

Preface

This book offers an exploration of the relationships between epistemology and probability in the work of Niels Bohr, Werner Heisenberg, and Erwin Schrödinger, and in quantum mechanics and in modern physics as a whole. It also considers the implications of these relationships and of quantum theory itself for our understanding of the nature of human thinking and knowledge in general, or the “epistemological lesson of quantum mechanics,” as Bohr liked to say.¹ These implications are radical and controversial. While they have been seen as scientifically productive and intellectually liberating to some, Bohr and Heisenberg among them, they have been troublesome to many others, such as Schrödinger and, most prominently, Albert Einstein. Einstein famously refused to believe that God would resort to playing dice or rather to playing with nature *in the way* quantum mechanics appeared to suggest, which is indeed quite different from playing dice. According to his later (sometime around 1953) remark, a lesser known or commented upon but arguably more important one: “That the Lord should play [dice], all right; but that He should gamble according to definite rules [i.e., according to the rules of quantum mechanics, rather than by merely throwing dice], that is beyond me.”² Although Einstein’s invocation of God is taken literally sometimes, he was not talking about God but about the way nature works. Bohr’s reply on an earlier occasion to Einstein’s question

¹ Cf., “Quantum Physics and Philosophy: Causality and Complementarity,” *Philosophical Writings of Niels Bohr*, 3 vols. (Bohr 1987, vol. 2, p. 91; vol. 3, p. 12), hereafter to be referred to as *PWNB* followed by a volume number. A supplementary volume of Bohr’s essays was published as Niels Bohr, *The Philosophical Writings of Niels Bohr, Volume IV: Causality and Complementarity, Supplementary Papers* (Bohr 1998) and will be referred as *PWNB 4*. These four volumes contain most of Bohr’s works on quantum mechanics and complementarity to be cited here. The essays from these volumes cited here are listed separately in this book’s bibliography with the original publication date, to be given in the text as well (e.g., the article just cited will be referred to as “Bohr 1958, *PWNB 3*,” followed by page numbers).

² Cited in John A. Wheeler and Wojciech H. Zurek, eds., *Quantum Theory and Measurement* (Wheeler and Zurek, p. 8). This collection, which contains a number of articles to be cited here, will hereafter be referred to as *QTM*. All the articles from this collection are, however, also separately indicated in the text and are separately listed in the bibliography with the original publication date.

whether “we could really believe that the providential authorities took recourse to dice-playing” in the same “humorous spirit that animated the discussions” is nevertheless worth recalling: “I replied by pointing at the great caution, already called for by ancient thinkers, in ascribing attributes to Providence in everyday language” (Bohr 1949; *PWNB* 2, p. 47). Einstein was reluctant to believe that nature, at the ultimate level of its constitution, would behave in this way. In other words, he was unwilling to accept that quantum mechanics, or any theory of the same (epistemological) type, ultimately reflects nature. Nor did he think that an alternative theory that would be more philosophically palatable and, by his criteria (essentially derived from classical physics), more complete could not eventually be found. He often said that quantum mechanics revealed a beautiful element of truth in nature, but not its ultimate truth, and he thought that “it offers no useful point of departure for future development” (Einstein 1949a, p. 83).

Quantum mechanics has, however, been around for near a century now, and within its proper scope has remained the standard theory, well confirmed experimentally, as are most currently standard quantum theories, such as and in particular quantum electrodynamics, arguably the best confirmed physical theory ever, and other quantum field theories.³ In part by virtue of its epistemologically complex and controversial character, quantum mechanics or quantum theory, more generally, has occupied a special place in physics and philosophy, and in intellectual history as a whole in the twentieth and by now the twenty-first centuries. In either respect, relativity has been and remains its main rival—at

³ Throughout this study, by “quantum mechanics” or “the standard quantum mechanics,” I mean the *standard* version of quantum mechanics, covered by Heisenberg’s or Schrödinger’s formalism, or other, more or less mathematically equivalent, versions of the quantum-mechanical formalism, such as those of Paul Dirac or John von Neumann. As will be seen, there are certain differences between these versions and in how they are used, but these are not essential for my main epistemological argument here, which applies to any of these versions. In any event, the term “quantum mechanics” will not refer to alternative accounts of the experimental data in question, such as those offered by Bohmian mechanics, for example (and there are several versions of the latter as well). On the other hand, “quantum theory” will refer more generally to theoretical thinking concerning quantum phenomena. This denomination, thus, also includes the quantum theory (sometimes referred to as the old quantum theory) that preceded quantum mechanics; the alternatives to the standard quantum mechanics just mentioned; and higher level quantum theories, such as quantum electrodynamics and other quantum field theories (e.g., quantum chromodynamics, which deals with quantum processes inside atomic nuclei), comprising the so-called standard model. “Quantum phenomena” will refer to those observable phenomena in considering which, for example and in particular by means of quantum mechanics, the role of Max Planck’s constant h (which has a very small magnitude) cannot be disregarded, as it can be in the case of the phenomena considered by classical physics. Unless specified otherwise, “quantum phenomena” will refer to those phenomena that fall within the scope of quantum mechanics, which are my main concern in this study. Finally, “quantum physics” will refer to the overall assembly of the available quantum phenomena (including the quantitative experimental data involved, beginning with h) and theoretical accounts, of whatever kind, of these phenomena. The terms “classical mechanics” (or “Newtonian mechanics”), “classical (physical) theory,” and “classical physics” will be used along the respective parallel lines.

least among physical theories, since certain developments of modern mathematics, computer sciences, and biology may be argued to have a similar cultural prominence and impact. Indeed, more recently biology and information sciences appear to have surpassed physics as the dominant sciences in our culture. The recent completion of the Large Hadron Collider (LHC) at the *Organisation Européenne pour la Recherche Nucléaire* [The European Organization for Nuclear Research], known as CERN, near Geneva, and its promise to reveal “the deeper secrets of nature,” as newspapers like to have it, appear to have brought fundamental physics back to the cultural center stage. (After a brief period of preliminary runs, the Collider is on hold at the moment due to a major problem with its superconducting bending magnets, but it is expected to be operational again later in 2009.)

Whatever its role in our culture, the state of contemporary fundamental physics is in part defined (and some would say marred) by the physical incompatibility between quantum theory and general relativity as the currently accepted theory of gravity, as against the unity of classical mechanics and Newton’s classical theory of gravity. The fact that each theory itself has, thus far, been confirmed as, within its proper limits, a correct theory of the corresponding phenomena with an extraordinary degree of precision makes the incompatibility all the more glaring. In one respect, the situation is somewhat mitigated by the fact that gravity is much weaker than other forces of nature (on the scale of 10^{35} weaker in its order of magnitude than electromagnetism). This discrepancy makes it possible to make progress in quantum theory without taking gravity into account, or conversely in relativistic physics without considering quantum effects, and many developments in both areas in recent decades have been spectacular. On the other hand, the discrepancy (also known as “the hierarchy problem”) is enigmatic and, many feel, needs to be theoretically explained and, as it were, bridged by a theory where it would appear logically. This situation provides the impetus for string theory and its extensions to brane theories and beyond, or for certain other proposed alternatives. There are also other, more physically immediate, motivations for developing such a theory or theories. Arguably the most pressing among these motivations are the following two. The first arises from a generally (albeit not quite universally) shared assumption that, just as that of other forces of nature, the ultimate nature of gravity is quantum. The second arises from another, equally generally (but, again, not universally) shared, assumption that the earliest stages of the Universe, which would explain its current architecture and dynamics, are shaped by quantum processes, possibly of a unified character. The corresponding theories, when and if developed, might or might not be related, or be the same theory. In any event, a theory or a set of theories that would bring general relativity and quantum theory together or at least that are operative at deeper levels but consistent with both within their proper limits, appears to be far away, although string and brane theories, and a few other approaches do offer some, but thus far tenuous, hope. In this respect, in addition to, hopefully, straightening out as yet unresolved difficulties of the standard model, the currently, by and large, accepted quantum theory of the

known forces of nature (electroweak and strong) apart from gravity, the experiments to be performed at the LHC may offer us some new clues.⁴ These experiments might reveal the existence of particles predicted by hypothetical theories beyond the standard model, such as the so-called supersymmetry (there are several versions of the latter as well, including of the string-theoretical variety), which offer some hope for a theory of quantum gravity. They can also send physicists back to the drawing boards as concerns our current theories, not inconceivably quantum mechanics among them, although this appears somewhat less likely given that these are higher level quantum theories and, again, most especially the standard model, that are about to be tested in these experiments.⁵

It is difficult, if not impossible, to estimate what such theories will reveal philosophically, even though they do pose significant philosophical questions, extending those already posed by relativity and quantum mechanics and some new ones.⁶ Even in the near future the situation may change considerably in any

⁴ The standard model has thus far only been able to unify (quantized) electromagnetism and weak (nuclear) force, but not all three forces just mentioned. Such a more complete unification (which is expected to be accomplished by string theory or other fundamental theories just mentioned) appears desirable to many and is often stated as a goal, and the inability of the standard model to achieve this goal thus far is sometimes held against it. There is, however, some debate as to whether, even assuming that it is possible in the first place, this more complete unification is necessary, or that the failure, thus far, to offer it is a real drawback of the standard model. The latter does account for the three fundamental forces in question, even if it does so without unifying them. The problem of quantum gravity is of course different, since we do not have a quantum theory of gravity as such, although it is assumed to be ultimately quantum, and some of the properties of its quanta, gravitons, are predicted already.

⁵ Proposals to test quantum mechanics, usually in order to prove it wrong, even within its own limits, continue to be advanced. Given the epistemological discontent with the theory on the part of the majority of physicists and philosophers (Einstein seems to have won this battle for now), it would be difficult to expect that they will stop worrying and learn to love quantum mechanics. There is of course nothing wrong with offering such proposals. It is possible that quantum mechanics will prove to be wrong even within its own limits in view of some experimental discovery, similarly to the way Newton's gravity was proved wrong in its account of the behavior of Mercury, which requires general relativity to be properly accounted for (although Newton's theory is still an excellent approximation, sufficient in most cases).

⁶ Cf., a relatively recent (although already requiring considerable updating, especially as concerns brane theory) collection (Callender and Huggett 2001), for some among the philosophical aspects and implications of such future theories. One of the more philosophically, as well as physically, significant areas of investigation is that of the (thus far mostly hypothetical) cosmological theories that attempt to relate quantum theory and relativity. Some of the attempts along these lines, such as the so-called "cosmic landscape" theories, also significantly involve the question of chance, including potentially the type of chance found in quantum physics (as against classical statistical physics), one of my main subjects here. I shall comment on some of these developments later in this study. For an excellent recent survey, see Carroll (2006), and for good nontechnical discussions of the brane-theory-oriented cosmology, see Randall (2005) and Randall (2007). For the "landscape" cosmology, see Susskind (2006). See also a survey "Year of Physics: A Celebration" published during the centenary of Einstein's *annus mirabilis* in 2005 (*Nature* 433, 213 [2005]), which, although it requires some updating, still offers a good picture of the current state of fundamental physics.

given direction or reveal new, yet unknown and even unimagined, gradients of new thinking. It is possible that these theories will return us to more classical and, in particular, more realist and causal ways of thinking and knowledge in physics, and, following Einstein, many hope that they will. However much quantum theory appears, at least to some of us, to suggest otherwise, it is not inconceivable that nature, or our thinking concerning it, might offer new support for such hopes. It is also possible, however, that these theories will reveal something that is even more radical philosophically than quantum theory, difficult as it may be to think of something epistemologically more radical than quantum mechanics. As I shall suggest later in this study, quantum field theory already appears to lead us beyond quantum mechanics.

Whatever the future holds in store for physics or philosophy, quantum theory has radically transformed our understanding of the nature of human knowledge, and of the relationships between physics and philosophy, the discipline primarily concerned with human thinking and knowledge. It may indeed be noted that, if quantum mechanics had proven to be incorrect even within its proper scope and were to be replaced by an epistemologically more classical theory, similar, say, to classical mechanics, it would not devalue the alternative “nonclassical,” as I shall term it, epistemology of quantum mechanics adopted in this study. This epistemology, which I shall outline in detail in the Introduction, may be developed into a corresponding theory elsewhere, for example, in philosophy (as to some degree it will be here) or biology. This transformation and the relationships themselves between physics and philosophy are among the primary concerns of this study, as they have been in most philosophical treatments of quantum theory, or, in the case of these relationships, in philosophical treatments of all physics, beginning with Galileo or Aristotle, both of whom were concerned with these relationships as well. However, the mathematical or, more accurately, mathematical–experimental character of modern physics, from classical physics to relativity to quantum physics, as, in Galileo’s language, “a mathematical science of nature,” unavoidably converts these relationships into those *among physics, mathematics, and philosophy*.⁷ These triple relationships are significant not only for our philosophical *understanding* of quantum mechanics and its interpretation, but also for this *interpretation* itself. However implicit these relationships may be, they are, in the language of Immanuel Kant, among the *conditions of possibility* of the interpretation of quantum mechanics, including as concerns the question of probability there. By “interpretation” I mean, most immediately, giving a proper explication of physical content and meaning to a given physical theory, in particular as concerns the relationships (descriptive or predictive) between the mathematical formalism and the measurable quantities established by experiments. As will be

⁷ The concept of a “mathematical science of nature,” rather than that of “physics,” defines (perhaps against Aristotle’s conception of physics) what we now call physics in Galileo’s *Dialogues Concerning Two New Sciences* (Galileo 1991). For a related discussion of Galileo, see Plotnitsky and Reed (2001).

seen below, a more complex concept of interpretation is required even in classical physics or relativity, and especially in quantum theory. These triple relationships among physics, mathematics, and philosophy are central to my argument in this study, and this preface and the Introduction are designed to position this argument accordingly.

Quantum theory was initiated by Max Planck's discovery, in 1900, of his black body radiation law, which revealed that radiation, such as light, previously considered a continuous phenomenon in all circumstances, could also exhibit certain features of discreteness or of particle-like behavior in some circumstances. The limit at which this discontinuity appears is defined by the frequency of the radiation and a universal constant of a very small magnitude, h , 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 of radiation in each case is the product of h and the frequency ν , $E = h\nu$. The role of Planck's constant h may be seen as analogous to the role of c in special relativity (the constancy of the speed of light in a vacuum in its independence of the speed of the source) in terms of both necessitating a departure from classical theory and of introducing the first principles of a new theory. The rest, one might argue, follows "naturally" in both cases, even though it might have taken a bit longer to develop the consequences of Planck's assumption in the case of quantum theory. The parallel formulas for energy, $E = mc^2$ (admittedly, a consequence rather than a postulate in special relativity theory) and $E = h\nu$, amplify the parallel between the two situations.

Other earlier developments, sometimes referred to as the "old quantum theory," made apparent yet further complexities of quantum phenomena and posed new questions concerning these phenomena. Arguably, the most significant among these developments was Einstein's introduction of the idea of photon, eventually understood as "the particle of light," in 1905 (Planck himself thought of discrete portions, *quanta*, of energy, rather than of particles); Bohr's 1913 theory of the hydrogen atom, extended, primarily by Bohr, Arnold Sommerfeld, and others to larger atoms during the decade to follow; Einstein's further work on Planck's law in 1909 and 1916; Louis de Broglie's conjecture, introduced in the early 1920s and quickly confirmed experimentally, that not only radiation but also the elementary constituents of matter, such as electrons, exhibit the same dual, particle-like and wave-like, aspects in their behavior; and Wolfgang Pauli's exclusion principle, which imposed rigorous constraints, fundamentally quantum in nature, upon the behavior of electrons in atoms. Although established by means of the old quantum theory, Pauli's exclusion principle and, to some degree, de Broglie's theory, may be seen as on the borderline between the old quantum theory and quantum mechanics, with which the *new* quantum theory, quantum theory as it is currently constituted, commenced. Even closer to quantum mechanics was the work of Satyendra N. Bose, and following him, that of Einstein (who used de Broglie's ideas) on Planck's law and quantum statistics published just before the discovery of quantum mechanics by Heisenberg in 1925.

It is worth noting (this is often forgotten retrospectively) that the old quantum theory was spectacularly successful in many respects, and parts of it are still used now, sometimes with surprising successes.⁸ It did have, however, major physical problems, which ultimately proved to be insurmountable for the theory and which quantum mechanics, discovered by Heisenberg and Schrödinger in, respectively, 1925 and 1926, was able to solve, while retaining all those predictions of the old quantum theory that were correct. The consistency between both theories on that score was an important part of the development of quantum mechanics. Quantum mechanics was further developed in the work of Born, Jordan, Dirac, Pauli, and (primarily in terms of interpretation) Bohr. One should also acknowledge the contribution of lesser known but highly accomplished theoretical physicists, such as Hendrik Kramers, Ralph Kronig, Cornelius Lanczos, and others, and of course of many experimentalists.⁹ The theory was nonrelativistic and dealt with the motion of electrons at speeds significantly slower than those of light, although the initial work on relativistic quantum theory, quantum electrodynamics, was virtually contemporary, and Dirac introduced his famous relativistic equation for the electron in 1928. Schrödinger's equation treats the behavior of the electron in quantum mechanics.

While, however, quantum mechanics resolved most *physical* difficulties that beset the old quantum theory and brought with it a certain closure of non-relativistic quantum theory by becoming and remaining ever since the standard theory, it brought with it new and more radical *epistemological* complexities.¹⁰ Indeed, to some, beginning, again, with Einstein, these complexities were even more troubling than those of the old quantum theory. Bohr registered this fact by noting, in 1929, that in this regard quantum mechanics proved to be a “disappointment” to some, and it has remained a disappointment to many ever since (Bohr 1929, *PWNB* 1, p. 92). The majority of even the most resilient critics, Einstein and Schrödinger among them, acknowledged that quantum mechanics brought with it considerable improvements as concerns the predictive capacity of quantum theory. What bothered these critics and even some proponents was the manifest deficiency of the explanatory-descriptive capacity of quantum mechanics with respect to quantum objects themselves. The situation was as follows.

⁸ See, for example, Svidzinsky et al. (2005).

⁹ Most key founding papers on quantum mechanics are assembled in *Sources of Quantum Mechanics*, ed. B. L. van der Waerden (1968) and will be cited from this volume, hereafter referred to as *SQM*.

¹⁰ Heisenberg spoke in terms of a “closed theory” in the following sense. While the technical work in such a “closed” theory would continue (in principle indefinitely), this work will, by and large, remain within the scope of an already established, even if not altogether fixed, conceptual architecture. The concept has some affinities with Thomas Kuhn's distinction between “revolutionary science” (corresponding to Heisenberg's open theory, such as quantum electrodynamics was in the late 1920s, as opposed to quantum mechanics) and “normal science” (closed theory) in *The Structure of Scientific Revolutions* (Kuhn 1962).

The old quantum theory dealt reasonably well with statistical matters and was or, rather, seemed to be analogous to classical statistical physics. What was lacking was the mechanics describing individual objects that would underlie the manifest statistical behavior of multiplicities in a manner similar to Newtonian mechanics, which explains causally the motion of individual molecules in the classical statistical theory. Bohr's 1913 theory of the hydrogen atom (and much of his work that followed it prior to quantum mechanics), Einstein's 1916 work on the so-called induced and spontaneous emissions, and several other earlier theories did deal with individual quantum processes, which were encountered already in the case of radioactivity and were predicted by the corresponding formulas.¹¹ While, however, describing well the atomic spectra in terms of the discontinuous transition ("quantum jumps") of electrons in the atom from one energy level to another (even at the expense of both classical mechanics and classical electrodynamics, both incompatible with such a view), Bohr's theory did not account for the mechanism of this transition. Indeed, the theory was *incompatible* with classical mechanics and classical electrodynamics alike. Einstein's arguments just mentioned suggested that probability might be irreducible even in considering the individual quantum processes (rather than those involving large multiplicities of quantum objects), yet one more of Einstein's revolutionary insights and a defining feature of quantum theory ever since, which, however, was also to contribute to Einstein's discontent with quantum mechanics later on. This point was amplified by the 1924 proposal of Bohr, Kramers, and John Slater (BKS), which aimed to resolve some of the difficulties of the old quantum theory by suspending the strict application of the energy conservation law in quantum processes, where the law would only apply statistically (Bohr et al. 1924). The proposal, controversial to begin with, was abandoned in view of the new experimental findings, most especially those by Walther Bothe and Hans Geiger, which confirmed the exact energy conservation in quantum interactions. These works, thus, further showed that the true mechanics was lacking, before quantum mechanics revealed that such a "true" mechanics (i.e., if conceived on the model of classical mechanics) was perhaps no longer possible. It became clear almost immediately in the wake of Planck's discovery of his law, however, that, contrary to Planck's original argument (accordingly incorrect in this respect, as Einstein was among the first to show), this law was incompatible with a classical-like underlying picture. For that reason the way of statistical counting is different in classical and quantum statistics. Planck's counting was correct, even though part of his physics was wrong, an error that, as Einstein observed, was most fortunate for physics.¹²

¹¹ For useful discussions and references on Einstein's work on this subject, see Pais (1982, pp. 402–414) and Pais (1991, pp. 191–192).

¹² See Einstein's discussion, leading from his commentary on the imperfections of Planck's argument to his assessment of Bohr's 1913 theory of the hydrogen atom as "the highest form of musicality in the sphere of thought" (Einstein 1949a, pp. 37–43).

The new quantum mechanics, which was expected to resolve these problems, was, however, nothing like classical mechanics, and hence was not a theory that was expected or hoped for by most at the time either. Certain aspects of the old quantum theory, in particular, again, Bohr's 1913 theory of the atom and most of Einstein's work on quantum theory, were harbingers of the new, and to many disconcerting, features which quantum mechanics was to retain and enhance rather than to eliminate, as some hoped a proper mechanics would or should. Skipping for the moment greater epistemological complexities, the new quantum theory could only predict, in general only probabilistically or statistically, the outcome of certain events, such as collisions between particles and a silver bromide photographic screen, but it appeared unable to describe the motion of quantum objects in a manner analogous to classical physics. In short, quantum mechanics would *predict* the outcome of the experiments in question (classical-like theories would fail to do so), but it would *not describe* the behavior of physical objects in the way classical physics would. Indeed, classical mechanics predicts *because* it describes.

Nor, again, would quantum mechanics predict in the same way either. Far from having eliminated chance at the ultimate level of the theory (as it would be in classical statistical physics, where the ultimate underlying objects and processes are treated as causal), quantum mechanics gave chance a more radical character. It made chance irreducible in principle, even and in particular in dealing with individual, rather than only collective, behavior. At least, it suggested that such might be the case, since in principle one could still contemplate or hope for the ultimate causality of quantum nature and the (idealized) realism of a future theory describing it. Peculiarly, the collective behavior could exhibit a certain correlational order in certain circumstances, reflected in what was previously perceived to be a wave behavior of quantum objects. Thus, quantum mechanics does not proceed in the way classical statistical physics does, from causal and, often, deterministic individual behavior to statistical collective behavior. Instead it combines or rather responds to a combination, found in nature, of the irreducibly lawless individual behavior with a relatively ordered (statistically correlated) collective behavior, which combination is one of the great mysteries and miracles of quantum phenomena. This combination leaves space for probabilistic predictions, which space quantum mechanics appears to use maximally. But it leaves little, if any, space to the description of the actual physical processes responsible for such predictions.

This, as Bohr was eventually to call it, "entirely new situation as regards the description of physical phenomena" (Bohr 1935b, p. 700) was not helped by Bohr's understanding of quantum mechanics in terms of complementarity, arguably the first reasonably consistent attempt to interpret both quantum phenomena and quantum mechanics, introduced in 1927. There are several reasons why Bohr's argument for complementarity, while welcome to some, offered little to alleviate epistemological discontent concerning quantum mechanics. Most significant among these reasons were, and still are, the following two. The first is the apparent impossibility to have a proper (by the

standards of classical physics) hold on the actual behavior of individual quantum systems and in particular to offer a realist and, especially, causal description of this behavior, a situation to be understood in this study as epistemologically “nonclassical,” the concept, again, to be properly explained in the Introduction. The second, in part correlative, is that the theory retains the irreducible role of randomness and probability, as against the causal character of classical mechanics, at least in principle and in the case of idealized models. But then, from Galileo and Newton on, modern physics deals only with such idealized models (which then can be used in considering actual physical objects); and no such models appear to be possible, and on the view to be ultimately adopted in this study are not possible in quantum theory. Similarly to Heisenberg in his work on his new quantum mechanics (as discussed in Chapters 3 and 4), Bohr saw these complexities as a way to a solution rather than a problem. He built the edifice of his interpretation of quantum mechanics upon both features, the lack of realism and the lack of causality in the quantum mechanical description of the phenomena in question. This, however, was not the kind of solution that would be palatable to Einstein and others who shared his concerns. In addition, Einstein and others argued (correctly, at least at the time) that certain questions concerning the quantum mechanical account of these phenomena remained unresolved. It took Bohr another decade and, in some respects, even longer to resolve some of these difficulties, although not everyone, beginning, again, with Einstein, accepted this resolution as satisfactory. The situation led to an intense debate, in particular to the great confrontation between Einstein and Bohr concerning, to use the title phrase of Bohr’s 1949 seminal essay “Discussion with Einstein on Epistemological Problems in Atomic Physics” (Bohr 1949), “epistemological problems in atomic physics.” This confrontation began in 1927 and has overshadowed the history of quantum mechanics and the debates concerning it ever since, debates that still continue with undiminished intensity.

Bohr’s thinking, on the philosophical side, and that of Heisenberg, on the physical side, shape the argument of this book most significantly, and most of the book is devoted to them. One of the book’s objectives is to reconsider, from a perspective that joins epistemology and probability, Bohr’s work on complementarity and its significance in the history of both modern physics, from Galileo and Newton on, and modern philosophy, from Descartes on. First of all, this reconsideration concerns the significance of probability for Bohr’s thinking. The epistemological problematic, especially the questions of reality and causality, has been the primary concern of most studies devoted to Bohr and many commentaries on his work, although this book offers a more radical view on the subject than most of the previous treatments. On the other hand, the book’s focus on *probability*, rather than *only on causality* or *determinism*, and especially the book’s affinities with the Bayesian view of probability are unusual in the literature on Bohr, or on Heisenberg and Schrödinger, and this focus is among the distinctive new contributions of the book’s project. (I shall properly define the terms “reality,” “causality,” “determinism,” “probability,”

and “Bayesian probability” in the Introduction.) This shift of the primary focus to the question of probability also distinguishes the book from the previous treatments of Bohr and quantum theory by the present author (e.g., Plotnitsky 2006b). I shall argue, however, that probability had a much greater significance in Bohr’s thinking and work, or those of Heisenberg and Schrödinger (in the latter case along more classical lines of resistance to the lack of causality in quantum mechanics), than has been commonly acknowledged.¹³

This focus also helps to clear some misconceptions concerning Bohr’s main concepts and arguments. (I am not saying that these arguments are always free of difficulties or problems.) In particular, I shall argue here that the wave–particle complementarity (the capacity of quantum objects to exhibit both the wave and the particle behavior, but each in different, mutually exclusive circumstances), with which the concept of complementarity is arguably associated most, did not play a significant, if any, role in Bohr’s thinking or that of Heisenberg. I shall further argue that it was not seen by either as a rigorously defined or even rigorously *definable* concept, a view that this study will support and amplify, in part by using the relationships between epistemology and probability in quantum theory. One might even say, perhaps a bit too strongly, that the wave–particle complementarity is one of the greatest and least productive fictions that have accompanied the history of reading Bohr and of quantum theory and its interpretation in general. To be candid, the present author, too, on occasion contributed to propagating this fiction in his earlier work, although not for quite some time now.

Nor, I shall also argue, can one rigorously speak of the mutually exclusive or complementary nature of the space–time description (provided by an act of observation, which uncontrollably “disturbs” the behavior of quantum objects) and the causality of independent, “undisturbed,” behavior of quantum objects. This is another common and persistent misconception, and Bohr briefly entertained the idea himself. It was proposed by him in 1927 in the so-called Como lecture and even was used to define the concept of complementarity (Bohr 1927, *PWNB* 1, pp. 53–54). Bohr, however, quickly abandoned this idea, in part under the impact of his initial exchanges with Einstein in 1927. He also significantly refined and gave a proper rigor to the concept of complementarity itself.

While the concept was not quite ever stated in the form about to be formulated here by Bohr himself, a more rigorous meaning of complementarity may be surmised from his later formulations, although one would generally need several of Bohr’s separate statements to properly establish this definition. He comes closest to it in his 1949 “Discussion with Einstein on Epistemological Problems in Atomic Physics.” Bohr states there: “Evidence obtained under different experimental conditions cannot be comprehended within a single

¹³ A notable exception is F. S. C. Northrop’s “Introduction” to Heisenberg’s *Physics and Philosophy* (Northrop 1962; Heisenberg 1962), which is focused on the role of probability in Heisenberg’s book.

picture [i.e., is mutually exclusive], but must be regarded as *complementary* in the sense that only the totality of the phenomena exhausts the possible information about the objects” (Bohr 1949, *PWNB* 2, p. 40). Accordingly, complementarity is defined by (a) a mutual exclusivity of certain phenomena, entities, or conceptions; and yet (b) the possibility of applying each one of them separately at any given point; and (c) the necessity of using all of them at different moments for a comprehensive account of the totality of phenomena that we must consider. Part (b) is not stated in the above formulation from “Discussion with Einstein” either. It can, however, easily be established from Bohr’s other elaborations there, such as the one, via the Compton effect, immediately following this formulation (Bohr 1949, *PWNB* 2, p. 40) or elsewhere, especially in his reply to EPR, where, as will be seen, Bohr’s whole argument essentially depends on this possibility. Parts (b) and (c) of this definition are just as important as part (a); and to miss or disregard them, as is often done, is to miss much of the import of Bohr’s conception. As noted above and as will be discussed in detail in Chapter 5, Bohr himself to some degree contributed to this misunderstanding by his Como argument. The complementarity, just mentioned, of the space–time description, obtained by observation, and the causality of the independent, “undisturbed,” quantum behavior, central to the Como argument, does not properly conform to this more rigorous definition. Arguably the most significant examples of complementarity rigorously following this definition are those of the complementary nature of the position and the momentum measurements, and of the space–time coordination and the application of momentum or energy conservation laws (there are, thus, two complementarities here), correlative to Heisenberg’s uncertainty relations (e.g., Bohr 1958, *PWNB* 3, p. 5).

This conception of complementarity will be termed here “*complementarity in the narrow sense*.” Because complementary phenomena are characteristic of quantum vis-à-vis classical physics, the concept also guided Bohr’s overall thinking concerning quantum phenomena and quantum mechanics. Ultimately the concept came to ground his interpretation of jointly both, and the term complementarity came to designate this interpretation as well, to be termed here “*complementarity in the broad sense*.”

It would, however, be difficult and, I would argue, impossible to properly consider complementarity without substantively addressing the work of Heisenberg and Schrödinger, the co-discoverers of quantum mechanics in, respectively, its matrix and wave versions. Although based on very different physical approaches and philosophical views, the two versions quickly proved to be equivalent in terms of their mathematical formalism and their predictive capacity. Both discoveries, and the ideas that led to them, had a decisive influence on Bohr’s thinking. The contributions of Heisenberg and Schrödinger are also extraordinary in their own right, physically, mathematically, and philosophically, including in shaping our understanding of the relationships between epistemology and probability in quantum theory. Accordingly, this study is equally concerned with their work.

The influence of Bohr's thinking upon that of Heisenberg and that of Heisenberg's on Bohr's is well known, although the latter has been given less attention in the literature, as against the more symmetrical treatment of the case offered in this study. Arguably, the greatest examples of this mutual influence are the impact of Bohr's ideas on Heisenberg's thinking leading to his discovery of quantum mechanics and, conversely, that of Heisenberg's ideas and findings, in particular, the uncertainty relations, on Bohr's work on complementarity. Heisenberg's later (roughly post-1930s) thinking concerning quantum theory retains its affinity with Bohr's thought, but it also departs, sometimes significantly, from Bohr's views. While Heisenberg's later ideas will be given less attention in this study than his earlier work on quantum mechanics, considering them is important for my overall argument. There were also differences in their views at earlier stages of Heisenberg's work on quantum theory, which I shall address as well. It may be argued, however, that the affinities between their respective ways of thinking were more prominent and significant than the differences at all stages of their thinking.

Schrödinger's case is different. His wave mechanics was crucial for Bohr's early thinking concerning complementarity, in this case (as against that of Heisenberg's work) in contrast to his subsequent thinking, which led to significant refinements and, in some cases, the abandonment of his earlier ideas. Bohr, of course, continued to recognize the significance of Schrödinger's equation itself. Schrödinger's physical ideas and philosophical views are a different matter altogether. These views have a very different genealogy, and his philosophical ideas are in direct conflict with those of Bohr and Heisenberg, at least from the time of Schrödinger's invention of his wave mechanics on. Intriguingly, some of Schrödinger's earlier views concerning, indeed *against*, causality were similar to those of Bohr and Heisenberg. This conflict led to a number of heated exchanges between them, without, it is worth noting, ever having affected their mutual respect for each other. These exchanges and Schrödinger's opposition to Bohr's epistemological position helped Bohr to sharpen his ideas, arguably as much as did the affinities (or differences) between his philosophical thinking and that of Heisenberg. The primary positive role of both Heisenberg's and Schrödinger's work for Bohr's thinking was, however, defined by the extraordinary physics this work contained.

Schrödinger's philosophical views were, at least, again, from the time of the creation of quantum mechanics on, close to those of Einstein, with whom he had close intellectual affinities and important exchanges on quantum theory throughout his life. The two shared a discontent concerning quantum theory, which both of them helped to create (Einstein at earlier stages of quantum theory), and for which Schrödinger's wave mechanics, as against Heisenberg's theory, initially offered better prospects in their view. These hopes for Schrödinger's theory, however, failed to materialize, since it proved to be all but impossible to bring its mathematics in line with these philosophical desiderata. Schrödinger's view of quantum theory, even if not his general philosophical orientation, ultimately diverged from that of Einstein as well.

Einstein's critique of quantum mechanics and his great confrontation with Bohr concerning, to return to Bohr's expression, "epistemological problems in atomic physics" have overshadowed the history of quantum mechanics and of the debates concerning it. Einstein's name may, thus, be conspicuous by its absence in this book's title. On the other hand, Einstein's thought is hardly absent in the book itself. Indeed, it would be impossible to avoid his towering presence in the history of quantum theory, which he helped to shape and advance both at the earlier stages of its development and, against the grain of his own views, in his later criticism of quantum mechanics. His ideas and arguments are repeatedly invoked and are often considered in detail throughout the book. Although several other founding figures of quantum theory, such as Born, Dirac, Pauli, and von Neumann, will also be extensively addressed, Einstein remains the most frequent guest in this study as much as he is in the works of Heisenberg, Schrödinger, and, most especially, Bohr. Einstein and Schrödinger also became uncompromising critics of quantum mechanics and, especially, of "the spirit of Copenhagen," as Heisenberg called it (which, as I shall explain in the Introduction, is not the same as "the Copenhagen interpretation" of quantum mechanics). Their criticism helped both Heisenberg and Bohr refine and develop their key physical and philosophical ideas, and this criticism is, accordingly, important for this study.

In addition, as I said, Einstein made several extraordinary contributions at earlier stages of quantum theory, beginning with the idea of photon, but far from ending there. These contributions were indispensable to the emergence of quantum mechanics. Later on, in 1935, as part of his critique of quantum mechanics, he also introduced, in an article cowritten with Boris Podolsky and Nathan Rosen, the famous thought experiment, known as the experiment of Einstein, Podolsky, and Rosen or the *EPR experiment*, to be distinguished from *EPR's argument* concerning this experiment. The experiment posed deep questions concerning quantum phenomena and quantum mechanics, in particular the question of correlations, "the *EPR correlations*," between distant (spatially separated) quantum events. The experiment has had a decisive impact on foundational thinking in quantum mechanics, especially from the 1960s onward, following Bell's theorem and related developments, which extended and amplified the problematic established by the experiment. The correlations themselves in question are sometimes also known as the *EPR–Bell correlations*.

Indeed, in large measure, this problematic defines the current stage of this thinking and the debate (as intense as ever) concerning quantum phenomena and quantum mechanics. The subject is, accordingly, important for the argument of this book, and will be addressed in detail in it, especially in Chapters 8 and 9, where the concepts just mentioned will be properly explained as well. As will also be seen in Chapter 8, however, the essential questions at stake in the *EPR* experiment, specifically those concerning reality and locality and their relationships, were raised and reflected upon by Bohr already in 1925, even before (albeit only by a few months) Heisenberg's introduction of quantum mechanics. This is one of the reasons for Bohr's contention that *EPR's*

argument contained nothing essentially new. While this contention may not be altogether justified, Bohr has a point. It is also worth noting that the concept of entanglement [*Verschränkung*], which reflects one of the most crucial aspects of the EPR experiment, arguably the most central to the developments just mentioned, was introduced by Schrödinger, rather than by Einstein.

Important as it may be, however, the EPR–Bell problematic is only a consequence, one of many consequences, of the situation defined by quantum phenomena and quantum mechanics, established well before this problematic was introduced as such. I would even argue that, while productive, centering the discussion and debate concerning quantum theory on the EPR–Bell problematic and entanglement has led to overfocusing and sometimes narrowing our quantum-theoretical thinking as concerns the foundations of both quantum mechanics itself and higher level quantum theories, such as quantum field theory. I would also contend that the discovery of quantum mechanics was a much more momentous discovery than the EPR experiment or Bell’s theorem, which, combined, acquired a dominant and sometimes nearly fetish-like status in recent discussions. This assessment is not aimed to deny the achievement or significance of either contribution, but instead to put quantum theory and its history into a broader and, I would argue, more balanced perspective. Quantum mechanics, especially keeping in mind its extension to quantum electrodynamics and quantum field theories, is arguably the single most important discovery in the history of quantum physics. It might be added that it has also had a major impact on the twentieth- and by now twenty-first-century mathematics, including, as will be seen, in some among the most advanced areas of mathematical research.

Accordingly, my subtitle designates, with Heisenberg and Schrödinger, the creators of quantum mechanics and, with Bohr, the figure whose contribution was uniquely significant for the history of the interpretation of quantum phenomena and quantum mechanics, especially from the perspective of the relationships between epistemology and probability, my main subject in this study. This significance can, I would argue, be ascertained regardless of how one assesses Bohr’s own interpretation of both as complementarity, although the present study of course views this interpretation as a major achievement as well.

More generally, I aim to focus this study on the *positive* significance (physical, mathematical, and philosophical) of our understanding of quantum phenomena and of quantum mechanics, as an effective theory of these phenomena, rather than on the criticism that it elicits, even though this criticism, again, remains important, including for our understanding of this positive significance. Part of this significance, especially in the case of Heisenberg’s work, is defined by the connections between quantum mechanics and Bohr’s work in quantum theory preceding quantum mechanics, especially, as mentioned above, his 1913 theory of the hydrogen atom, which brought him his Nobel Prize. This theory already reflected some among the physical and epistemological complexities that came to define quantum mechanics and complementarity. The work of other figures

mentioned above was important as well, in particular, again, the work of Einstein that preceded quantum mechanics and the work of Dirac on both quantum mechanics and, especially, on quantum electrodynamics, the invention of which by Dirac and Jordan closely followed the invention of quantum mechanics. However, since the rise of modern physics in the work of Galileo and Newton, nothing, with the possible exception of relativity, can in my view be compared to the significance of quantum mechanics for our thinking about nature and physics, and for the nature of our thought and knowledge. The greatest philosophical significance of Bohr's thinking lies in capturing the essence and power of this transformation and in grounding complementarity in the fundamentals responsible for it. This transformation, however, would not be possible apart from the discovery of quantum mechanics by Heisenberg and Schrödinger.

The physical significance of quantum mechanics is hardly in question and has been readily acknowledged even, as I said, by those who have been dissatisfied with it philosophically, beginning with Einstein. On the other hand, as indicated above, the case is complex as concerns the philosophical questions raised by quantum mechanics or, again, already by earlier developments of quantum theory, beginning with Planck's discovery of quantum phenomena in 1900. Historically, while Bohr's philosophical thought had a major impact on several figures mentioned above, most especially Heisenberg and Pauli, it is difficult to think of a *positive* shaping impact of the philosophical thought of any of these figures on Bohr. Although Heisenberg was an exception in this respect, the philosophical impact of Heisenberg on Bohr was primarily a result of interactions between them, whose philosophical aspects were, at least at the time of the creation of quantum mechanics, largely shaped by Bohr's thought, as against the physical and mathematical aspects of these interactions, shaped primarily by Heisenberg's ideas.

Bohr's thought was, again, greatly helped by criticism, specifically that of Schrödinger at earlier stages of Bohr's thinking concerning quantum mechanics and, most crucially, that of Einstein, to the point of transforming Bohr's initial argument concerning complementarity almost immediately after its introduction in 1927. Einstein's skeptical attitude toward and his criticism of quantum mechanics continued to shape Bohr's thinking on quantum physics for the rest of his life. Indeed it appears that Bohr's active work on complementarity, which, as he said, was his *life*, pretty much ended with Einstein's death in 1954. One is tempted to argue the case, even though there are subsequent writings on quantum mechanics and complementarity, and some important interviews, literally until the day he died, just (literally the next day) after his interview with Thomas Kuhn in 1962 (Bohr 1962). Bohr appears to have needed Einstein to arrive where he did, even though and perhaps because Einstein did not see the road taken by Bohr as possible for himself (he admitted that it was possible in principle) and never stopped his search for, to him, epistemologically more palatable alternatives. Bohr did not appear to have needed Einstein (only Heisenberg and Schrödinger) to start on this road by introducing

complementarity in the Como lecture. He appears, however, to have needed Einstein to continue to move forward, at least in the way he did, which, as I shall argue, was a powerful way to do so. On the other hand, helped by Einstein, Bohr had reached quite far, perhaps as far as it appears possible to reach on this particular road, at least for now. Would he have arrived there without Einstein? It would be difficult to argue that this would not have been possible, and it is intriguing (albeit very hard) to contemplate how Bohr's thought on quantum mechanics would have developed if Einstein had taken a positive, rather than critical, view of quantum mechanics. As it happened, Einstein's critical impact seems to have been an overdetermining factor.

Einstein was preoccupied with the subject all his life as well and continued to comment on the subject until his death, although, unlike his previous work on quantum theory, his contribution remained limited to his criticism of quantum mechanics. This criticism was, again, far from unproductive, but it was only a criticism, except when it was made against his own grain, as in the case of his conception of the experiments of the EPR type, which laid fertile ground for much productive positive thinking concerning quantum phenomena and quantum theory, including of the kind to be explored here. As his response to Bohr's argumentation shows, this kind of thinking was not something Einstein was willing to accept as a "useful point of departure for future development" (Einstein 1949a, p. 83). He did acknowledge this thinking to be "logically possible without contradiction," but found it "contrary to his scientific instinct" (Einstein 1936, p. 375; Bohr 1949, *PWNB* 2, p. 61).

But then, we need not be always guided by Einstein's scientific or (which is really the case here) philosophical instincts, and we should not be afraid to follow other paths or be in turn critical of Einstein. Einstein is not God, any more than Bohr or anyone else is. When Friedrich Nietzsche famously said that God is dead, he meant that all human gods are now dead, too, for us. More generally, significant and even unique as the contributions of these figures might have been, they, their names, function in this study primarily as the indicators of or signatures (sometimes collective) under conceptual formations or problems, each of which requires a critical exploration and analysis. In other words, each of these names represents a conceptual field under investigation in interaction with each other. This is, for example, how I would see Bohr's essay "Discussion with Einstein on Epistemological Problems in Atomic Physics," beginning with the title (Bohr 1949, *PWNB* 2, pp. 32–66). It is a confrontation of fields of thought and more than two such fields. For this confrontation involves fields of thought to which history assigns names or signatures other than Einstein or Bohr, in particular Heisenberg and Schrödinger, but also Planck, Rutherford, de Broglie, and others.

Whatever positive, shaping philosophical influences Bohr's thinking concerning complementarity might have had, these influences came from elsewhere, for example, from Bernhard Riemann's mathematical ideas (these ideas were also philosophical, however) or from the philosophical critique of causality, extending from David Hume and Immanuel Kant to Nietzsche. For

Nietzsche, the death of God (it has many meanings) is also the death of causality and determinism—when the latter are seen as gods governing thought. They do have their place, indeed their necessary place, in our thinking otherwise. A friend of Bohr's father, Georg Brandes, whom Bohr admired, was one of the early champions of Nietzsche and taught the first ever university course on Nietzsche at the University of Copenhagen. Primarily, however, Bohr arrived at complementarity, at least as an interpretation of quantum phenomena and quantum mechanics, through thinking *philosophically*, or both physically *and* philosophically, *through physics*, the physics created, along with Bohr himself, by Heisenberg and Schrödinger, and other figures just mentioned. It was above all physics that made complementarity both possible and necessary for him, and that made it philosophy through a radical transformation of our understanding of the nature of scientific knowledge and, ultimately, of all human knowledge.

The same type of argument can also be made, and will be made here, for Heisenberg, who was compelled to make some of his radical epistemological moves, just as some of his radical mathematical moves, in order to solve physical problems he had to confront. By contrast, although physics was still crucial for him as well, Schrödinger's program for his wave mechanics was guided to a much greater degree by certain philosophical principles (classical-like in nature), in part in a deliberate juxtaposition to Heisenberg's matrix mechanics. The mathematical equivalence of both types of formalism became apparent later, albeit quickly, and Schrödinger was one of the first to establish it, which fact of course took from under his feet much of the ground for his objections to matrix mechanics. It is much more difficult to argue against mathematics than against philosophy, especially if it is the same mathematics that is used to support the opposing philosophy in which this argument was based. Schrödinger did not change his philosophy. Instead, he came to doubt and even to repudiate quantum mechanics, at least as a desirable way of doing physics, although he acknowledged that the theory and even understanding it in "the spirit of Copenhagen" (which remained philosophically deplorable to him) may have been imposed on us by nature itself. This view came to define, as he called it in his famous cat-paradox paper of 1935, "the present situation in quantum mechanics" (Schrödinger 1935a, *QTM*, p. 152), with, however, the hope at the time that it might change, in part in view of the EPR experiment, just introduced then, and perceptively analyzed by Schrödinger in the paper itself.

On that score the situation is not that different now: It is still "the present situation of quantum mechanics," although subsequent developments, including those around the EPR experiment, enriched it. The controversy surrounding quantum theory and the intensity of the debates concerning it have remained undiminished, which is a testimony to the impact of quantum theory on our thinking in physics and beyond. No end of either appears to be in sight, and, as they deepen our understanding of quantum phenomena and quantum theory, certain recent developments, such as quantum information theory, add more fuel to this controversy and the debates concerning quantum phenomena and quantum theory. One can witness the intensity of this continuing process,

as I have throughout the writing of this book, virtually on a daily basis. Every other issue of *Nature* or *Science*, to mention only the two most prominent scientific journals, contains an article or a review that reflects and continues these debates.

At the same time, in spite of the enormous and ever-proliferating number of accounts of and commentaries on the subject, some of the deeper aspects of quantum physics and of the thought of the figures considered in this study, most notably, but far from exclusively, Bohr, often remain missed or misunderstood and as a result unexplored. I am not saying that these figures were always right. They were, as I said, not gods (although they might appear to be sometimes) and had to struggle hard in confronting the difficulties of quantum physics, and they have made mistakes. Such mistakes often help us understand the deeper complexities of quantum theory nearly as much as correct arguments offered by these figures, and sometimes more than do the latter. In particular, as noted above, Bohr's initial argument concerning complementarity in the so-called Como lecture of 1927 required considerable revisions, and they ultimately led Bohr to what was in effect a different interpretation of quantum mechanics. Although this study ultimately sides with Bohr and Heisenberg as against Einstein and Schrödinger, it by no means unconditionally accepts the arguments of the first two thinkers or unconditionally rejects the arguments of the last two. There are also differences, sometimes significant, between Bohr's and Heisenberg's views, or between those of Einstein and Schrödinger, which differences play their roles in shaping this study's view concerning quantum theory.

Of course, even leaving aside those parts of this study's argument that expressly depart from those of Bohr, Heisenberg, and Schrödinger, this study can only offer an *interpretation*, one among several possible interpretations, of quantum mechanics itself or of the views held by each of these figures, or by any other figure considered in this study. This interpretive "inflection" is unavoidable, no matter how close one's reading is or how attentive to the proper norms of rigor and scholarship. Respecting such norms is imperative, for otherwise one would be free to say just about anything and unable to argue for the rigor or validity of one's interpretation or against the problems of other interpretations. Both types of argumentation are essential for maintaining the intellectual and ethical integrity of our knowledge and discussions. It is a greater conceptual and historical rigor of reading that allows us to understand better certain key aspects of the thought of Bohr or others, such as the greater than previously perceived significance of mathematics in Bohr's work. It also allows us to see the problems of other readings or inflections of Bohr, Heisenberg, and Schrödinger.

There is, however, no uninflected reading that would guarantee us the true meaning of a given work; not even a reading by Bohr himself could do so, although, were he around, he *might* have done better than most other readers. Might! For, as will be seen, he is not always helpful or does not always avoid misreading or at least "inflections" in readings of his earlier works in his later

works. Bohr was interminably interpreting and reinterpreting quantum mechanics and his interpretation of it in the process that was, as he said, “his life,” and that indeed was terminated only by his death, speaking nearly literally, since he was explicating and, given the way his thought worked, quite possibly reinterpreting his interpretation in an interview with Kuhn, cited above, just before he died (Bohr 1962). Hence, my quotation marks around “inflected.” For, given these (irreducible) conditions, the question would be: Against what uninflected meaning does such an inflection occur? Even if it existed, such an uninflected meaning could never be available, although, as just indicated, one can speak rigorously of relative inflections, or one might say inflections between earlier and later inflections. In any event, Bohr is no longer around to help us, and neither are Heisenberg and Schrödinger. We must try our best without them, and pay our debt and tribute to them by trying to do our best in reading them, both for the reasons of scholarly rigor and, more crucially, in order to gain a better understanding of quantum theory.

The ultimate aim of this book is to contribute to this understanding, and to the understanding of the reasons for its extraordinary impact and for the controversies surrounding it, in particular, again, those related to the difficulties of developing a realist and causal theory of quantum phenomena of the type classical mechanics offered for classical physical phenomena. One might feel, with Einstein, Schrödinger, and others, such as John S. Bell (of Bell’s theorem fame), that the beauty and power of classical physical and epistemological thinking or what Schrödinger called the “classical [physical] ideal” are lost with quantum mechanics (Schrödinger 1935a, *QTM*, p. 152). On the same occasion, Schrödinger referred to quantum mechanics in the type of interpretation to be adopted here as “the doctrine born of distress” (Schrödinger 1935a, *QTM*, p. 154). One could understand and even sympathize with Einstein’s or Schrödinger’s view of the “doctrine.” One need not, however, agree with this view or share his sense, that of desperation, concerning “the present situation in quantum mechanics,” which is still much the same as it was 70 years ago as concerns the essential features of nature and the theory considered by Schrödinger. While, however, this situation itself may not be that different *epistemologically*, we, I would argue, have a different and deeper understanding of this situation.

In part for that reason, the kind of feeling that the present author has or that this book aims to convey concerning quantum mechanics is quite different from that of Einstein and Schrödinger, even though this book does aim to convey the beauty and power of classical thinking, physical or philosophical, along with the beauty and power of quantum-theoretical thinking. We need both ways of thinking, even in quantum theory, let alone elsewhere in physics. Even if and to the degree that this loss of the classical ideal is unavoidable, it is, at least for some of us, compensated by gaining a different kind and a different understanding of thought and knowledge. This understanding is perhaps equally beautiful and powerful, if also more modest, since the unknowable and the unthinkable become a permanent part of our knowledge and thought. Nature,

or our thought, given to us courtesy of the brain, appears to exceed the capacity of our thought to fully comprehend it. We are able, however, to comprehend something about it, actually quite a bit—not the least, with quantum mechanics, the limits at which the possibility of this excess must be posed as a rigorous physical and philosophical question. This is an extraordinary achievement of quantum-theoretical thinking, which, beginning with quantum mechanics itself, a great product of this thinking, is a testimony that the brain is one of nature's more remarkable products.

Epistemology and Probability

Bohr, Heisenberg, Schrödinger, and the Nature of
Quantum-Theoretical Thinking

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