Preface

I would like to begin with the endpoint of the history to be traversed by this study, the discovery of the Higgs boson, arguably the greatest event of fundamental physics in the twenty-first century thus far, and, thus far, a culminating event in the history of quantum physics. This discovery has been discussed at all levels and in all media, with photographs of the "events" testifying to the existence of the Higgs boson and of various components, staggering in their complexity, of the Large Hadron Collider (LHC), and the relevant parts of the mathematical formalism of quantum field theory (e.g., "The Higgs Boson," *Wikipedia*; CERN: Accelerated Science: Images). These pictures are well known and easily located on the Web. I only cite the key part of the formalism, the epistemological nature of which will be discussed in Chap. 6:

> In the Standard Model, the Higgs field is a four component scalar field that forms a complex doublet of the weak isospin SU(2) symmetry:
>
> $$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^1 + i\phi^2 \\ \phi^0 + i\phi^3 \end{pmatrix}$$
>
> while the field had charge +1/2 under the weak hypercharge U(1) symmetry (in the convention where the electric charge, Q, the weak isospin, I_3, and the weak hypercharge, Y, are related by $Q = I_3 + Y$).
>
> The Higgs part of the Lagrangian is
>
> $$\mathcal{L}_H = \left| \left(\partial_\mu - igW_\mu^\alpha \tau^\alpha - i\frac{g'}{2} B_\mu \right) \right|^2 + \mu^2 \phi^\dagger \phi - \lambda \left(\phi^\dagger \phi \right)^2,$$
>
> where W_μ^α and B_μ are the gauge bosons of the SU(2) and U(1) symmetries, and g and g' their respective coupling constant, $\tau^\alpha = \sigma^\alpha / 2$ (where σ^α are the Pauli matrices) a complete set of generators of the SU(2) symmetry, and $\lambda > 0$ and $\mu^2 > 0$, so that the ground state breaks the SU(2) symmetry. The ground state of the Higgs field (the bottom of the potential)

is degenerate with different ground states related to each other by an SU(2) gauge transformation. It is always possible to pick up a gauge such that the ground state $\phi^1 = \phi^2 = \phi^3 = 0$. The expectation value of ϕ^0 in the ground state (the vacuum expectation value or vev) is then $\phi^0 = \frac{v}{\sqrt{2}}$, where $v = \frac{|\mu|}{\sqrt{\lambda}}$. The measured value of this parameter is $\sim \frac{246\text{GeV}}{c^2}$. It has units of mass, and is the only free parameter of the Standard Model that is not a dimensionless number. Quadratic terms W_μ and B_μ arise, which give masses to the W and Z bosons:

$$M_W = \frac{v|g|}{2}$$

$$M_Z = \frac{\sqrt{g^2 + g'^2}}{2}$$

with their ration determining the Weinberg angle, $\cos\theta_W = \frac{M_W}{M_Z} = \frac{|g|}{\sqrt{g^2 + g'^2}}$, and leave a massless U(1) photon, γ.

("The Higgs Boson," *Wikipedia;* Peskin and Schroeder 1995, pp. 690–700)

Now, what does all this (the photographs of the corresponding events, computer generated images and data, staggering machinery of the LHC, and the mathematics just described) mean? And how is it possible? Without attempting to definitively answer these questions, this study will consider a particular perspective on them, indeed a particular way of asking them, and will suggest partial answers that arise if one adopts this perspective. This perspective is guided by understanding the nature of quantum reality, or the quantum reality of nature, and of quantum theory, from quantum mechanics to quantum field theory, in "the spirit of Copenhagen [*Kopenhagener Geist der Quantenheorie*]," in Heisenberg's memorable phrase, the spirit that guides this study, as indicated by its subtitle (Heisenberg 1930, p. iv). This understanding relates nature and spirit (a relation that we seem unable to do without even when a materialist view of the world is adopted) in a new way. The spirit of Copenhagen, I argue, is defined by three great divorces from the preceding understanding of these relationships between nature and spirit, or, to use a less theologically charged expression, nature and mind (technically, German *Geist* means both), specifically scientific thought in modern physics: reality from realism, probability from causality, and locality from relativity. It is true that the last of these divorces did not shape the rise of the spirit of Copenhagen in the way the first two did, but it became a major part of this spirit nevertheless.

I shall comment on these three "divorces" and define the corresponding concepts below, and discuss them in detail in Chap. 1 and elsewhere in this study. For the moment, the spirit of Copenhagen has its history in the preceding understanding of nature and mind, and their relationships. This history extends even as far as the pre-Socratics, and I shall address some of these more distant historical connections later in this study. However, the most significant historical trajectory of this study prior to the birth of quantum theory, inaugurated by Planck's discovery of the quantum of action, h, begins with scientific modernity. There is no modernity other than scientific, because modernity is defined, partially but decisively, by the rise of modern, mathematical-experimental, sciences of nature.

Consider John Milton's description of chaos in *Paradise Lost*. This description and Milton's poem itself were written in the aftermath of the rise of mathematical-experimental science, at that stage physics and astronomy, with Copernicus, Kepler, and Galileo; and the poem was a response to a different world that emerged with and because of this rise, a world to which we now refer as the world of modernity. Milton's stated aim in writing the poem is "to justify the ways of God to man," with "justify" referring to both the nature and the justness of these ways (Milton 2004, p. 3, *Paradise Lost*, Book I, ll. 25–26). But why would one have needed such a book? Don't we already have the Bible that should do so? Well, not exactly, or rather the Bible, Milton realized, was no longer sufficient to do so. As is clear from Milton's references in *Paradise Lost* to post-Copernican astronomy, and Galileo's and Boyle's physics, Milton acutely realized that the world he lived in, the world of modernity, was defined by, in Galileo's words, "new mathematical sciences of nature," which brought mathematics and experiment together (Galilei 1991). "Modern science," M. Heidegger says, "is experimental because of its mathematical project" (Heidegger 1967, p. 93). The world, as envisioned by Milton, was post-Copernican and post-Galilean. R. Boyle has already conducted his famous experiments on the properties of air and the existence of the vacuum, and Newton, Milton's equally famous fellow Cambridge graduate, was soon to appear on this stage and to shape the thinking of modernity even more decisively. (Both Boyle and Newton had major alchemical and theological interests, and left voluminous writings on these subjects.) It was no longer the world of the Bible, and Milton reread or re-envisioned the Bible as consistent with this new world. For Milton, God created the world as understood by modern science and (they are, again, inseparable) scientific modernity. This world called for a new justification of the ways of God to man, assuming that this justification is possible, given that this new world compelled some to deny this possibility, or the existence of God in the first place. The question of this justification or its possibility, which is still with us, is well outside the scope of this study. But Milton's argument for the extraordinary complexity of this world, which, however it came about, requires the utmost reach of and may ultimately be beyond human thought, is relevant to this project. This complexity and this relevance are shown, for example and in particular, by Milton's description of chaos in the poem:

> Before their eyes in sudden view appear
> The secrets of the hoary Deep—a dark
> Illimitable Ocean without bound,
> Without dimension: where length, breadth, and height,
> And time, and place, are lost; where eldest Night
> And Chaos, ancestors of Nature, hold
> Eternal anarchy, amidst the noise
> Of endless wars, and by confusion stand.
> For Hot, Cold, Moist, and Dry, four champions fierce,
> Strive here for maistrie, and to battle bring
> Their embryon atoms: they around the flag
> Of each his faction, in their several clans,
> Light-armed or heavy, sharp, smooth, swift or slow,

Swarm populous, unnumbered as the sands
Of Barca or Cyrene's torrid soil,
Levied to side with warring winds, and poise
Their lighter wings. To whom these most adhere,
He rules a moment: Chaos umpire sits,
And by decision more embroils the fray
By which he reigns: next him, high arbiter,
Chance governs all. Into this wild Abyss,
The womb of Nature, and perhaps her grave,
Of neither Sea, nor Shore, not Air, nor Fire,
But all these in their pregnant causes mixed
Confus'dly, and which thus must ever fight,
Unless th' Almighty Maker them ordain
His dark materials to create more worlds—
(Milton 2004, p. 20, Paradise Lost, Book II, 890–916)

The physical universe in this view is, thus, chaos, unless order emerges from it, and this happens continuously, too, even if, generally, without giving this order stability. Milton's description is presciently close to the understanding of the ultimate constitution of nature arising from quantum theory, arguably more so than Lucretius's atomism in *De Rerum Natura* (Lucretius 2009), commonly claimed to be the main precursor of modern atomic theory (along with Leucippus and Democritus, and then Epicurus, on whose ideas Lucretius relies) and one of Milton's sources. Boyle's experiments were undoubtedly on Milton's mind as well. Milton's conception does not quite reach the radical form of this understanding to be advocated in this book. Both randomness and chance, and the birth and disappearance of "particles" in chaos, and thus unstable, fleeting nature of any order that might emerge in and from it (unless some power manages to be stabilized and built on this order), are all part of this book's view of nature at the ultimate (quantum) level of its constitution. The second aspect just mentioned is specifically found in high-energy regimes and reflects or is reflected in the concept of virtual particle formation in quantum field theory, according to which the unstable, fleeting forms of order emerge from and disappear back into the foaming bubbling of chaos. This is what J. A. Wheeler refers to as "quantum foam" (Wheeler and Ford 2000, pp. 245–263). However, according to this study's view, the ultimate character of this constitution, of Milton's "embryon atoms," which we now refer to as "elementary particles" (still an unsettled concept in fundamental physics, as is its companion concept, that of quantum field), is "dark" beyond the reach of our understanding or possibly even any conception we can form. This view is closer to, but still ultimately transcends, the ancient Greek sense of chaos as *areton* or *alogon*, as that which is beyond all comprehension, than to Milton's conception of chaos here. On the other hand, Milton does appear to imply that our ways of experiencing the world and conceptions we could form of it, such as space, time, and causality (Kant's three great a priori givens of our thought), are "lost," that is, no longer applicable to chaos. Milton was certainly aware of the ancient Greek's idea of chaos as *areton* or *alogon*. So perhaps he was closer to the argument of this book on this point, except for the ultimately theological nature of his thinking. This book is concerned with the unrepresentable and possibly unthinkable "dark materials" of nature as they appear in quantum physics, placed outside or even assumed to be incompatible with theology. I prefer to leave theology to Milton. If anything, this study's understanding of the physical world, also because our interaction with it is governed by probabilistic thinking, is closer to the world of Shakespeare's plays (often invoked by Wheeler [e.g., Wheeler 1983, p. 204]), which tend to put the theological aside. They leave it to us "to take arms against a sea of troubles," a *sea*, a place governed by chance and probability (Shakespeare 2005, p. 700, *Hamlet*, III.2.55-87). The sea is often invoked by Shakespeare as such a place, and Wheeler's reference just mentioned is *The Tempest* (Shakespeare 2005, p. 1238, Act IV.1, 148–158). As Nestor says in *Troilus and Cressida*:

> … In the reproof of chance
> Lies the true proof of men. The sea being smooth,
> How many shallow bauble-boats dare sail
> Upon her patient breast, making their way
> With those of nobler bulk!
> But let the ruffian Boreas once enrage
> The gentle Thetis, and anon behold
> The strong-ribbed bark through liquid mountains cut,
> Bounding between the two most elements
> Like Perseus's horse. Where's then the saucy boat
> Whose weak untimbered sides but even now
> Co-rivalled greatness? Either to harbor fled,
> Or made a toast for Neptune. Even so
> Doth valor's show and valor's worth divide
> In storms of fortune. For in her ray and brightness
> The herd has more annoyance by the breeze
> Than by the tiger; but when the splitting wind
> Makes flexible the knees of knotted oaks,
> And flies fled under shade, why, then the thing of courage,
> As rous'd with rage, with rage does sympathize,
> And with an accent tun'd in selfsame key
> Retorts to chiding fortune.
> (Shakespeare 2005, p. 749, Act I.iii.33–54).

Shakespeare's music is the music of the sea, the music of chance and its complex harmonies, mixing chaos and order—chaosmic harmonies, as they were called by James Joyce, from whose *Finnegans Wake* M. Gell-Mann famously borrowed the term "quark" (Joyce 2012, p. 118). These chaosmic harmonies are opposed to the music of the spheres, that of Pythagoras or that of Kepler, another contemporary of Shakespeare. As my epigraph suggests, however, Joyce's masterpiece was in turn influenced by quantum theory, not inconceivably by the discovery of antimatter, which was widely discussed at the time, just as the Higgs boson or black holes are now, and was known to Joyce (Joyce 2012, pp. 383, 149). In Joyce's novel words transform into each other just as particles do in high-energy quantum physics. The appearance of Thetis in Shakespeare's passage is not by chance, and she is mentioned, again, in the play: Thetis is the mother of Achilles, the greatest of heroes. It is the rage of Achilles and his concern for the lack of virtue where *The Iliad* of Homer begins. While the chance to kill Achilles is small, it is bound to happen at some point with probability 100 %, but it is difficult to predict when, although the Trojan War increased this probability. Achilles is an important character in Shakespeare's play, where, great hero as he is, he is portrayed far less than heroically. He kills Hector by violating all possible rules of fair play, and by taking advantage of Hector's following these rules and sparing Achilles's life a bit earlier. Hector took a chance on this, but Achilles was not about to take any chances with Hector, by giving Hector a chance. Games of chance and probability are quite complex in Shakespeare's plays.

Dark beyond all thought as nature's "dark materials" are, they allow nature to create new and stable, including highly stable, forms of organization, which may be dynamic. They also allow us, by experimenting with nature, to create new *configurations* of experimental technology and even of nature itself, and through them, enable us to develop new understandings of nature and of our interactions with it. It is true that these interactions are ultimately nature as well, but they are specific to us. Of course, only nature, at least thus far, could create new worlds on the ultimate scale, new Universes, or even on smaller scales, like new stars and planets, apart from science fiction, fond of giving humans such capacity in a distant future. It is prudent to leave God aside or, again, to leave God to Milton. It is certainly more than merely prudent not to assume a god-like role in our scientific experimentation with nature in physics or elsewhere, in biology, for example. This is one of many lessons of twentieth-century physics, or of all modern science throughout its history, from Galileo on, which reminds us that the philosophy of physics is sometimes also a moral philosophy. Our experimentation, however, need not depend on and be measured by assuming such a role, given that the creation in question from the dark materials of nature is ongoing on local scales as well, including the minutest scales in question in quantum physics. The commitment itself to creative experimentation may well be imperative, or, in the language of (Kant's) moral philosophy, be the *categorical imperative* of all good science. That is, our aim in our pursuit of mathematics and science, no less than of philosophy and art, should be that of creative experimentation, in the service of the discovery of new features and principles in the workings of nature in our interaction with it, and of thought itself, from which, in particular mathematical thought, such principles cannot be separated. This is a point on which all forms of physics (classical, relativistic, or quantum) converge: creative experimentation, physical, mathematical, and sometimes philosophical, is the categorical imperative and the primary force of the *causality* of both, whatever the nature of this causality may be, a difficult problem in its own right, as it is in physics. However, quantum physics, this study argues, introduces new fundamental features and principles of this experimentation, as against classical physics and relativity, although relativity has already done so vis-à-vis classical physics, even if it did not depart from classical physics as radically as quantum mechanics did.

This book's title, "the principles of quantum theory," alludes to those of Werner Heisenberg's *The Physical Principles of the Quantum Theory* (Heisenberg 1930), based on his 1929 lectures given at the University of Chicago, and Paul Dirac's *The Principles of Quantum Mechanics* (Dirac 1930), both published in the same year. It also alludes, more obliquely and by way of a *partial* contrast between "principles" and "foundations," to the title of John von Neumann's *Mathematical Foundations of*

Quantum Mechanics, originally published in 1932 (Von Neumann 1932), in part as a response to Dirac's book. I shall explain the nature of this contrast below, indicating for now that it is partial, because the mathematical aspects or the specific mathematical character of quantum mechanics or quantum field theory is crucial to all three books and to this study. Von Neumann's response to Dirac (to which von Neumann's book was of course not limited) was motivated primarily by von Neumann's aim of establishing quantum-mechanical formalism as fully legitimate mathematically, vis-à-vis that of Dirac's version. While recognized for its great lucidity and formal generality, Dirac's formalism was not considered mathematically rigorous at the time. This was because of Dirac's reliance on his famous delta function, which was not a mathematically legitimate object then. Although this was to change, because the delta function was given a mathematical legitimacy by means of the so-called distribution theory later on, von Neumann's version of the formalism became standard and has remained standard ever since. Along with H. Weyl's 1928 *Theory of Groups and Quantum Mechanics*, translated into English in 1931 (Weyl 1931), and N. Bohr's (more philosophical) 1931 *Atomic Theory and the Description of Nature* (Bohr 1987, v. 1), Heisenberg's and Dirac's were the most important early books on quantum mechanics. The significance of these books has been momentous. They have had and continue to have a strong impact on our thinking concerning quantum theory. The impact of Bohr's essays assembled in *Atomic Theory and the Description of Nature* and his subsequent communications on the subject has been more indirect and more often than not defined by resistance to his ideas. These circumstances, however, have not diminished this impact itself, amplified by that of Bohr's confrontation with Einstein, which has overshadowed the history of the debate concerning quantum mechanics.

Von Neumann's *mathematical foundations* are not the same as Heisenberg's or Dirac's *physical principles*, and not only because of the difference between the mathematical nature of the former and the physical nature of the latter, important as this difference, on which I shall comment presently, may be. Von Neumann's foundations have physical dimensions or, in any event, are essentially related to physics, and Heisenberg's and even more so Dirac's principle thinking is fundamentally mathematical, albeit their work was not quite *mathematics* in its disciplinary sense in the way most (but not all) of von Neumann's book was, and this difference was reflected in their books. (Von Neumann was a mathematician.) Dirac's title, for one thing, says "principles," and the principles that ground his book are both, and often jointly, physical and mathematical. This is true for Heisenberg's book as well, as is testified to by his appendix (which was not part of the Chicago lectures, on which the book was based, but is nearly half of the book) "The Mathematical Apparatus of the Quantum Theory" (Heisenberg 1930, pp. 105–183). This title notwithstanding, the appendix is as much physical as it is mathematical, and there is plenty of mathematics in the main text as well. Still, von Neumann's primary aim was to give, to the maximal degree possible, a mathematical rigor and legitimacy to the formalism of quantum mechanics in its standard version, which was not a primary concern, or at least not an imperative, for Heisenberg or Dirac. According to Heisenberg, "the deduction of the fundamental equation of quantum mechanics" could not be seen as "a deduction in the mathematical sense of the word, since the equations to be obtained form themselves the postulates of the theory. Although made highly plausible [by mathematical considerations], their ultimate justification lies in the agreement of their predictions with the experiment" (Heisenberg 1930, p. 108). Bohr's *Atomic Theory and the Description of Nature* was a collection of previously published essays on complementarity, his central and most famous concept, grounding his interpretation, under the same name, of quantum phenomena and quantum mechanics, an interpretation considered, along with the concept of complementarity, in Chap. 3. As will be discussed there, even this early volume already presented more than one such interpretation, and Bohr's interpretation was to undergo yet further revisions subsequently. It is important that, in each case, it was an interpretation of both quantum mechanics and quantum phenomena, and thus also of quantum objects, which are rigorously distinguished from quantum phenomena in Bohr's interpretation. Thus, Bohr's interpretation would, at least in most of its aspects, hold for quantum phenomena, even if theories other than quantum mechanics were used to predict the data associated with quantum phenomena, although such a theory would of course have to allow for this interpretation. However, for the sake of convenience the term "interpretation," when applied to quantum mechanics or other forms of quantum theory (such as quantum field theory), as in Bohr's interpretation, will generally refer to interpretations of both quantum phenomena or, again, quantum objects, and the corresponding quantum theory, qualifying when necessary.

More generally, "foundations" and "principles" are, at least as they are defined in this study, different categories of thought. Both are important for our understanding of *fundamenta*l physics (which is yet another separate category) and for the argument of this book, even though its makes principles its main focus. This study deals with *foundational* thinking, most especially *principle* thinking (which is a form of foundational thinking), in *fundamental* physics. As other concepts considered here, these concepts may be understood differently, sometimes by reversing this pairing of foundational with thinking and fundamental with physics. Indeed, I shall, along with *foundational* concepts and theories, also speak of *fundamental* concepts and theories, because they belong to fundamental physics, although these concepts are also part of foundational thinking in fundamental physics and define this thinking. By "fundamental physics" I mean those areas of experimental and theoretical physics that are concerned with the ultimate constitution of nature, as we, as human beings, understand this constitution. I qualify because, in the view adopted by this study, this constitution could only be something conceived by the human mind or something assumed (by a human mind) to be beyond human conception. By "foundational" thinking or theories, I mean thinking or theories that concern fundamental physics, for example, the nature of space and time in relativity or the nature of elementary particles, as the ultimate material constituents of matter, in quantum mechanics. Thus, while "fundamental" refers, ontologically, to how *nature* is ultimately constituted, "foundational" refers, phenomenologically and epistemologically, to our *thinking* concerning the *fundamental* constitution of nature. It follows that our view of what is fundamental is unavoidably, even if often implicitly, defined by our foundational thinking. "Principle thinking" is foundational as well ("foundations" is a more general category). It is defined, in Einstein's terms (which I shall follow in this study), as grounded in "empirically discovered … general characteristics of natural processes, *principles* that give rise to mathematically formulated criteria which the separate processes or the theoretical representations of them have to satisfy" (Einstein 1919, p. 228; emphasis added).

To preliminarily illustrate the concept of principle and principle thinking, I would like to consider one of the earliest examples of the use of a principle in modern physics, Pierre de Fermat's "principle of least time," eventually developed into the principle of least action. A number of figures were involved in formulating the latter principle, beginning with G. Leibniz and P. L. Maupertuis (the priority has been disputed), and then L. Euler, J.-L. Lagrange, and Sir Rowan Hamilton, who gave the principle its rigorous mathematical form in classical mechanics, although the principle proved to be more general, extending to relativity and quantum theory. Fermat used the principle of least time to explain the so-called Snell law describing the refraction of light passing through a slab of glass. The principle was not necessary or even especially helpful at the time, because one could more easily use the Snell law in doing calculations in specific cases, while one would ultimately need the calculus of variations to do so from Fermat's principle and to give it a proper mathematical expression. However, Fermat's principle defined *how nature works*, and as such, it was profound and far reaching, especially once it was developed into the principle of least action. The subsequent history of physics has demonstrated the profundity and power of this principle on many occasions, including in relativity and quantum theory. It played key roles in D. Hilbert's derivation of Einstein's equations of general relativity (the Einstein-Hilbert action), E. Noether's proof of her celebrated theorems relating symmetry and conservation laws (equally at work in classical physics, relativity, and quantum theory), Schrödinger's derivation of his wave equation, and R. Feynman's path-integral formulation of quantum mechanics.

As will be seen, principles, in the sense of this study, are different from axioms and postulates, although a principle may involve postulates, as Fermat's principle of least time or the principle of least action does. Axioms and postulates (the latter concept is, as I shall explain, generally more suitable in physics) are also found in quantum foundations apart from principles, for example, "the quantum postulate" introduced by Bohr in 1927, as part of his interpretation of quantum phenomena and quantum mechanics in terms of complementarity (Bohr 1987, v. 1, p. 53). This postulate should not to be confused with Bohr's quantum postulates (plural) used in his 1913 atomic theory in connections with the discontinuous transitions (quantum jumps) of electrons from one energy level to another, ultimately subsumed, but also reinterpreted, by his 1927 quantum postulate. The latter refers to the fundamentally discrete and strictly individual nature of all observable quantum phenomena, defined strictly by what is observed in measuring instruments under the impact of quantum objects, and to be distinguished from quantum objects themselves. Planck's constant, h, *reflects* this discreteness and individuality, but does not necessarily represent them. In Bohr's view, it does not; instead h "symbolizes" them and the quantum postulate itself (Bohr 1987, v. 1, pp. 52–53). The quantum postulate, defined by Bohr as a postulate, rather than a principle (in contrast, for example, to his correspondence principle), may, however, be seen as a manifestation of a principle, the quantum discreteness principle, which, even though it was not expressly formulated as such, was central to both Heisenberg's work leading him to quantum mechanics and Bohr's interpretation of it. In effect, it functioned as a principle in Bohr's thinking all along, even, implicitly, in his 1913 theory of the hydrogen atom. Bohr's thinking was principle throughout his work on quantum theory, including his earlier work in the old quantum theory, beginning with his 1913 theory, which brought him to the center stage of quantum theory, where he remained a central figure throughout his life. This position was equally due to his, *more* physical, contribution to the old quantum theory and his, *more* philosophical, contribution to quantum mechanics. (The difference here is that of balance, as Bohr's contribution was both physical and philosophical in both cases.)

Principle thinking has a pronounced practical dimension, at least as this thinking is understood here. Principles guide one's work, including one's technical work, especially when it comes to the invention of new theories or changing the character of theoretical physics and its practice. This is what happened in Einstein's, Bohr's, Heisenberg's, and Dirac's work, my primary historical examples of principle thinking by the founding figures of quantum theory.

While, then, also addressing foundational thinking in quantum theory (unavoidably, given that principle thinking is foundational), this study will focus on principles and principle thinking. That also means thinking that leads to the invention of new such principles, which is, I would argue, one of the ultimate achievements of theoretical thinking in any field. Although not entirely absent, this focus has been less common in more recent discussions and debates concerning quantum foundations, with a few exceptions to be noted as this study proceeds. I would argue, however, that exploring the nature of quantum principles and principle thinking is exceptionally helpful in addressing the key issues at stake in quantum foundations and the debate concerning it. Principle thinking has been significant and led to major breakthroughs throughout the history of quantum theory, beginning with the old quantum theory and quantum mechanics, the first definitive quantum theory, which it remains within its proper (nonrelativistic) scope. It has, I shall argue, been equally important in quantum field theory, which has been the main frontier of quantum theory for quite a while now, and more recently in quantum information theory, where principle thinking was given new prominence.

The main questions at stake in the ongoing debate about quantum phenomena and quantum theory have been and remain the following two questions concerning *reality* and *realism* in quantum theory. Both concepts involve important qualifications and complexities, which I shall address in Chap. 1. For the moment, their preliminary definitions will suffice to convey the most essential points. By reality I refer to the nature of quantum objects and processes that are ultimately responsible for observed quantum phenomena, which cannot be identified with quantum objects in the way classical objects can, at least ideally and in principle, in classical physics. By realism, I refer to the possibility of *representing*, at least ideally and in principle, the architecture of quantum reality (which architecture may be temporal), in this case and in all modern, post-Galilean, physics, by means of a mathematical model.

Realism, in physics, could be and here will be defined more generally by this possibility of such a representation, or at the very least by the assumption that physical reality has a structure or architecture (usually conceived on the model of classical physics) even though this architecture cannot be captured, at least for now, by a mathematical model. It follows that, in this definition (others are possible), realism is not only a claim concerning the *existence* (reality) of something but also and primarily concerning the *character* of this existence.

Now, the first question is whether quantum mechanics, which provides excellent probabilistic or statistical predictions of the outcomes of quantum experiments (only such predictions appear to be possible, at least thus far, on experimental grounds), is also a realist theory *in this sense* of providing an idealized mathematical representation of quantum objects and processes. The difference (explained in Chap. 1) between the probabilistic and statistical predictions may define different interpretations of quantum mechanics, even if they are nonrealist, as will be discussed in Chap. 4. The second question, arising in view of the difficulties of developing realist interpretations of quantum mechanics, is whether such a realist theory of quantum objects and processes is possible at all, a question further complicated by the considerations of locality, on which I shall comment below.

These questions are hardly surprising, because they can be asked about any physical theory, or any fundamental theory in science or elsewhere, certainly in philosophy, or, with qualifications concerning the nature of mathematical reality, commonly assumed to be mental, in mathematics. They have been asked beginning with the pre-Socratics, for example, as concerns the Democritean materialist atomism or, conversely, its idealist counterparts, such as Parmenides's and then Plato's philosophy, which was inspired by Parmenides, but went further by assuming a mathematical, and specifically geometrical, nature of the ultimate reality. However, quantum phenomena and quantum mechanics (more so than the so-called old quantum theory that preceded quantum mechanics) presented major difficulties in answering these questions in the way they could be answered in classical physics or even relativity, although the latter already presented difficulties in this regard, especially given the behavior of photons there. (Ultimately, photons are quantum objects.) Accordingly, different answers and even a different way of asking these questions may be necessary, although many, beginning with Einstein, would not necessarily agree with this assessment. As Bohr said in 1949 (20 years into his debate with Einstein), most did not think that one needed to go that far in "renouncing customary demands as regards the explanation of natural phenomena," that is, as far as Bohr thought it was necessary to go (Bohr 1987, v. 2, p. 63). This renunciation was far reaching and ultimately led Bohr to the concept of a *reality* of quantum objects that precludes one from considering quantum mechanics as a realist theory or even assuming the existence of any *realist* theory of this reality, *at least as things stand now* as regards the experimental evidence available. This is a crucial qualification assumed by Bohr in all of his writings and to be assumed throughout this study (the essential nature of this evidence has not changed). This conception of reality may thus be defined as that of "reality without realism," and the principle corresponding to this concept and assumed by Bohr and in this study, the reality-without-realism (RWR) principle.

This concept leads to the first "divorce" between quantum physics understood in the spirit of Copenhagen and the preceding fundamental physics—the divorce of reality from realism, previously joined together and seemingly requiring each other.

The questions concerning the nature of reality behind quantum phenomena and the possibility, or impossibility, of realism in quantum theory came into the foreground early in the history of quantum mechanics, especially in the Bohr-Einstein confrontation. This confrontation has shaped the subsequent debate concerning quantum theory and its interpretations, and it continues to do so, as this debate itself continues with undiminished intensity, with no apparent end in sight. Einstein argued that quantum mechanics is incomplete because it is not able to describe, at least not completely, elementary individual quantum objects and processes, *analogously* to the way classical mechanics or electromagnetism, or relativity does, at least ideally and in principle, for the objects and processes each considers. In other words, it is not a realist theory or does not provide a realist mathematical model representing the elementary individual processes responsible for quantum phenomena. I will term this concept of completeness "Einstein-completeness." I stress "analogously" because it became clear early on that a new kind of theory would be necessary to provide such a classical description, as Einstein was careful to qualify. Indeed, it was Einstein who was the first to make this apparent. In addition to being the creator of relativity (a theory different from classical mechanics and classical electromagnetism as well), he was the first to show the incompatibility between quantum theory and the assumptions of classical statistical physics (Einstein 1906). This incompatibility suggested that probability and causality might have needed to be separated, *divorced*, from each other. This is because classical statistical physics is fundamentally linked to classical mechanics, which is assumed to apply to the individual behavior of the elementary constituents of the systems considered in classical statistical physics. This assumption is no longer sustainable in quantum theory, which, in the first place, is probabilistic or statistical even as concerns its account of elementary individual quantum processes, such as those associated with elementary particles (photons, electrons, neutrinos and so forth).

According to Einstein's concept of a realist and (they are, thus, related) complete theory, then, the observables representing the state of any individual system considered could be assigned definite values, defining the physical state of the system at any moment of time and its evolution in a classically causal way, and thus allowing one to predict its behavior (ideally) *exactly*. In principle, one could assume, as some do in interpreting quantum mechanics, that a physical theory could causally represent the behavior of the individual systems considered, while also assuming that any predictions concerning this behavior are probabilistic or statistical. This is, however, not Einstein's view of completeness.

Bohr counterargued that, while Einstein's claim concerning the Einstein-incompleteness of quantum mechanics may be true, and while, in view of the RWR principle, it is strictly true in Bohr's and other interpretations based on this principle, quantum mechanics may be seen as complete in a different sense. It is as complete as nature allows a theory of quantum phenomena to be within the proper scope of quantum mechanics, again, as things stand now. Quantum mechanics is complete insofar as it correctly predicts the outcomes of all quantum experiments performed thus far, even though it does not describe the behavior of quantum objects themselves in the way classical mechanics or relativity does, which (and thus, the Einstein-completeness of the theory) *may not* be possible. I shall term this concept of completeness "Bohr-completeness." Because this study follows Bohr's argument on this point and is primarily concerned with Bohr-complete interpretations of quantum phenomena, I shall henceforth mean by the completeness of quantum mechanics its Bohr-completeness, qualifying when at stake is the Einstein-completeness or the contrast between them.

The concept of Bohr-completeness and, in this case, correlatively the lack of realism are in the spirit of Copenhagen, initiated and shaped by Bohr's thinking. The designation "the spirit of Copenhagen" is preferable to "the Copenhagen interpretation," because there is no single such interpretation. Even within the spirit of Copenhagen, there are different views, which, moreover, have often undergone historical evolutions even as concerns the views of the single figures involved. As indicated above and as will be discussed in detail in Chap. 3, this is notably true even in Bohr's own case. In part under the impact of his exchanges with Einstein, Bohr changed his views a few times, sometimes significantly, on his way to fully grounding his interpretation in the RWR principle in the late 1930s. Some interpretations designated "Copenhagen interpretations" only partially conform to the spirit of Copenhagen as understood in this study. Accordingly, one should be careful in specifying which interpretation defines a *particular* Copenhagen interpretation that one refers to, and I shall try do so throughout this study, which offers its own interpretation, in the spirit of Copenhagen, designated as "the statistical Copenhagen interpretation," proposed in Chap. 4. For convenience and economy, I shall henceforth refer to RWR-principle-based interpretations as "nonrealist interpretations," qualifying when the term nonrealist is used otherwise, as it is sometimes, for example, in referring to interpretations or theories that would be realist in the definition adopted in this study.

I might add that the so-called dominance of "the Copenhagen interpretation" is largely a myth. Indeed, given that there has never been a single such interpretation, the very existence of "*the* Copenhagen interpretation" is a myth, propagated by its advocates and opponents alike, because it can help both sides. As concerns more specifically the alleged dominance of Bohr's views, Bohr's own statement, made in 1949, after two decades of this presumed dominance, may well be the best evidence against it. He said: "I am afraid that I had in this respect only little success in convincing my listeners, for whom the dissent among the physicists themselves was naturally a cause of skepticism about the necessity of going so far in renouncing customary demands as regards the explanation of natural phenomena" (Bohr 1987, v. 2, p. 63). Einstein was undoubtedly foremost on his mind, especially on this occasion. The 1949 article just cited, "Discussion with Einstein on Epistemological Problems in Atomic Physics," was his contribution to the so-called Schilpp volume, *Albert Einstein: The Philosopher Scientist*, edited by P. A. Schilpp (Schilpp 1949). Einstein spearheaded this dissent and the resistance to the spirit of Copenhagen, a resistance still as widespread as ever. Nonrealism in quantum theory, or pretty much anywhere, has always been and remains a minority view, even though most of its opponents, beginning, again, with Einstein, admitted that this view is "logically possible without contradiction" (Einstein 1936, p. 349). It is not a matter of logic but of irreconcilable philosophical positions concerning fundamental physics.

Admittedly, the denomination "the spirit of Copenhagen" is not fully definitive either, and it is not aimed to be, as is suggested by the word "spirit." Whether this spirit had "directed the entire development of modern atomic theory" even by that point (1930) may be questioned, given, for example, Einstein's role in its development prior to quantum mechanics (1905–1924), or Schrödinger's discovery of his wave mechanics in 1926, which were not in this spirit or, as in the case of Schrödinger's program, aimed against it. The spirit of Copenhagen was, nevertheless, a major force, however resisted, shaping and driving this development. Clearly, too, as indicated above, in choosing this impression, Heisenberg has in mind the confrontation between nature and the human spirit or mind (as I noted, German *Geist* has both meaning), given the philosophical implications of German *Geist*, the word that G. W. F. Hegel made central to German and European philosophy with his *Phenomenology of Spirit* (Hegel 1977). This confrontation, I argue, took a new form with quantum theory, both in general, because it posed a new task for physics and philosophy, and specifically as that between the quantum reality of nature and the spirit of Copenhagen. The spirit of Copenhagen is, again, defined by its questioning of the possibility of realism in considering the ultimate (quantum) constitution of nature, ultimately by adopting the RWR principle, which, in its strongest form, disallows not only a representation but also a conception of this constitution.

As will be seen, the absence of causality, as classically understood, is automatic under the RWR principle, thus joining the divorce of reality from realism and (again, as a consequence) the divorce of probability from causality, as classically conceived. If understood classically, causality implies, ontologically, that the state of a given system, at least as idealized by a given theory or model, is determined at all moments of time by their state at a particular moment of time, indeed at any given moment of time. Determinism, by contrast, implies, epistemologically, that we can make ideally exact predictions concerning the behavior of causal systems, which is not always possible. Until the emergence of quantum physics, probability or statistics was merely a practical means of dealing with causal system of great mechanical complexity, rather than a fundamental aspect of physics, necessary even in considering elementary individual processes and the events they lead to. Classical causality in physics implies that the behavior of the *individual* systems considered in classical physics (classical mechanics, classical electrodynamics, or classical statistical physics) or relativity could be predicted exactly, at least ideally and in principle, rather than only probabilistically, as in the case of such processes in quantum physics. The difficulties of not being able to do so in classical statistical physics or chaos theory are merely practical, defined by the mechanical complexity of the system considered in these theories, and in certain circumstances these difficulties could be circumvented. One could, for example, sufficiently isolate a molecule of a gas and make deterministic predictions concerning its behavior. As discussed in

Chap. 5, it is possible to define the concept of causality as compatible with the probabilistic or statistical nature of quantum predictions. Deterministic predictions are, again, precluded on experimental grounds even when they concern elementary individual quantum processes, such as those associated with elementary particles.

That quantum mechanics provides only probabilistic or statistical predictions even in these cases is, thus, a fundamental, rather than merely practical, matter. These predictions, however, are strictly in accord with what is actually observed, because identically prepared quantum experiments, in general, lead to different outcomes. There are no kinds of quantum processes and events, no matter how elementary, concerning which even ideally exact predictions are possible, as things stand now. This fact gives rise to a principle, the quantum probability principle, the QP principle, one of the starting points, even *the* starting point, of Heisenberg's thinking leading him to the discovery of quantum mechanics. As will be discussed in Chap. 4, these predictions may be seen, or interpreted, still assuming the RWR principle, as statistical rather than only probabilistic, insofar as only the statistics of multiple repeated experiments dealing with individual quantum processes could be estimated, rather than the probability of each such event, say, on Bayesian lines. In other words, it is a matter of interpretation whether one could assign probabilities to the outcomes of individual quantum experiments or could only deal with the statistics of (multiple) repeated experiments. In the case of statistical interpretations, the QP principle becomes the quantum statistics, QS, principle. When either interpretation is assumed possible, I shall, for the sake of economy, refer to the QP/QS principle.

The RWR principle and, with it, the suspension of causality are *interpretive* inferences from the QP/QS principle. It is, in principle, possible to have a realist and causal—and hence Einstein-complete—theory of elementary individual quantum processes, but as things stand now, any such theory must give these predictions, that is, predictions that coincide with those of standard quantum mechanics. One such theory, arguably the best-known one, is Bohmian mechanics (in all of its versions), which is, however, nonlocal. Given the appeal of the realist imperative of the type Einstein insisted on, there is no shortage of proposals, some of which will be mentioned later in this study. For the moment, I only note that (the standard form of) quantum field theory, underlying the so-called standard model of elementary particles, which accounts for all known forces of nature apart from gravity, is a probabilistic or statistical theory of the same type as quantum mechanics, at least when given a nonrealist interpretation. The question, then, becomes whether nature will at some point allow us to have an Einstein-complete theory of quantum phenomena. Einstein, taking Einstein-completeness as a fundamental principle, thought it should. Bohr thought that it *might not*, which is not the same as saying that it never will (e.g., Bohr 1949, in Bohr 1987, v. 2, p. 57).

Einstein remained unconvinced and never retreated from his position. His uncompromising refusal to accept that the ultimate theory of individual quantum processes *might* ultimately have to be probabilistic or statistical may appear surprising, given his deep understanding of statistical physics and the relationships between it and quantum theory, and his extraordinary contributions to both by exploring these relationships in the old quantum theory. Einstein's revolutionary 1906 argument, mentioned above, that Planck's law is incompatible with classical statistical physics, was the most powerful early indication that quantum phenomena may not allow for an analysis of individual quantum processes on classical lines, if at all (Einstein 1906). This is, again, because classical statistical physics presupposes that the elementary constitutive individual components of the systems in question behave in accordance with classical mechanics, which would, given Einstein's argument, suggest that quantum mechanics might be an irreducibly probabilistic or statistical theory even in dealing with elementary individual quantum processes. Most of Einstein's work on the old quantum theory may be viewed from this perspective and interpreted in this direction, ultimately pursued by Bohr in his 1913 atomic theory and then in his interpretation of quantum mechanics, but clearly rejected by Einstein himself as unacceptable, or at least incompatible with his understanding of fundamental physics and its principles. I shall explain some of the reasons for Einstein's attitude later in this study, merely noting at the moment that, in this work too, he appears to have always believed that a classical-like realist, Einstein-complete, and also causal theory of elementary quantum objects and processes should one day be found. All of his work on statistical physics and quantum theory, and their relationships, has retained this belief and was guided by it, a pursuit that, at least if viewed from the present perspective, was against the grain of his own analysis of quantum phenomena for two decades. Quantum mechanics ran contrary to these expectations, although Schrödinger's wave mechanics (much favored by Einstein, as against Heisenberg's matrix version) initially offered some hopes to meet them. As Einstein was quick to realize, these hopes were unwarranted. Einstein accepted that quantum mechanics was a viable statistical theory. But because it was not a theory describing or representing, ideally exactly, individual, especially elementary individual, objects and processes, it was incomplete. As far as he was concerned, quantum mechanics was epistemologically even worse than the old quantum theory (things would get even worse and move even further away from Einstein's ideal of a fundamental theory with quantum field theory). As such, the theory was a great disappointment to him, and not to him alone. Schrödinger was hardly less discouraged, after his hope for his initial program for wave mechanics had dissipated, although these hopes were partially revived later. The story of Einstein's engagement with and disappointment in quantum theory nearly repeated itself with Schrödinger, whose work prior to his discovery of his wave mechanics and his famous equation was on statistical physics and the relationships between it and atomic theory, established by Einstein. Schrödinger followed Einstein's work on both statistical physics and the old quantum theory, and Einstein's view of what the fundamental quantum theory should be. Schrödinger's work that immediately preceded and in part led to his discovery of wave mechanics was inspired by Einstein's work, via de Broglie's ideas (also crucial for Schrödinger's wave mechanics), on the Bose-Einstein theory of the ideal quantum gas.

At a certain stage of the Bohr-Einstein debate, in the 1930s, the question of locality was injected into this debate and our understanding of quantum mechanics, primarily owing to thought experiments invented by Einstein, especially those of the EPR (Einstein-Podolsky-Rosen) type, first proposed in the famous paper of

A. Einstein, B. Podolsky, and N. Rosen (Einstein, Podolsky, and Rosen 1935). (Einstein pursued this line of thought even earlier.) Einstein subsequently proposed somewhat, but not essentially, different versions of the experiment. By using these experiments, Einstein argued that quantum mechanics could be considered as offering a complete in his sense (Einstein-complete) description of individual quantum processes only if quantum mechanics or nature itself violates the principle of locality. The principle dictates that physical systems could only be physically influenced by their immediate environment or, in this case, specifically, that the instantaneous transmission of physical influences between spatially separated physical systems is forbidden. Einstein famously spoke of "a spooky action at a distance," found, or so he believed, in the EPR-type experiments, if quantum mechanics was complete, even Bohr-complete (A Letter to Born, 3 March, 1947 [Born 2005, p. 155]). Bohr counterargued that, even given these experiments, quantum mechanics could be shown to be both complete, by his criterion (Bohr-complete), and local, even if short of assuming the RWR principle and nearly automatically under this assumption, or at least that EPR or Einstein in his subsequent communications did not prove otherwise (Bohr 1935). I shall consider Bohr's argument in Chap. 3. As did Einstein, Bohr ruled out nonlocality, again, at least on the basis of the evidence available thus far, which is one of the reasons why neither Einstein nor Bohr saw Bohmian mechanics (introduced in 1952), which is nonlocal, as a viable alternative. Bohr's argument, thus, left open the question whether a more complete and specifically an Einstein-complete local theory of quantum phenomena is possible, a question that remains open.

Einstein later qualified that, if quantum mechanics is considered as only a statistical theory of quantum phenomena, a theory providing only a statistical estimate of the outcomes of multiple repeated individual experiments (including those of the EPR type), then it could be considered local (e.g., Einstein 1936; Born 2005, pp. 166–170, 204–205, 210–211). Thus, Einstein de facto accepted an argumentation of the type offered by Bohr, although he misread Bohr's 1935 reply itself to EPR's paper differently, by assuming that Bohr in fact allowed for nonlocality, which is in manifest conflict with Bohr's argument there (Einstein 1949b, pp. 681–682, Plotnitsky 2009, pp. 244–246). Bohr expressly speaks of the compatibility with "all exigencies of relativity theory," and locality is one of them (Bohr 1935, p. 700). In any event, this view would still leave quantum mechanics Einstein-incomplete, and hence, again, would also leave open the question whether nature allows us to have an Einstein-complete theory of these phenomena, or only a Bohr-complete theory of them. In Bohr's view, quantum mechanics is a probabilistic or statistical theory of quantum phenomena, even those resulting from elementary individual quantum processes, insofar as it only provides probabilistic or statistical estimates concerning the data observed in measuring instruments, which data defines quantum phenomena, again, in contradistinction to quantum objects. As noted above, however, this is fully in accord with the experimental evidence available thus far, because identically prepared (as concerns the physical state of measuring instruments) quantum experiments, in general, lead to different outcomes, even when they concern elementary individual quantum processes. Einstein wanted local *realism*, which relativity satisfied and in which the concept in part originated (although locality is a more general concept). Bohr, with quantum mechanics as the best available theory of quantum phenomena in hand, argued for local *reality* that precludes realism, in accordance with the RWR principle, and as such, given that it automatically precludes causality as well, entails the irreducibly probabilistic or statistical nature of our predictions concerning quantum phenomena. By the same token, quantum mechanics' ability to offers such predictions made it Bohr-complete. Eventually, especially in the wake of the Bell and the Kochen-Specker theorems, and related findings, the question of locality, rather than that of completeness, came to dominate the debate concerning quantum phenomena and quantum theory. However, because realism has remained a major concern, in particular given the lack of realism as a possible alternative to nonlocality, the question of completeness has remained germane to this debate.

The concept and principle of locality is commonly associated with relativity, especially special relativity, although general relativity conforms to the principle as well. However, while thus implied by relativity, locality is not equivalent to compatibility with relativity and is independent of other key concepts with which it is linked in relativity, such as the Lorentz invariance. Indeed, the latter is only locally or infinitesimally valid in general relativity. On the other hand, general relativity is, again, a local theory. Also, technically relativity prohibits the propagation of physical influences faster than the speed of light in a vacuum, c, which is finite, rather than instantaneously. Accordingly, this requirement could, in principle, be violated, while still allowing for locality. Einstein, in invoking, in the context of the EPR-type experiments, a "spooky action at a distance," clearly had in mind the principle of locality, rather than only the compatibility between quantum mechanics and relativity. Indeed, standard quantum mechanics is not relativistic and hence, technically, not compatible with special relativity (unlike quantum electrodynamics or quantum field theory, which deal with high-energy quantum phenomena), but it is or may be interpreted as local, or in any event may be required to be local. Nor does locality require one to maintain the concept of realism, which is less of a problem for relativity than for quantum physics, and is, quite possibly, a reflection of this difference between locality and relativity. Locality is fully consistent with the concept of reality without realism and the RWR principle. The principle allows for a local quantum reality, demanded by both Einstein and Bohr, but precludes local *realism*, demanded by Einstein. This makes quantum mechanics, while Einstein-incomplete, Bohr-complete, as complete a *local* theory of quantum phenomena as nature allows us, at least as things stand now. It is not insignificant either that relativity is a classically causal and in fact deterministic theory, while quantum mechanics or quantum field theory is neither deterministic nor, at least in nonrealist interpretations, (classically) causal, and thus is a local probabilistic or statistical theory. The locality principle may, thus, reflect deeper aspects of the ultimate reality of nature than those captured by relativity theory, general relativity included. I am not saying that the locality principle is quantum in nature, although it is conceivable that it might be, especially if the ultimate nature of gravity is quantum. This separation of locality from relativity is the third major divorce argued for in this study, along with that of reality from realism and that of probability from causality.

The project of this book is a philosophical account of the fundamental principles of quantum physics and their significance. As such, this project belongs to the philosophy of physics. It represents, however, a different form of philosophy of physics, vis-à-vis most other forms of the institutional philosophy of physics and specifically the philosophy of quantum theory, apart from some more historically oriented studies, where some aspects of the present approach could occasionally be found. Even more than in my emphasis on principles (which is, as I said, uncommon as well), this difference is reflected in my emphasis on *thinking* concerning quantum physics. By this I mean both thinking by the key figures considered here and our own thinking, that of this book's readers included, not the least *principle thinking* itself. Einstein, from whom I borrow the concept of principle theory, also expressly spoke about principle *thinking* and principle *thinkers*, among whom he counted both Bohr and himself. This was, it is true, before quantum mechanics and their debate concerning it. This fact, however, does not change this assessment. It was a debate between two principle thinkers about what the fundamental principles of quantum theory should be, even though Einstein's thinking by this point was as much what he called "constructive" as it was principle. Constructive thinking is effectively defined by the imperative of sufficiently closely, even if not fully, representing, in mathematical terms, the ultimate constitution of nature, or more accurately by *constructing* such a representation. While Einstein's own definition of a constructive theory (to be discussed in Chap. 1) is worded somewhat differently, it is conceptually equivalent to the one just given. Bohr thought that this type of representation might not be possible in quantum theory by virtue of the fundamental principles of quantum physics, as he saw them. This view implies that quantum mechanics is strictly a principle and not constructive theory, unless it is seen as constructing the ultimate reality behind quantum phenomena as beyond the possibility of a representational construction. This, however, would run against Einstein's definition of a constructive theory, while remaining compatible with his definition of a principle theory. Einstein's argument clearly concerned as much the character of thinking about fundamental physics as the physical and mathematical architecture of the theories resulting from this thinking, from classical physics to relativity to quantum theory. It may of course happen that the same theory results from different way of thinking, as was in fact the case in Heisenberg's principle (and nonrealist) thinking and Schrödinger's constructive (and realist) thinking that, nevertheless, led each of them to quantum mechanics.

Although the term thinking is commonly used without further explanation, generally referring to mental states or processes as effects of the neurological processes in the brain, which would probably suffice here as well, I would like to say a few words about the type of thinking, essentially creative scientific thinking, most especially at stake in this study. This thinking is a way in which our brains confront chaos in our interactions with the world. G. Deleuze and F. Guattari, whom I follow here, speak in this connection of "thought" [*la pensée*] rather than "thinking."

Chaos, too, is given a particular concept by Deleuze and Guattari, as a certain "virtual[ity]" leading to the birth and disappearance of "particles" with infinite speed, referring to the speed of thought, as this speed appears to us (Deleuze and Guattari 1994, p. 118). This concept does not appear to have been previously used in philosophy. It is borrowed by them, at least in part from quantum field theory and its concept of virtual particle formation to be discussed in Chap. 6, as is suggested by their use of the terms "virtual" and "particle." The connection between quantum field theory and this concept of chaos is obviously a transfer of a concept from one domain of theoretical thinking to another. While one might see this transfer as a metaphor, it is the functioning of this concept as such in Deleuze and Guattari's understanding of thought that is crucial. The quantum-theoretical concept in question deals with matter and is approached by way of exact, mathematical science, quantum field theory; Deleuze and Guattari's concept deals with thought and is approached by way of philosophy, which is not mathematical. Milton's description of chaos discussed earlier would work here just as well as that of Deleuze and Guattari. First, this description is consistent with Deleuze and Guattari's conception of chaos as the birth and disappearance of "particles" from chaos, which, as I noted, is invoked by Milton. Second, Milton's is a richer conception because it adds chaos as randomness or chance and, by implication, chaos as the unrepresentable or the unthinkable to chaos as the virtual. Of course, one can also add both to Deleuze and Guattari's concept of chaos. My point here is that this extended concept of chaos is necessary for understanding the nature of creative thinking as a confrontation with chaos. I might add that Milton's Satan never engages in any confrontation with chaos, because his thinking is never truly creative. Creative thinking must certainly confront randomness and chance, and *take chances*, *bets*, often with uncertain probabilities to succeed.

The view of creative thinking as a confrontation of chaos (now in all three senses just described) is hardly surprising: most thinking may be seen as giving order to our perceptions, images, ideas, words, and so forth, and thus as involving a confrontation with chaos. Thought (in Deleuze and Guattari's sense) is, however, a special form of this confrontation, because it maintains an affinity with and works together with chaos, rather than merely protecting itself from chaos, as would, for example and in particular, the dogmatism of opinion (*doxa*), including scientific opinion, if dogmatically accepted. The character of thought as a *cooperative* confrontation with chaos, making thought and chaos work together for the benefits of thought, makes thought creative, and, according to Deleuze and Guattari, art, science, and philosophy are, each in their own way, among the primary means, or even *the* primary means, of creative thought. This is why they see chaos not only as the greatest enemy but also as the greatest friend of thought, and its best ally in its yet greater struggle, that against opinion, always an enemy only, "like a sort of 'umbrella' that protects us from chaos." On the other hand, thought's "struggle with chaos is … the instrument in a more profound struggle against opinion, for the misfortune of people comes from opinion" (Deleuze and Guattari 1994, pp. 202, 206). This is equally true in physics or science, or mathematics. All major advances in physics were born in or required profound struggles against prevailing opinion. These struggles defined the thought of all key thinkers considered in this study, sometimes, as, famously, in Planck's case, without them quite realizing the degree to which they were waging this struggle. In the cases of Einstein, Bohr, Heisenberg, and Dirac this struggle was manifest and pursued with an unwavering determination and courage. Physics, especially fundamental physics, could not be advanced otherwise.

Physics is a product of human thinking, of creative human thinking or thought in the sense just described, under complex material, technological, psychological, historical, and sociological conditions. Accordingly, one can pursue, as I shall do in this study, a philosophy of physics that attempts to understand how physicists think under these conditions, especially at the time of and in the process of making new discoveries, for example, by means of inventing new concepts and principles, and sometimes changing the very nature of physics in the process. Galileo accomplished this by giving modern physics its mathematical or mathematical-experimental character, in this case, a descriptive or representational one. Newton accomplished this by making calculus the main mathematical technology of theoretical physics. Einstein accomplished this by rethinking the concepts of space, time, and motion, and discovering the principle of relativity defining these concepts in his special relativity theory, and by bringing together the mathematical principles of Riemann's geometry (which radically changed the principles of geometry and physics alike) and the principle of equivalence between gravitational and inertial mass in his general relativity. Heisenberg accomplished this by divorcing the mathematical formalism of quantum theory from the task of representing quantum objects and their behavior, and hence from the principles of realism, and making probability and the QP/QS principle and, by implication, the RWR principle his primary principles. Dirac accomplished this by bringing together the principles of special relativity and quantum mechanics, which also led him to the discovery of new principles, those that came to define quantum field theory. Other examples will be discussed in this study as well, such as those found in quantum information theory, the most recent incarnation of foundational and specifically principle quantum-theoretical thinking.

This study's approach is, thus, different from that of dealing primarily with the logical-axiomatic structure of quantum theory or that of addressing, in more general terms, broader epistemological or ontological questions, such as reality and causality, as is more common, especially, again, in the institutional (analytic) philosophy of physics. More recently the question of quantum information came to prominence as well, although, arguably, more so among foundationally inclined quantum physicists than among the philosophers of physics, some of whom, however, have addressed quantum information theory. Such questions are important to our thinking, too, including when it comes to the key principles of quantum theory, and these questions will be considered in this study. But they will be considered as part of human thinking, which is not inconsistent with giving them the same rigor that the analytic philosophy of physics requires and may help to do so.

Physics is thinking about nature by particular persons and communities, which share certain aspects and trends of thought. It is thinking about what is true or probable about nature or those aspects of nature that physics considers, and not infrequently, especially in dealing with foundations, it is also, more philosophically, thinking about the *nature* of our thinking about nature, again, the main philosophical concern of this study. In modern (post-Galilean) physics, classical, relativistic, or quantum, this truth or probability is determined by means of mathematical models. Such theories may do so either by using a mathematical representation of the processes responsible for these data and predicting them on the basis of this representation, as in classical physics or relativity, or just by using a mathematical formalism to predict these data in the absence of such a representation, as in quantum mechanics. How close we come to the ultimate constitution of nature in this way may depend on a given theory or on nature itself or rather our interactions with nature, on how far nature could allow our mathematical theories and experimental technologies to reach. These interactions are, again, ultimately part of nature, too, but a very particular part of it, specific to us.

Given the aims and scope of this study, I will not be concerned with psychological and sociological aspects of quantum-theoretical thinking. On the other hand, history will play a significant role in it. History is unavoidable in theoretical (or experimental) thinking in physics, which always builds on preceding thinking in physics, even at the time of new discoveries, however revolutionary or unexpected such discoveries may be. Every physical (or of course philosophical) idea, no matter how original or new, has a history, some trajectories of which may be short and others long, sometimes extending to ancient thought. Conversely, the history of physics or, again, philosophy is the history of concepts, although, in the case of physics, it is, in addition to the mathematical nature of these concepts, also the history of experimental technology, a combination that makes modern physics an experimental-mathematical science of nature. We create our ideas by engaging with this history, which helps us to understand earlier ideas and to create our own, especially when these concepts are created by the likes of Einstein, Bohr, Heisenberg, Schrödinger, Pauli, or Dirac. But they, too, created their ideas by engaging both with a more immediate history of these ideas, sometimes in each others' works (as in Heisenberg's engagement with Bohr's thought, or Dirac's with that of Heisenberg), and with a longer history of physics and philosophy, in some respects going back as far as Aristotle and Plato, or even to the pre-Socratics.

A qualification is in order. When I speak of the thinking of any particular figure, I do not claim to have a determinable access to this thinking. Such an access is limited even when the author is alive and could, in principle, provide one with as much information as possible concerning this thinking, or if the author had left an extensive record of this thinking, say, in letters and notes, that could supply this kind of information. Instead, I refer to thinking that one can follow and can engage with in one's own thinking on the basis of certain works of a given author, and even then in a particular reading or interpretation of these works, which can be interpreted differently, and, thus, related to different ways of thinking. A proper name, such as Einstein, Bohr, Heisenberg, Schrödinger, Pauli, or Dirac, is the signature underneath a given work or set of works, a signature that attests to one's role as a creator of these works, which serve as a guide for thinking that we can pursue as a result of reading them. In the process, one can of course also gain insights into how a given author might actually have thought. However, claims to that effect are hard to make with certainty, although some among such claims may be probable and even highly probable.

Be it as it may on this score, any theory or interpretation only becomes effective or, again, operative, to begin with, when it becomes part of our thinking, and a theory or interpretation advances physics, or the philosophy of physics, when it moves this thinking beyond itself. This does not mean that, helpful as they might be, the thinking and works of any particular author, no matter how great or important, or the understanding of this thinking and these works is the only path towards a better understanding of a given physical theory and, especially, advancing this understanding or the theory itself. When it comes to advancing thought and knowledge, one's loyalty to anyone's thinking becomes a secondary matter and is only valuable if it helps this advancement. My discussion of the figures considered in this study aims to be faithful to their thinking and writings as much as possible, as a matter of maintaining proper scholarly standards, and this study is motivated by my belief in the helpfulness of their thinking for understanding and advancing quantum theory. The project of this study is, however, not driven by loyalty to their particular ideas, but by a dedication to understanding, through these ideas, how thinking works in quantum physics, and it often works by moving along different trajectories. In part for that reason, this study also presents different and even conflicting ways of thinking in quantum theory, such as that of Bohr, Heisenberg, and Dirac, as principle thinking, vs. that of Schrödinger, as primarily constructive rather than principle thinking (although it had a principle dimension as well). At a certain point, our thinking concerning quantum physics will inevitably have to move beyond the authors discussed here (both founding figures just mentioned and others), and there is no special reason to assume that it will do so following the paths established by any of them. An entirely different trajectory, either already in place but unknown to us (or to some of us) or yet to be discovered, may be necessary for this task.

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