between quantum objects and measuring instruments that is responsible for the radical (Derrida would say "supplementary") epistemology of quantum effects without quantum causes, or any ultimate causes.[48] The interaction in question cannot be seen as the ultimate cause here, given that its ultimate nature is itself quantum.

Throughout his writing, Bohr stresses this interaction and its irreducible nature, which, he argues, define any phenomena that can be meaningfully considered in quantum physics. These are the circumstances that he has in mind when he says that "under these circumstances an essential element of ambiguity is involved in ascribing [any] conventional physical attributes [single or joint] to quantum objects [themselves]."[49] Given that this interaction is, in fact, irreducible, he is able to argue "a criterion like that proposed by [EPR] contains . . . an essential ambiguity when it is applied to the actual problems with which we are here concerned."[50] For, in view of this interaction, we cannot unambiguously ascribe, again as EPR do in accordance with their criterion, independent properties to quantum objects, ultimately even to a single such property, let alone both complementary ones, or again, at the limit, even independent identity to quantum objects.[51] Thus, "the apparent contradiction [found by EPR] in fact discloses only an essential inadequacy of the customary viewpoint of natural philosophy for a rational account of physical phenomena with which we are concerned in quantum mechanics."[52] Instead, the irreducibility of this interaction "entails the necessity of the final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality," or, again, at least this interpretation of quantum mechanics allows one to effectively reply to the EPR argument.[53] This interpretation of quantum mechanics rigorously limits and redelimits (which is not to say abandons) both causality and reality in the sense of classical physics and of the classical philosophy of nature. Bohr's language here and throughout his works is the language of the disciplinarity of physics, and the language of concern with this disciplinarity.

The preceding summary is hardly adequate to do justice to, or fully to evaluate the merits of both sides of, the argument between Bohr and EPR, or the Bohr-Einstein debate more generally.[54] This is not the aim of, nor is it required for, my argument here, however, which concerns only Bohr's conclusions and the implications of these conclusions for his view of the basic principles of science. To cite these conclusions,

> [T]he argument of [EPR] does not justify their conclusion that quantum-mechanical description [of physical reality?] is essentially incomplete. On the contrary this description, as appears from the preceding discussion [i.e., in Bohr's interpretation], may be characterized as a rational utilization of all possibilities of unambiguous interpretation of measurements, compatible with the finite and uncontrollable interaction between the [quantum] objects and the measuring instruments in the field of quantum theory. In fact, it is only the mutual exclusion [in view of this interaction] of two experimental procedures, permitting the unambiguous definition of complementary physical quantities [such as position and

> momentum], which provides room for new physical laws [i.e., the laws of quantum mechanics], the coexistence of which might at first sight appear irreconcilable with the basic principles of science [but is ultimately not]. It is just this entirely new situation as regards the description of physical phenomena, that the notion of *complementarity* [now in Bohr's extended sense] aims at characterizing.[55]

Bohr, intriguingly, omits "reality" here. This omission may have been deliberate, and is certainly telling. The completeness of quantum-mechanical physical description may no longer allow for reality in EPR's sense, that is, an independent physical reality, defined by postulating the existence, on the classical model, of physical properties of objects (or, again, conceivably, such classical-like objects themselves) as independent of their interaction with measuring instruments. Instead, in Bohr's interpretation, quantum-mechanical physical description refers to "phenomena" defined as the overall experimental arrangements within which quantum effects (such as marks left in our measuring devices) manifest themselves.[56] Thus, according to Bohr, the irreducible interaction between quantum objects and measuring instruments, while indeed incompatible with the classical ideals of causality and reality, is by no means incompatible with "the basic principles of science." This compatibility, however, is only possible if one properly interprets what is, in fact, available to an unambiguous account in the entirely "new situation" we encounter in the field of quantum theory, and what this theory actually unambiguously accounts for and how it goes about this accounting.[57] Bohr's interpretation, which rigorously follows this requirement, "may be characterized as a rational utilization of all possibilities of unambiguous interpretation of measurements, compatible with the finite and uncontrollable interaction between the [quantum] objects and the measuring instruments in the field of quantum theory." As such it also "provide[s] room for new physical laws [the laws of quantum physics], the coexistence of which might at first sight appear irreconcilable with the basic principles of science."

Bohr's argument is, thus, as follows: were it not for the irreducibility of "the finite and uncontrollable interaction between the [quantum] objects and the measuring instruments in the field of quantum theory,"

> **a.** EPR would be right: quantum theory would be incomplete, or else nonlocal (or at least short of an interpretation that ensures both completeness and locality); and
>
> **b.** there would be no room for the laws of quantum mechanics as physical laws (the same type of parenthesis as in statement "a" is required).

The laws of quantum mechanics may appear, in particular to EPR, to be "irreconcilable with the basic principles of science." Quantum mechanics, however, accounts for its data as well as any classical theory does for its data, which is what EPR tried, ultimately unsuccessfully, to question. It may, thus, depend on which principles one sees as basic to science, both in general and insofar as such principles can be applied in the case of quantum physics. Bohr argues as follows: if, rather than a conformity with a particular criterion of physical reality, such principles or criteria are the logical consistency of a given theory and its correspondence with the available experimental data, and if a theory can be seen as "exhausting the possibilities of observation," as, according to Bohr, quantum mechanics does within its proper limits and properly interpreted, then he cannot see how Einstein's argumentation could be directed toward demonstrating the inadequacy of quantum mechanics.[58]

"The Basic Principles of Science"

Accordingly, along with the reexamination of the classical ideals of causality and reality necessitated by quantum mechanics, a similar, and indeed parallel and interactive, reexamination of what constitutes the basic principles of science appears to be rigorously necessary. For, on the one hand, the EPR criterion of reality cannot unambiguously apply to the "entirely new situation as regards the description of physical phenomena" in question in quantum mechanics. On the other hand, quantum mechanics itself comprehensively accounts for these phenomena and, hence, is as rigorously scientific as any (classical) mathematical science in every respect (other than causality and reality). Clearly, one needs to (re)consider what the basic principles of science are. This is a crucial point: physics itself, not philosophy, requires this reconsideration, as Heisenberg observes in the passage cited earlier. Indeed, according to Heisenberg, "Bohr was primarily a philosopher, not a physicist, but he understood that natural philosophy in our day and age carries weight only if its every detail can be subjected to the inexorable test of experiment."[59] In the present case, this test may entail the irreducibly nonclassical character of natural philosophy once one considers nature at the quantum level, the level of its ultimate constituents. The basic principles of science must be weighed and, if necessary, adjusted accordingly.

Ironically, however, the basic principles of science (I shall spell them out presently), as seen by Bohr, are in accord with the defining aspects of the project and practice of classical physics, beginning with Galileo, to whom Bohr specifically refers in this context.[60] It is true that Einstein and many others would see certain other (philosophical) principles as equally basic. Accordingly, Bohr's argument concerning quantum mechanics also suggests that the basic principles of science qua science may, at a certain point, come into conflict with those metaphysical principles, however consistent the latter may be with classical physics.

What are the basic principles of science, according to Bohr's view? What would define the science and the discipline (both as a field of study and as a system of governing laws) of physics as, to use Galileo's locution, a (modern) "mathematical science of nature"? There are, as I can see it, more or less four such principles, which are described in the next paragraph. Further qualifications and nuances are necessary, partly in view of the massive recent reconsideration of the nature and the character of scientific knowledge. It may be shown that, in essence, these formulations are consistent with this reconsideration—at its best. The works involved are not without their own problems, sometimes as severe as those of the classical views in question in this reconsideration, with which, at their best, the principles in question can in turn be correlated. At the moment, however, I am more interested in arguably a stronger point, that of the compatibility of nonclassical epistemology even with the basic principles of science as seen from a traditional perspective, or at least with some of these principles, and possibly with the most crucial ones.

1. *The mathematical character of modern physics*. By this I mean the following; and I think, with both Galileo and Bohr, that this is what modern physics most fundamentally is: it is the usage of mathematics as a particular way of offering *convincing* arguments about certain aspects of and certain facts pertaining to the physical world, rather than necessarily mathematically representing the ultimate nature or structure of this world.[61] The latter, as we have seen, is rigorously impossible to do in quantum physics, at least in Bohr's interpretation. This point is crucially implicated in the Bohr-Einstein debate, and there appear to be significant differences in this respect between Galileo's and Newton's project and philosophy of science, or their philosophy of nature itself, as well. For Galileo a science of motion is a construction of convincing mathematical arguments about certain facts and aspects of nature. For Newton, it is a representation of nature, grounded in the classical realist claim that nature possesses a structure that can ultimately (at least by God) be represented mathematically. The latter view in fact defines the attitude, or one might say, ideology of most physicists including many of those who do quantum physics. Exceptions are few.[62]

2. *The principle of consistency*. While these physical theories (or the arguments and interpretations involved) may exceed their mathematical aspects—as may be the case especially in quantum physics—they must also offer logically consistent arguments. In his *The Interpretation of Quantum Mechanics*, Roland Omnès bases his whole interpretation of quantum mechanics around logical consistency.[63] There are important further nuances to this principle as well, which I must bypass here. In any event, these theories must be as logically consistent as anything can be.

3. *The principle of unambiguous communication*. These theories, in their mathematical and nonmathematical aspects alike, must allow, within the practical limits of the functioning of science, for the (sufficiently) unambiguous communication of both the experimental results and theoretical findings involved. This is what Bohr's interpretation of quantum mechanics also "provides room for," in part by virtue of exploring the possibilities of the unambiguous definition of all physical variables and aspects of physical description involved. (The concepts of "unambiguous definition" and "unambiguous communication" become especially crucial for Bohr in the wake of the EPR argument.)

4. *The principle of experimental rigor* (based, at least from Galileo on, on the concept of measurable quantities). These theories must correspond to and, within their limits, exhaust the experimental data they aim to account for, although this data is, of course, itself subject to interpretation. Certainly, in quantum physics, the question of how one interprets its data is as crucial as, and reciprocal with, that of how one interprets quantum theory. Much more is to be said on this point as well (even leaving aside the question of the social construction of theories and related arguments, which would affect the principles of consistency and unambiguous communication as well). The principle itself, however, remains crucial.

Physical laws would then be seen and defined as physical laws in accordance with these principles, which—this is my point—define *both* classical and quantum physics. In order, however, to maintain them rigorously in the case of quantum physics, one must, according to Bohr, accept the radical epistemology of quantum physics. If one does so, however, one must also abandon, at the level of the quantum world, certain other, primarily epistemological and ontological, principles, applicable, alongside the basic principles of science as just outlined, in classical physics. The epistemological radicality of quantum physics becomes, rigorously, the condition of its disciplinarity as physics, and indeed establishes the continuity with classical physics, which would otherwise be broken.[64]

According to this view, the break from classical physics occurs at the level of epistemology, not at that of the character and the practice of physics as a mathematical science or, since, as Heidegger argues, both define each other in science, as a mathematical-experimental science.[65] As I have stressed throughout, classical epistemology is not simply abandoned either. Along with classical science it continues to function within its proper limits and is often part of nonclassical theories as well, which often depend on it. Quantum epistemology itself is, of course, fundamentally and irreducibly reflected in both the specific character of the phenomena observed (unexplainable by means of classical physics) and the mathematical formalism that explains these phenomena. This is why Bohr often speaks of the *epistemological* lesson of quantum mechanics. He rigorously derives his radical epistemology from the mathematical-experimental structure of quantum theory.

The laws of quantum physics are the laws of nature only in the sense of corresponding to the "regularities" that nature allows to our interaction with it, specifically by means of experimental technology. The term is used by Bohr in speaking of "the new types of regularities," which we encounter as effects of the interaction between the ultimate quantum constituents of nature and our measuring technology, and which cannot be accounted for by classical physics.[66] Quantum mechanics, however, does not describe the nature or structure of these ultimate constituents themselves. There is nothing that quantum theory, or in view of its laws, conceivably any theory, can say about these constituents as such. As an epistemologically nonclassical theory, quantum mechanics may be said to represent the interaction between what is representable by classical means (which may indeed be seen as defining representability, accordingly always classical)—here measuring instruments, described by the laws of classical physics (which allows for a realist and causal interpretation)—and what is unrepresentable by any means, classical or nonclassical—here, "quantum objects." This unrepresentable is ultimately unrepresentable even as something that is absolutely unrepresentable, which is, epistemologically, merely a Kantian, things-in-themselves-like, form of classical representation. (The degree to which Kant himself subscribed to this "Kantian" view is a separate question.) The view just presented is generalizable to nonclassical theories elsewhere, and may indeed be seen as defining them.

Otherwise, however, quantum mechanics and Bohr's interpretation of it conform to all traditional principles defining the project and practice of the "mathematical sciences of nature" beginning with Galileo (whose title I cite here). Indeed, as I said, one might argue that, in contrast to Newton, Galileo sees the project of his mathematical sciences of nature, specifically his mathematical science of motion of material bodies, in epistemologically similar terms, as exploring certain regularities in nature and accounting for them by means of mathematical arguments. Of course, Galileo's physics is classical in other respects, in particular as regards causality. Quantum mechanics at the very least allows for, even if not necessitates (it may ultimately do this too), compatibility between "the basic principles of science" and nonclassical epistemology, and was the first theory to do so. One might argue (as Bohr does) that Einstein's relativity would pose some of these questions already and perhaps all of these questions, once all the chips or (we may never have all) more chips are in.

I would argue that the overall situation here described can be extrapolated to a number of figures mentioned earlier, specifically Nietzsche, Heidegger, Bataille, Levinas, Blanchot, Lacan, Deleuze, Derrida, and de Man. This, it may be added, also applies to the relationships between the thought of these thinkers and modern science in its nonclassical aspects. This is why there is a certain, perhaps fundamental, philosophical connection between nonclassical science and nonclassical philosophy. The list of figures in question is, as

I said, not random, and my argument may be more difficult in some of the cases just mentioned (and it will not be applicable at all in still other cases). As in Bohr's case, however, some of the most radical epistemological thinking involves the deepest concerns in regard to the basic principles of their disciplines. Obviously, in some of the cases just mentioned, the disciplinary determination itself—Philosophy? Criticism? Psychoanalysis?—or the determination of the stratifications within, and the interactions among, such fields is extremely difficult. Accordingly, some adjustment of the preceding argument will be necessary, to some degree in contrast with science and especially physics. There at least we have the discipline (in either sense) of mathematics, on the one hand, and of conformity to the experimental data, on the other, however complex these determinations become at certain points, or perhaps, in fact, always are. My argument, however, is that

> **a.** even in the case of science, nonclassical epistemology is not in conflict with its basic principles—it is or at certain points becomes the conditions of applicability of such principles; and
>
> **b.** one encounters what I called earlier the extreme disciplinary conservatism of the thinkers in question—a conservatism that runs contrary to common claims and some appearances, and that arises out of their extreme reluctance to bring a radical change in or shift to nonclassical accounts, which they finally do only at points and in regions where there is really no choice, in the sense that their discipline (in either sense) in fact requires it. Indeed, it appears that in such cases one needs to be both an extreme radical and an extreme conservative, along different lines, and sometimes even the same, or at least interactive and mutually depending, lines.[67]

That both of these facts are commonly overlooked largely accounts for the persistent misunderstanding of the thought of the figures in question, and for the misshapen nature of some of the recent debates in which they figure prominently.

"The Highest Musicality in the Sphere of Thought"

Einstein deeply understood this aspect—the simultaneously radical and conservative nature—of Bohr's thought, even though and perhaps because he never accepted his views or quantum mechanics as a way to describe nature. (He did, however, recognize its practical effectiveness.) In 1949, after a quarter of century of their debate, he spoke of some of Bohr's radical (in the present sense) physics as "the highest musicality in the sphere of thought."[68] A very good violin player and an admirer of Haydn, in particular, Einstein wanted and tried to give this music a more classical shape, and urged others to do so. Neither he nor others ever succeeded. Bohr, although, by contrast, a bad piano player, was in every sense a contemporary of Schönberg. Haydn, however, let alone Bach, Mozart, and Beethoven, may be much closer to Schönberg than Einstein thought. This is not merely, or even primarily, a statement about how to perform Haydn's music differently (although it is this, too). Instead this is a statement about Haydn as a classical composer, in either, or neither, sense of this strange, nonclassical word "classical."

Notes

Epigraph is from Bohr's article, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" in *Quantum Theory and Measurement*, ed. John Archibald Wheeler and Wojciech Hubert Zurek (Princeton: Princeton University Press), 145–51.

1. I cannot here consider Planck's law and its history, or key events following Planck's discovery and leading to quantum mechanics and its interpretation. For arguably the best account of the early stages of this history, see Thomas S. Kuhn's *Black-Body Theory and the Quantum Discontinuity, 1894–1912* (New York: Oxford University Press, 1978). Bohr gives an excellent and conceptually crucial account in his "Discussion with Einstein on Epistemological Problems in Atomic Physics," *The Philosophical Writings of Niels Bohr* (hereafter *PWNB*), 3 vols. (Woodbridge, Conn.: Ox Bow Press, 1987), 2:32–36. Some of Werner Heisenberg's essays, in particular "Development of Concepts in the History of Quantum Mechanics" and "The Beginnings of Quantum Mechanics in Göttingen," both in *Encounters with Einstein* (Princeton: Princeton University Press, 1983), as well as his more technical works, are also exceptionally useful. See also introductory and historical material in volumes 5, 6, and 7 of *Niels Bohr: Collected Works*, 10 vols. (Amsterdam: Elsevier, 1972–96).

2. The latter concepts are not independent of other conventional idealized physical or mathematical attributes. In the case of particles, such attributes would include "position" and "momentum" (in their simultaneous application, no longer possible in quantum mechanics in view of uncertainty relations) or "trajectories of motion" in classical physics (classical-like trajectories are in turn, and indeed correlatively, prohibited in quantum mechanics in most interpretations). In the case of elementary particles of modern quantum physics, such attributes would also include their mathematically point-like (structureless) character, which is the standard and seemingly irreducible idealization in quantum physics. Short of string theories, it appears impossible to treat elementary particles otherwise, even though such "objects" are not seen as likely to exist in nature. Of course, from Newton on, the objects of classical physics, too, are often idealized as (massive) dimensionless material points, and more often the motion of classical objects as that of such points. There, however, this idealization is necessary because of practical complexities, rather than, as in quantum physics, because of the conceptual contradiction of the theoretical model itself. On the other hand, the "size" of the electron was also the problem for the classical electrodynamics (the theory of bodies moving in an electromagnetic field).

3. One can, in fact, consider this situation either in terms of Jacques Derrida's *différance* or in terms of Deleuze's matrix of "difference and repetition," or indeed by combining both—an intriguing, and as yet unexplored, combination in its own right.

4. Paul de Man, *Aesthetic Ideology* (Minneapolis: University of Minnesota Press, 1996), 51.

5. The formulations of both physicists were quickly proven to be mathematically equivalent. They do, however, entail subtle and significant differences in physics and epistemology—questions that remain largely unexplored in the historical and philosophical literature on the subject. The same point can be made concerning other versions of mathematical formalism of quantum mechanics, such as those of Paul Dirac, John von Neumann, and Richard Feynman. The work of other key figures, such as Wolfgang Pauli, Max Born, Pasqual Jordan, and, on the philosophical side, most especially Bohr, was equally crucial in the development of quantum mechanics.

6. Literature dealing with the subject is immense, matched by the number of interpretations of quantum mechanics itself. Already within the cluster of the standard or Copenhagen (or, as it is also called, orthodox) interpretations, to which Bohr's belongs, the range is formidable, even if one restricts oneself to such founding figures as Heisenberg, Born, Pauli, Dirac, von Neumann, and Wigner, in addition to Bohr. Bohr's interpretation itself underwent considerable evolution and refinement, and I here use primarily his later (after 1935) version of complementarity, specifically as explicated in "Discussion with Einstein" and related later works. The two main lines of thought within the Copenhagen cluster are defined by the argument whether or not the formalism of quantum mechanics describes the behavior of quantum objects themselves. The first line follows Dirac's and von Neumann's views; the second, pursued here, Bohr's. It may also be argued that Schrödinger's wave mechanics, too, is epistemologically more conducive to (which is not to say entails) the first view. Heisenberg's is more conducive to (and perhaps entails) the second. Feynman's version is still another story. Dirac's and von Neumann's versions are presented in their seminal works, P.A.M. Dirac, *The Principles of Quantum Mechanics* (Oxford: Clarendon, 1995) and John von Neumann, *Mathematical Foundations of Quantum Mechanics*, trans. Robert T. Beyer (Princeton: Princeton University Press, 1983), both of which are technical, however. The profusion of new interpretations during recent decades was in part motivated by the famous argument of Einstein, Podolsky, and Rosen (EPR), offered in 1935, concerning the incompleteness (or either incompleteness or nonlocality) of quantum theory, to which I shall later return. This profusion may, however, have been triggered by David Bohm's reformulation of the EPR argument in terms of spin and then his hidden-variables version of quantum theory (mathematically different from the standard version), introduced in 1952. This interest in new interpretations received a further impetus from John Bell's theorem (1966) and related findings, and then from Alan Aspect's experiments (around 1980) confirming these findings. Bell's theorem states, roughly, that any classical-like theory (similar to Bohm's) consistent with the statistical data in question in quantum mechanics is bound to involve an instantaneous action-at-a-distance and, hence, violate relativity theory. Bohm's theory does so explicitly, in contrast to the standard quantum mechanics, which does not. There are arguments stating that quantum mechanics does, in fact, involve an instantaneous action-at-a-distance, but these arguments remain at best inconclusive. These developments recentered the debate concerning

quantum mechanics around the question of nonlocality and the so-called quantum correlations, which correlations cannot be explained classically. *Philosophical Consequences of Quantum Theory: Reflections on Bell's Theorem*, ed. James T. Cushing and Ernan McMullin (South Bend, Ind.: Notre Dame University Press, 1989) offers a fairly comprehensive sample of the debates, although it requires some updating. David Mermin's essays on the subject of quantum mechanics in *Boojums All the Way Through* (Cambridge: Cambridge University Press, 1990) is one of the better nontechnical, although demanding, expositions of these subjects. By now, dealing only with nonrelativistic quantum mechanics, the list of interpretations of quantum mechanics includes, among others (and with many variations within each denomination) the many-worlds interpretation; the modal interpretation; the histories interpretation; the relational interpretation; and finally the hidden-variables versions. Among the most recent additions is Mermin's provocative proposal for what he calls "the Ithaca interpretation," which maintains that only statistical correlations between quantum events, not events (correlata) themselves, can be meaningfully considered by quantum theory. See David Mermin, "What Is Quantum Mechanics Trying to Tell Us?" *American Journal of Physics* 66, no. 9 (1998): 753–67, and references there. It may be argued, however, that Bohr's interpretation is at the very least as consistent and comprehensive as any available, albeit to some only unsatisfactorily so because of its radical epistemology. As I shall argue, however, his interpretation not only avoids a conflict with the disciplinarity of physics as science, but enables this disciplinarity. I have considered Bohr and quantum epistemology along the lines followed by this essay in further detail in my following works: *The Knowable and the Unknowable: Modern Science and Nonclassical Thought* (Ann Arbor: University of Michigan Press, 2001); "Reading Bohr," in *Proceedings of the NATO Advanced Research Workshop on "Decoherence and Its Implications for Quantum Computation,"* ed. Antonios Gonis and Patrice Turchy (Dordrecht: Kluwer, 2001); and in "Techno-Atoms: The Ultimate Constituents of Matter and the Technological Constitution of Phenomena in Quantum Physics," *Tekhnema: Journal of Philosophy and Technology* 5 (1999): 36–95; as well as in several earlier works: *Complementarity: Anti-Epistemology after Bohr and Derrida* (Durham: Duke University Press, 1994); "Complementarity, Idealization, and the Limits of Classical Conceptions of Reality," in *Mathematics, Science, and Postclassical Theory*, ed. Barbara H. Smith and Arkady Plotnitsky (Durham: Duke University Press, 1997); and "Landscapes of Sibylline Strangeness: Complementarity, Quantum Measurement, and Classical Physics," in *Metadebates*, ed. G. C. Cornelis, J. P. Van Bendegem, and D. Aerts (Dordrecht: Kluwer, 1998).

7. See Albert Einstein, Boris Podolsky, and Nathan Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" in *Quantum Theory and Measurement* (hereafter *QTM*), ed. John Archibald Wheeler and Wojciech Hubert Zurek (Princeton: Princeton University Press, 1983), 138–41. Bohr's essay by the same name appears in *QTM* on pages 145–51. (Due to a printing error, the order of pages is reversed in this edition: page 149 should precede page 148.) The exchange led Bohr to significant refinements of his previous version of complementarity, and, as I said, throughout this essay I refer to the post-EPR version.

8. The potential inapplicability of these terms and concepts appears to have prompted Bohr to say in a famous (reported) statement: "There is no quantum

world." The alleged statement appears in Aage Petersen, "The Philosophy of Niels Bohr," *Niels Bohr: A Centenary Volume*, ed. A. P. French and P. J. Kennedy (Cambridge: Harvard University Press, 1985), 305. One must exercise caution in considering such reported statements. It would be very difficult to conclude on the basis of Bohr's written works that he denies the existence of that to which the expression "the quantum world" refers. The statement may be read, especially given the context (the question of whether quantum mechanics actually represents the quantum world), by putting the emphasis on "quantum." Rather than indicating the nonexistence of "quantum" objects, it indicates the inapplicability to the latter of conventional "quantum" attributes—such as discontinuity (of radiation), invisibility (of quanta themselves), or any other physical attributes or, conceivably, any attributes at all; or even "objects," "constituents," and so forth; or of course individuality of quantum objects ("particles") or the wave-like character of quantum processes, once considered independently of observation. At the level of phenomena, certain individuality remains and the existence of the micro-level (that of the ultimate constituents of matter) efficacity of these phenomenal effects remain essential. Both have been at stake in quantum physics ever since Planck. In fact, Planck's law is incompatible with assigning identities to individual particles (or distinguishing them) within quantum-physical multiplicities, which is what makes Planck's and other statistical counting procedures of quantum physics differ from those of classical statistical physics. This statistical configuration is already phenomenologically inconceivable or, in Bohr's language, beyond pictorial visualization—an impossibility, as will be seen, that defines quantum physics for Bohr. This fact has far-reaching consequences in quantum physics, from Planck's law on. On the one hand, the identity in the sense of interchangeability of all particles of a given type (photon, electron, and so forth) is crucial; on the other, the identity also peculiarly manifests itself in the impossibility of assigning particle individual identity in certain situations, perhaps ultimately ever. In quantum field theories, such as quantum electrodynamics (QED), beyond the impossibility of distinguishing individual particles, one can no longer quite speak of the particles of the same type. An investigation of a particular type of quantum object (say, electrons) irreducibly involves other types of particles, conceivably all existing types of particles. This is the main reason why Heisenberg saw Dirac's discovery of anti-particles in 1928–32 (the process was somewhat prolonged), which entails this situation, as one of the greatest discoveries of modern physics, "perhaps the biggest of all the big changes in physics of our century" (*Encounters with Einstein*, 31). According to Heisenberg, quantum field theories push the complexities in question to their arguably most radical available limits, even beyond those of the standard quantum mechanics of Heisenberg and Schrödinger (31–35). The latter is a highly complex and little developed subject, which cannot be addressed here. The circumstances themselves in question, however, are not only consistent with but would reinforce the present argument.

9. I use Bohr's careful language when he points out that "the classical theories do not suffice in accounting for the new types of *regularities* [emphasis added] with which we are concerned in atomic physics" (*QTM*, 150). The classical theories are far from discountable in quantum physics (where they are necessary, for example, in the description of the behavior of the measuring instruments involved), let alone elsewhere.

10. This circumstance poses the question whether the *interpretations* of classical

theories pursued by such investigations are in fact radical or nonclassical, rather than classical readings of both classical and nonclassical theories in question. If (and when) this is the case, the paradox disappears. On the other hand, as has been pointed out (by, among others, Kant), there will always be "savants" who would find something pre-Socratic in anything, provided they are told what to look for. I am saying this not in order to dismiss all such rereadings of old texts via new theories, but to suggest that new theories always entail a precarious balance of (re)reading both the "old" and the "new," and new complexities in deciding which is which.

11. *PWNB*, 2:34.

12. I discuss these issues in *Complementarity* and in *The Knowable and the Unknowable*.

13. *PWNB*, 2:1–2.

14. Werner Heisenberg, *Philosophical Problems of Quantum Physics* (Woodbridge, Conn.: Ox Bow Press, 1979), 13

15. Compare, in particular, Gilles Deleuze and Félix Guattari's *What is Philosophy?* trans. Hugh Tomplinson and Graham Burchell (New York: Columbia University Press, 1993). The philosophical disciplinarity is defined and maintained in their analysis specifically as the invention of new "concepts" in their specific sense of the term. At the same time, however, this form of philosophical disciplinarity also gives uniqueness to each particular case—as posed by Descartes, Leibniz, Kant, Hegel, Nietzsche or, of course, Deleuze, or Deleuze and Guattari.

16. I am also not considering related but different questions of the creation of new disciplines, of paradigm change, and so forth (such as, "the Copernican revolution," for example). There is a large body of well-known literature on these subjects, most famously Kuhn's work and commentaries on it. I must also bypass such cases as those of Marx and Freud, or a number of others, including Foucault, who himself famously commented on the particular disciplinary status of Marx's and Freud's work and Marxism and psychoanalysis in "What Is an Author?" *Language, Counter-Memory, Practice*, ed. Donald F. Bouchard (Ithaca: Cornell University Press, 1977). I also refer readers to my previous commentaries on some of the subjects and figures here mentioned (especially Nietzsche, Bataille, and Derrida) in *Reconfigurations: Critical Theory and General Economy* (Gainesville: University Press of Florida, 1993), 63–112, 149–212; *In the Shadow of Hegel* (Gainesville: University Press of Florida, 1993), 84–95, 97–135, 264–86; *Complementarity*, 225–70; and, on Lacan, in *The Knowable and the Unknowable*.

17. I have considered the latter subject in *Complementarity* and *In the Shadow of Hegel*.

18. I am not saying "Newton's own project," which is subject to a complex interpretation, even though Newton appears to have subscribed to realism and causality.

19. I consider this question in detail in my work *The Knowable and the Unknowable*.

20. Thus Einstein's position belongs to that type of realism rather than to a more naive claim that physical theories should represent independent physical reality as such. The same may be said about the positions of other critics of quantum epistemology, such as Schrödinger, and of many classical figures, beginning with Newton or, more radically, Galileo. Indeed it would be difficult to find exceptions among major figures in the history of physics. Compare Schrödinger's account of the classi-

cal view in terms of *models* of (or approximating) physical reality in juxtaposition to the (nonclassical) view of quantum theory, born, he claims, "of distress," in his famous "cat paradox" paper (1935), "The Present Situation in Quantum Mechanics" (in *QTM*, 151–54). Bohr's argument, however, applies to such more complex views and takes them into account, rather than (as is sometimes claimed by Bohr's critics) only to more naive forms of realism. Indeed it is crucial that Bohr's interpretation also makes this form of realism and, arguably, all conceivable forms of realism inapplicable to his interpretation and possible to "the entirely new situation as regards the description of physical phenomena" that we encounter in the field of quantum theory in general (*QTM*, 148). Discussions of Schrödinger's "cat paradox" are found in many accounts of quantum physics. I have considered it in *Complementarity* (284–85, note 20).

21. There exists the quantum-theoretical concept of state defined via the formalism of quantum theory and specifically the so-called state-vector, the concept bound by the uncertainty relations. The concept of state is more significant within the Dirac/von Neumann paradigm, whereby the formalism of quantum theory is seen as describing the behavior of quantum objects themselves, than in Bohr's, which does not assign physical reality to the state-vector.

22. *PWNB*, 2:73.

23. Ibid., 2:40.

24. I have considered the details of this situation in "Techno-Atoms."

25. *PWNB*, 2:39–40.

26. Ibid., 3:5. Compare to ibid., 2:73.

27. Ibid., 3:3.

28. Anthony J. Leggett, "Experimental Approaches to the Quantum Measurement Paradox," *Foundations of Physics*, 18, no. 9 (1988): 939–52.

29. *QTM*, 146–47; *PWNB*, 2:46–47.

30. Leggett, "Experimental Approaches to the Quantum Measurement Paradox," 940–41.

31. *PWNB*, 2:51.

32. Ibid., 2:39–40.

33. Ibid., 2:73. On quantum "techno-atomicity," see my article "Techno-Atoms."

34. *PWNB*, 3:7.

35. Ibid., 2:34.

36. Ibid., 2:70.

37. The point was well realized by Schrödinger in his analysis of quantum mechanics in the "cat paradox" paper, "The Present Situation in Quantum Mechanics," cited above, which was largely inspired by the EPR argument. In particular, he observes, "If a classical state does not exist at any moment, it can hardly change causally" (154).

38. The situation is more complex in classical statistical physics as well (including in relation to thermodynamics). The classical view even of classical statistical physics (i.e., physics disregarding quantum effects) has been challenged more recently, in particular in the wake of quantum mechanics. I shall bypass these complexities here. If "classical" chance is ultimately only a manifestation, approximation, or perhaps misunderstanding of the ultimately nonclassical nature of the configurations in question in classical statistical physics, so be it. It suffices for the purposes of the present

argument that classical statistical physics appear to allow at least for a classical interpretation. For a relevant commentary see Lawrence Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge: Cambridge University Press, 1998), and references there.

39. *PWNB*, 2:34.

40. David Bohm, *Wholeness and the Implicate Order* (London: Routledge, 1995), 73.

41. Compare to Schrödinger's comment cited in note 20.

42. See Abraham Pais, *Inward Bound: Of Matter and Forces in the Physical World* (Oxford: Oxford University Press, 1986), 262.

43. *QTM*, 138.

44. *QTM*, 145.

45. I offer a detailed analysis of the situation in "Reading Bohr" and in *The Knowable and the Unknowable*.

46. I say "in effect," because "nonlocality" was not the main concern of the article itself, which focused primarily on the incompleteness of quantum mechanics. However, the alternative in question (of quantum mechanics being either incomplete or nonlocal) clearly emerges there, and was the main concern of Einstein at the time and even more so in his subsequent arguments on the subject. As I have indicated, the question of nonlocality is subtle and has been a major issue in recent debates concerning quantum mechanics. There are, as I said, no convincing (or at least widely accepted) arguments that quantum physics itself is nonlocal in the sense of its incompatibility with relativity. It may be argued, in view of Bell's theorem, that the data in question in (and accounted for by) quantum mechanics is incompatible with a theory that is both local and realist (in the same sense that classical physics is). This is a reasonably accepted argument among physicists and philosophers of quantum physics alike, including those who aim to argue for the more general nonlocality of quantum mechanics or the quantum world. In Bohr's interpretation, quantum mechanics is not a realist theory to begin with, and part of Bohr's argument is that this interpretation is fully compatible with relativity and, hence, local.

47. *PWNB*, 2:39–40, 52, 61.

48. Among Derrida's many discussions of "supplementarity," arguably the closest to the present context is that in *Speech and Phenomena*, trans. David Allison (Evanston: Northwestern University Press, 1973), 88–90.

49. *PWNB*, 2:40.

50. *QTM*, 146.

51. The nonlocality part of the EPR-type argument can be readjusted so as to refer only to the outcomes of measurements, rather than to quantum objects, which would lead to the considerations mentioned above. For an excellent discussion, see Mermin's essays on the subject in *Boojums All the Way Through*, 81–185. These considerations would not affect either Bohr's interpretation (including its local character) or the overall argument presented here.

52. *QTM*, 145–46.

53. I omit some intermediate propositions concerning the interactions between quantum objects and measuring instruments. They are important in explaining the reasons for Bohr's argument. However, they are fully consistent with the preceding analysis, presented more in terms of Bohr's later "Discussion with Einstein." While

not a substitute (rather a complement), this later work (1949) may be seen as further qualifying and refining Bohr's argument in his original reply (1935), and appears to be so seen by Bohr (*PWNB* 2:61).

54. The exchange reflects the most profound and subtle aspects of quantum mechanics itself and of Einstein's and Bohr's thought.

55. *QTM*, 148.

56. That, again, is not to say that "the quantum world" or, again, the corresponding (ultimate?) level of the constitution of matter, does not exist, but that the attribution of physical properties, including those of individual identity of particles, or conversely of wave-like substances, may not be possible at that level. Nor, however, would it follow (as some contend) that this suspension of the independently attributable particle identities, such as those of two "particles" in the EPR situation, in fact entails nonlocality. The two-quantum entities (for lack of a better word) involved would still be spatially separate, and, according to Bohr, there is in the EPR case certainly "no question of a mechanical [i.e., physical] disturbance of [one] system under investigation" by our interference with the other quantum system involved in the EPR thought experiment (*QTM*, 148). It is just that we cannot attribute independent physical properties, ultimately, even that of a "particle," to them. Once we assume that we can, as Einstein did, nonlocality indeed appears to follow. So his argument is not logically wrong. His assumption may well be wrong, or at least is not necessary.

57. The essential ambiguity of the EPR criteria, as applied in quantum mechanics, arises precisely from their failure to do so, however subtle and revealing of new aspects and "mysteries" of the quantum it may be. In particular, it is, again, the failure to see that "an essential element of ambiguity is in ascribing conventional physical attributes to [quantum] objects themselves," ultimately each complementary attribute taken by itself or, again, even to seeing such objects as particles (or as waves). This is the same ambiguity.

58. *PWNB*, 2:56–57. While the aforementioned qualifications, especially those concerning nonlocality, must be kept in mind, they would not affect the points made at the moment.

59. Werner Heisenberg, "Quantum Theory and Its Interpretation," in *Niels Bohr: His Life and Work as Seen by His Friends and Colleagues*, ed. Stephan S. Rozental (Amsterdam: North-Holland, 1967), 95.

60. *PWNB*, 3:1.

61. Obviously, an appeal to "convincing arguments" would indicate the complexities mentioned above. However, the core of the present argument concerning the disciplinarity of physics under the radical epistemological conditions in question would be maintained, indeed, I would argue, all the more so once these complexities are taken into account.

62. I refer to a forthcoming article by David Reed and Arkady Plotnitsky, "Discourse, Mathematics, Demonstration and Science in Galileo's *Discourses Concerning Two New Sciences*," *Configurations* (Spring 2001).

63. Roland Omnès, *The Interpretation of Quantum Mechanics* (Princeton: Princeton University Press, 1994). See also his *Understanding Quantum Mechanics* (Princeton: Princeton University Press, 1999).

64. It is true that one can technically practice quantum physics while subscribing to the classical philosophy of nature or of physics, including quantum theory.

65. See Heidegger's *What Is a Thing?* trans. W. B. Barton, Jr., and Vera Deutsch (South Bend, Ind.: Gateway, 1967), 93.

66. *QTM*, 150.

67. As Sylvan S. Schweber argues in his *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga* (Princeton: Princeton University Press, 1994), in the case of quantum electrodynamics (QED), at a certain point in the history of quantum physics, it was the persistence in keeping the existing framework, with incremental modifications, rather than attempts at radically transforming it, that paid off. In the case of QED, it was, ironically, Dirac, its founder, who gave up on his creation and believed that yet another radical transformation, similar to that of the original quantum mechanics in relation to classical physics, would be necessary. Schweber speaks of the "extreme conservatism" of the figures mentioned in his title in this context and in this sense. From the present perspective, the extreme conservatism may apply even when a radical transformation is ultimately at stake. On the other hand, it cannot be seen as necessary in all conditions or at all points, even in science, although virtually all the founders of quantum mechanics appeared to conform to this view at the time of its emergence. We can never be certain what will ultimately pay off. In some respects the creation of modern QED was quite radical as well, particularly in employing rather unorthodox, and indeed mathematically strictly forbidden, techniques in the so-called renormalization procedure, the centerpiece of quantum field theory ever since. So the creators (it was mostly founded by Dirac and several others earlier) or perhaps "saviors" of modern QED, too, were both extreme conservatives and extreme radicals, just as were the founders of quantum mechanics earlier.

68. Albert Einstein, "Reply to Criticisms," *Albert Einstein: Philosopher-Scientist*, ed. Paul Arthur Schilpp (New York: Tudor, 1949), 45–47. It is true that Einstein here refers to Bohr's 1913 theory of the atom, which appeared at the time to hold some promise for a classical resolution, rather than to Bohr's and others' more radical view of the quantum. However, certain nonclassical features were in place in Bohr's work even then. Indeed, Einstein's statement refers precisely to Bohr's ability to do physics under these conditions of extremely uncertain foundations, of which Bohr was himself acutely aware at the time as well.