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"Dark Materials to Create More Worlds": On Causality in Classical Physics, Quantum Physics, and Nanophysics

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Abstract. This article addresses the role and limits of the idea of causality in classical and quantum physics. After considering in detail the concept of "classical causality," operative in classical physics and (with additional restrictions) in relativity, the article introduces an alternative concept of causality, designated as "quantum causality," which applies in quantum mechanics, even and in particular in those interpretations of it that reject the applicability of "classical causality" to quantum phenomena and, hence, exclude it from quantum mechanics. Finally, the article discusses the role of this problematic in nanophysics, which, the article suggests, may provide a new area for investigating foundational questions in physics and, reciprocally, benefit from doing so.

Key words: causality, classical physics, quantum causality, quantum mechanics, nanophysics

1. Introduction

My aim in this article is to explore the nature and limits of the idea of causality in classical and quantum physics. I shall also consider the role of this problematic in nanophysics, which may both provide a new area for investigating foundational questions and benefit from doing so.

Classical physics, in particular classical mechanics is customarily viewed as a causal theory, while quantum physics, in particular quantum mechanics, is often, although not uniformly, is viewed as a noncausal one. The situation, however, is more complex. First of all, while classical mechanics may indeed be meaningfully considered as causal in the (more or less) standard or, as I shall call it here, "classical" sense, the application of this concept of causality in classical mechanics is subject to significant qualifications and limitations. Secondly, quantum mechanics may be considered "causal" in turn. This, I shall argue, is possible even in the case of the standard version of quantum mechanics (introduced by W. Heisenberg and E. Schrödinger in 1925-1926) and also when it is interpreted as noncausal in the classical sense, as it is, for example and in particular, when one follows "the Spirit of Copenhagen," as Heisenberg called it [1, p. iv]. This spirit or inspiration often, as in N. Bohr's interpretation, known as complementarity, implies a radical epistemology, which questions the possibility of using not only the (classical) idea of causality but also, and in the first place, of the idea of reality in quantum theory.[1] This type of interpretation will be adopted here as well, but only as *an* interpretation, one of several possible interpretations, rather than as a theory that definitively establishes "the truth of nature." In particular, it is not my aim (which would be difficult to accomplish in any event) to exclude classically causal, or realist, interpretations of quantum mechanics or causal and realist alternative theories of quantum phenomena, such as various versions of Bohmian mechanics. On the other hand, if one still wants to speak of causality in the case of such classically noncausal interpretations, one needs an alternative concept of causality, and I shall introduce such as concept, "quantum causality," in this article.

The possibility of such an alternative concept has significant implications for the philosophy of causality. In particular, contrary to a long-standing philosophical inspiration, this possibility suggests that

[1] As referring to a shared set of views on quantum physics, this expression is preferable to "the Copenhagen interpretation," of which there are many, sometimes quite different, versions. As I explain elsewhere, even Bohr had several significantly different versions of his interpretation [2, pp. 179-186].

there might not be a single concept of causality, not even a very general single concept, under which all available and workable concepts of causality may be subsumed as special cases. Instead we may need to develop different concepts of causality for different purposes in physics and other sciences (for example, biology), or in philosophy. These concepts may share certain features, which would justify the application of the term "causality" to them. But they also contain other features, specific to each case. In some cases we may need more than one such a concept, for example in those fields, such as modern cosmology or nanophysics, which involve both classical and quantum physics, or relativity (which is classically causal).

I shall proceed as follows. Section 2 offers a discussion of the classical philosophical idea or ideal of causality. Section 3 considers classical physics and, briefly, relativity as classically causal theories. Section 4 considers quantum mechanics and proposes an alternative concept of causality, "quantum causality." Section 5 discusses implications of the epistemological problematic addressed in this article for nanophysics and nanotechnology.[2]

2. Classical Causality

I begin with a profound remark of Heisenberg, made by him in his discussion of I. Kant and specifically of Kant's argument for the idea and the law of causality (defined below) as given a priori, rather than derived from experience. This argument, Heisenberg contends, no longer applies in "atomic [quantum] physics" [4, pp. 89-90]. He makes, however, a broader point:

> Any concepts or words which have been formed in the past through the interplay between the world and ourselves are not really sharply defined with respect to their meaning; that is to say, we do not know exactly how far they will help us in finding our way in the world. We often know that they can be applied to a wide range of inner or outer experiences, but we practically never know precisely the limits of their applicability. This is true even of the simplest and most general concepts like "existence" and "space and time." Therefore, it will never be possible by pure reason to arrive at some absolute truth [as Kant thought it might be].
>
> The concepts may, however, be sharply defined with regard to their connections. This is actually the fact when the concepts become a part of a system of axioms and definitions which can be expressed consistently by a mathematical scheme. Such a group of connected concepts may be applicable to a wide field of experience and will help us to find our way in this field. But the limits of the applicability will in general not be known, at least not completely. [4, p. 92]

Helped by insights gained from quantum physics, Heisenberg's criticism of Kant has a point, and Kant, if he could have benefited from these insights, might have agreed with Heisenberg. Indeed, apart from the belief that it will be possible to arrive at some absolute truth by pure reason, Kant is not that far from Heisenberg, and Kant appears only to have argued that it *might be* possible to do so. First of all, although not embedded in "a mathematical scheme," Kant's analysis is also characterized by a search for a sharper definition and the limits of applicability of his concepts, in part through establishing the connections between these concepts. More importantly, Kant argued that concepts, either those given a priori, such as space, time, and causality, or those established from experience, generally apply only in the *phenomenal* domain (of what appears to our thought), and that their application to the *noumenal* domain (of things as they actually exist in nature or mind) is limited and is never guaranteed. The distinction between phenomena and noumena is the basis of Kant's philosophy, and his view of causality is fundamentally grounded in this distinction. As will be seen, one of the reasons that the philosophically classical, such as the Kantian, idea or ideal of causality works in classical, but not in quantum, physics is that in classical physics the distinction between phenomenal and noumenal entities, although technically valid, could be

[2] This article can only give a limited set of perspectives on the subject. Indeed, the subject is inexhaustible, as is the literature on it, and I shall only cite the works especially pertinent to the present arguments. For useful guidance and further references see articles on causality in [3].

disregarded, at least ideally or in principle. This does not appear possible to do, even ideally or in principle, in quantum physics.

In any event, Kant deserves credit for questioning the limits of the idea of causality, indeed, according to F. Nietzsche, who came to question these limits more radically than Kant, for doing so, arguably, for the first time: "Let us recall, ... Kant's tremendous question mark that he places after the concept of 'causality'—without, like Hume, doubting its legitimacy altogether. Rather, Kant began cautiously to delimit the realm within which this concept makes sense (and to this day we are not done with this fixing of limits)" [5, p. 305]. Nietzsche might not be giving enough credit to Hume for also exploring these limits, but he is right about Kant. Understanding these limits in physics involves complex negotiations of the experimental data, mathematical formalism, and philosophical conceptuality; it is only through these negotiations that the architecture of the concept of causality and its role and limits in physics can be established more firmly, even if (Heisenberg is right on this point) never completely.

Consider the following dictionary definition of causality: "*Causality* is the relationship between an event (the *cause*) and a second event (the *effect*), where the second event is a direct consequence of the first" [6]. This is a good definition, and it is not so easy to significantly improve on it. While most definitions in philosophical literature, from D. Hume and Kant, or even Aristotle, on, do refine it and probe the limits within which it applies, they retain the key elements of this definition (of course, in turn indebted to the philosophy of causality). One can make this definition more general by extending the application of terms "cause" and "effect" to entities (individual or, since there may be more than one cause to a given effect, collective), A and B, other than events, and without requiring that A and B should be entities of the same kind. This generalization is often useful in physics. For example, the gravity of the Sun (or of other bodies in the solar system), which is cumbersome (but not impossible!) to define as a spatio-temporal event, can be seen as the cause of the motion of planets in the Solar system, and hence of any *event* in this motion in space and time. The physical nature of gravitation may not be completely known (it was not known at all at the time of Sir Isaac Newton). This circumstance indicates the complexity of the relationships between causality and succession, and especially, the difficulties of using the idea of the ultimate cause in physics and elsewhere: the ultimate origins of things are not known.

M. Born offers the following (often cited) definition: "Causality postulates that there are laws by which the occurrence of an entity B of a certain class depends on the occurrence of an entity A of another class, where the word entity means any physical object, phenomenon, situation, or event. A is called the cause, B the effect" [7, p. 9]. Although one may need a set of sequential or parallel causes for a given event, and hence the concept of the complete set of causes to properly define entity A here, Born's and most other standard definitions of causality can be easily adjusted to accommodate this qualification. Born adds two other (again, common) postulates, that of antecedence and that of contiguity: "Antecedence postulates that the cause must be prior to, or at least simultaneous with, the effect" and "Contiguity postulates that cause and effect must be in spatial contact or connected by a chain of intermediate things in contact" [7, p. 9]. By starting with "effect," Born de facto formulates the *principle* of causality, which states that if an event takes place, it has a cause of which it is an effect. This principle is crucial for both the application of and the *critical* analysis of causality, from Hume and Kant on.

Thus, while Kant defines, similarly to the dictionary definition cited above, the relation of causality as that of, first, the cause and, secondly, the effect, the application of the principle of causality proceeds from the effect to the cause. Kant says: "the concept of the *relation of cause and effect*, the former of which determines the latter in time, as its consequence [*Folge*], as something that could merely precede it in the imagination (or not even be perceived at all)" [8, p. 305]. On the other hand, the *principle* of causality moves us from effects to causes: "If, therefore, we experience that something happens, then we always presuppose that something else precedes it, which it *follows* in accordance with a rule" [8, p. 308]. Kant is careful to qualify that "the logical clarity of this representation of a rule determining the series of occurrences, as that of the [particular] concept of cause, is possible if we have made use of it in experience." "But," he concludes (against Hume's empiricist view), "a consideration of [causal representation], as the condition of the synthetic unity of the appearances in time, was nevertheless the ground of experience itself, and therefore preceded it *a priori*" [8, p. 309].

In Kant, the principle also implies that under the same conditions identical events will take place and, thus, that, in science, identical experiments will lead to identical outcomes. As many others before and after him, Kant sees both the principle itself and this implication as, in Heisenberg's words, "the basis of all scientific work," a contention radically challenged by quantum physics [4, pp. 89-90]. Hume, too, uses, along more empiricist lines, this aspect of causality in his empirical ("regularity") theory of causality in nature, in which case he allows for a meaningful application of the concept (cf., [9, pp. 18-21]). By the same token, as Kant does, Hume also appears (there is some debate concerning Hume's view on this point) to allow for general causality in nature, even though the human mind can at most perceive it only partially, via regularity of certain causal conjunctions of events. Hume and Kant also maintain the antecedent and, hence, the asymmetric relationships between cause and effect.

The Kantian framework of causality is paradigmatic of most views of causality, at least as concerns the essential features just outlined, and I shall call this type of view *classical causality*, and the model defined by the view *the classical model of causality*. There are several reasons to adopt this terminology, beginning with the fact that the historical period of the Enlightenment (roughly the eighteenth century), is sometimes referred to as the Classical Age, and also as the Age of Reason. (Kant was of course a major figure of this period.) The terminology also correlates with the term "classical physics," where, especially in Newtonian mechanics, or in the *idealization* defined by it, classical causality works well. I shall properly explain the nature and role of idealization in classical physics below, merely noting for the moment that it implies considering only those properties of natural objects that could be suitably mathematized by classical physics. Newtonian mechanics was a key development of the Classical Age, and along with Euclidean geometry, Kant's main scientific inspiration in developing his philosophy.

Technically, in accordance with Kant's scheme, the idealization of classical mechanics only applies at the level of phenomena. Classical physics, however, at least classical mechanics, can in practice disregard this difficulty and, within the limits of its idealization, treat phenomena as objects.[3] Thus, *within these limits*, one can maintains both *(a)* that the configuration of the Solar system, defined by its gravity, at a given time causes any subsequent event in the motion of a given body, say, a planet, such as Mars, in this system (barring outside interferences) and *(b)* that, if the Sun and other bodies in the solar system were not there, the motion of a given planet would not be observed in the way it is. In other words, both the definition of cause given here and the principle of causality are permissible and are assumed within the limits of the idealization of classical mechanics. The latter, moreover, usually presupposes both antecedence ("the cause must be prior or simultaneous with the effect") and contiguity ("cause and effect must be in spatial contact or connected by a chain of intermediate things in contact"), which is why Born invokes them. These requirements were strengthened by relativity, which restricted the propagation all of physical influences by the speed of light in the vacuum. Relativity restricts causes to those occurring in the backward (past) light cone of the event that is seen as an effect of this cause, while no event can be a cause of any event outside the forward (future) light cone of that event. Sometimes the term "causality" is used in physics to designate the compliance with this requirement. The relativity requirements, or antecedence and contiguity, do not depend on the (classical) *principle* of causality. As will be seen, all three conditions are satisfied in quantum mechanics, at least in the type of interpretation adopted here.

It also follows that, in accordance with Kant's requirement for scientific practice, identically prepared experiments in classical physics lead to identical outcomes, at least, again, ideally, insofar as statistical errors in repeated experiments can in principle be neglected, and they are usually neglected in practice. The situation is different in the case of quantum phenomena, say, an emission of a photon by an electron or what—an *effect*—we so interpret from observing a spot on a photographic plate. Although we do know, with reasonable certainty, that such events occur, neither claim *(a)* or *(b)* can be made with certainty, as in classical mechanics, but only with a certain degree probability. In other words, while one can, in a certain sense, always speak of quantum "effects" (one of Bohr's preferred terms), their "causes"

[3] The kinetic theory of gases, electrodynamics, and relativity, complicate this view, as both Maxwell and Einstein noted [10][11]. See also [12, pp. 306-328], for a useful discussion. These theories, however, still allow one to retain classical causality or (in a more complex way) reality.

are similar to the way the *ultimate* causes function in philosophy or in classical physics: even if such ultimate causes exists, their connections to effects cannot be meaningfully tracked down. In classical physics, this difficulty is usually handled by establishing spatial and temporal frames that limit a given case to those causes that can be meaningfully tracked down, at least, again, in principle. In quantum theory, however, this type of framing does not appear possible, even for individual events, which, unlike in classical mechanics, are not comprehended by law, at least not by a causal law. In addition, it is difficult to meaningfully argue (although the assumption is made sometimes) that such a law could in principle exist, in the way, say, one could argue for the application of the causal laws of classical mechanics to individual molecules in classical statistical physics. To cite W. Pauli, quantum mechanics "predicts only the statistics of the results of an experiment, when it is repeated under a given condition. Like an ultimate fact without any cause, the individual outcome of a measurement is, however, in general not comprehended by laws" [13, p. 32].

Kant, again, was aware that the limits of application of his concept and principle of causality require qualification, including in classical physics. For one thing, as I said, the principle of causality rigorously applies only at the level of phenomena. As I noted above, both Hume and Kant appear to have believed (at bottom, not that differently from Laplace), that the world is, or is created by God as, governed by hidden causality. It is just that the ultimate causal architecture of nature, in its (hidden) particularities and its (manifest) complexity, is never available to our knowledge, even if not necessarily unavailable to our thought, which, however, could not be guaranteed to be correct in this regard [8, p. 115]. It is worth noting that, although Kant understood the significance of probability in practical matters, he argued against the use of the idea of probability in critical philosophy, especially metaphysics (foundations of a theory should be certain, he believed, using geometry as an example).

While Hume doubted the validity of the concept of causality at the human level more than Kant, he, as noted above, appears to have a similar view concerning nature, in light of his empirical regularity theory (cf. [9, pp. 18-20]. There is, again, some debate on this point among scholars as concerns Hume's view, which might be argued only to allow for "the relation of contiguity and succession … [as] independent of, and antecedent to the operations of the [human] understanding," [14, pp. 168-196]. As noted above, however, Hume's empirical regularity theory of causality does appear to suggest the ultimate causality in nature as "independent of our thought and reasoning" along with the antecedent nature of causality, implied by the successive nature of this relation [14, pp. 168-69].[4] In sum, Hume's and Kant's critique of causality applies primarily to the claims concerning causality in the human mind's experience of and representing the world, and not to the architecture of the world itself.

Historically, this view is not surprising. Although probability theory was quite advanced by then, the ultimate nature of the world was usually interpreted in terms of the underlying but unknown and perhaps unknowable classical causality, as it was for example by Laplace or, it appears, by T. Bayes (an interesting case here, which, however, I shall put aside). Indeed, until the twentieth century and quantum physics, very few, if anyone, except for Nietzsche (late in the nineteenth century, though), doubted that some form of classical causality would apply at the ultimate level of the world. As I said, many still hope that this will ultimately prove to be the case. Hume and Kant, however, deserve credit for their realization of the complexities and limitations of classical causality, and for their critical analyses of these complexities, aimed at the lack of sensitivity to these limitations and unwarranted extrapolations of classical causality. In sum, it is not a question of abandoning classical causality, since it is workable and effective within large limits, but instead that of demarcating these limits, and, beyond these limits, of possibly establishing other concepts of causality, as I shall attempt to so in Section 3. First, however, I would like to consider the role and limits of classical causality in classical physics and relativity.

[4] Cf., Dowe, who cites the passage [9, pp. 18-20].

3. Classical Physics and Classical Causality

I would like to begin with Pauli's discussion of the difference between classical and quantum mechanics in his letter to Born [15, pp. 221-223]. Pauli first considers "the determination of the path of a planet" as an example: "if one is in possession of the simple *laws* for the motion of the body (for example, Newton's law of gravitation), one is able to *calculate* the path (also position *and* velocity) with as *high* an accuracy *as one likes* (and also to test the assumed law again at different times). Repeated measurements of the position with limited accuracy can therefore successfully replace *one* measurement of the position with high accuracy. The assumption of the relatively simple law of force like that of Newton (and not some irregular zig-zag motion or other on a small scale) *then appears as an idealization which is permissible in the sense of classical mechanics*." By contrast, in quantum mechanics "the repetition of positional measurement with the same accuracy … is of *no use at all* in predicting subsequent position measurements. For [given the uncertainty relations, $\Delta q \Delta p \cong h$] every positional measurement to [the same] accuracy at [a given] time implies the inaccuracy [defined by the uncertainty relations] at a later time, and *destroys the possibility of using all previous positional measurements within these limits of error*! (If I am not mistaken, Bohr discussed this example with me many years ago)" [15, p. 219; emphasis added]. Bohr makes this type of argument on several occasions, beginning with the so-called Como lecture (1927), introducing complementarity [16, v.1, p. 68].

It is especially crucial that "the repetition of positional measurement with the same accuracy … is of *no use at all* in predicting subsequent position measurements." This circumstance reflects arguably the most essential difference between classical and quantum phenomena and, as a consequence, of (the idealizations of) classical and quantum mechanics. The difference between the outcomes of identically prepared experiments and the corresponding statistical errors are, in principle, reducible in classical physics, which fact allows us, ideally, to disregard these differences and treat classical experiments as ideally repeatable, as concerns both preparations and outcomes. This, however, is not the case in quantum physics. Identically prepared experiments (which are possible, since we can classically control the instruments involved) in general lead to different outcomes. While we can probabilistically predict these outcomes, for example, by means of quantum mechanics, these probabilities are irreducible (we cannot improve our predictions regardless of the precision of our instruments, at least we cannot do so beyond certain point, defined by Planck's constant h). This circumstance is correlative to the uncertainty relations, $\Delta q \Delta p \cong h$, which would, it follows, apply even to ideal instruments. By the same token, every quantum measurement renders any preceding measurement meaningless as concerns our predictions of the outcomes of any subsequent measurement.

The main reason that classical causality works in classical mechanics is that, within the idealization of the theory, the state of the object at a given point defines the states of this object at all future points, *within the range of the system's history as defined for a given case*. The state of the system is defined by its position and momentum, both of which can be, ideally, measured and predicted, and therefore considered as properly definable and determinable at the same time at any given point in the evolution of the system. Indeed, the present state is equally *defined by* the past states, and it would allow us to make definitive conclusions concerning past states and predict all future states, within the frame of a given experiment. I am reluctant to say that the present state of the system also *defines* all its past states. For, although the equations of classical mechanics allow us to know these past states, physically the relation of determination between states proceeds from the past or present to the future in most applications of this model. As I shall explain presently, while it is easier to speak of physical causes, defined by the laws of classical mechanics, in relation to which all states of the system are effects, viewing the relationships between such states themselves as those between causes and effects requires further qualifications.

These qualifications will also explain why the assumption that the cause precedes or is, at most, simultaneous with the effect is appropriate to the idealization of classical mechanics, or in relativity, where this assumption is amplified by the finite limit upon the propagation of physical influences, as explained above. Mathematically, the equations of classical mechanics or relativity are time reversible, as are the equations of quantum mechanics, although the case of quantum mechanics requires additional

qualifications.[5] This reversibility may suggest (and it does to some) that time reversal and backward-in-time causality are possible. In the present view, it seems more reasonable to exclude both from the idealization of classical mechanics or that of relativity, or that of quantum mechanics (where both ideas are sometimes entertained as well), because there is, thus far, neither experimental evidence nor, at least to the present author, other compelling reasons to consider them. I shall return to the subject later.

I insist on "idealization" here because, first, all modern physics deals only with idealized models, even vis-à-vis phenomena (since many properties of phenomena are disregarded), let alone nature itself, which has a noumenal constitution, although the latter difficulty may be circumvented in classical mechanics. Secondly, the role of idealization in classical mechanics is crucial to the use of classical causality there, which is rigorously applicable only to idealized systems, while allowing for very good approximations of and predictions concerning the behavior of the actual physical systems, thus idealized, and considered within suitably demarcated spatial and temporal limits.

Some would speak of classical causality in physics and beyond as "deterministic causality," which is not out of place (e.g., [9, p. 18]). I prefer to understand determinism as having to do more with our capacity to make predictions concerning the behavior of a given system. The causal character of classical mechanics allows for exact, deterministic predictions concerning individual systems in many practical cases, that is, this causal nature allows us to neglect unavoidable practical deviations (in view of the limited capacity of our measuring instruments) from strictly exact predictions. On the other hand, certain sufficiently complex systems may be seen as classically causal, even though we have no capacity to make exact predictions concerning their behavior. Consider the case of a coin toss, which may be seen as an ideally classical process (one can exclude the quantum aspects of the constitution of the coin as having no effect on the outcome of a toss). The system, however, is too sensitive to the initial conditions and outside interferences for us to be able to ever make exact predictions by means of the mechanical mathematical model we use in other cases of classical mechanics. In other words, in practice it would be very difficult or even, as things stand now, impossible to construct a good classical-mechanical model in this case.[6] Similarly, the models that we use in chaos theory may gives us reasonably reliable patterns of the behavior of the systems considered, not by predictive algorithms of the type more conventional or simpler cases of classical mechanics (say, those of many two-body systems) do. In principle, however, one could imagine a tracking technology that would enable us to follow the coin's trajectory and configure our mathematics accordingly so as to make exact prediction in each case, as exact as in such simpler cases. In short, it is reasonable to think of classical causality as a feature of these processes, at least as concerns our ideally descriptive, even if not practically predictive, capacity.

With due adjustments (defined, again, by the special significance of the speed of light in vacuum, c, as independent from the speed of the motion of the source), classical causality also applies in relativity. By contrast, it is difficult to adopt a similar conception in quantum physics, and, as I said, the limitations concerning the kind of determination necessary to apply the classical models would arise even if we assume ideal measuring instruments. Unlike chaos-theoretical models, quantum mechanics, at least in the present view, provides good, albeit, generally, probabilistic predictions concerning the outcome of quantum experiments (defined by phenomena observed in measuring instruments), without providing a descriptive mathematical model, however idealized, of the behavior of quantum objects themselves.

The question of cause and effect is more complicated in classical mechanics. One could still say that, for each given measurement and the corresponding prediction, the state of the object itself in question established by this measurement at a given point is a cause of and thus determines its future state, as an

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[5] I shall bypass these qualifications, since in the present interpretation, these equations have only a predictive role and do not describe any physical processes in space and time, and as such are always future oriented. Hence their time-reversible nature has no physical significance.

[6] It is true that there are alternative accounts of this case, for example, those along Bayesian lines, such as by E. T. Jaynes ([17, pp. 317-320]). These accounts, however, do not affect my point concerning the underlying classical causality (presupposed by Jaynes as well), if again, one assumes that quantum aspects of the constitution of the coin do not affect the situation.

effect, at any given future moment. This statement, however, is only true insofar as this causal determination is enabled and defined by the laws of motion used, say, those of Newton's laws for gravity, and the corresponding equations, which are assumed to reflect certain physical forces in nature itself. This *determination* descriptively (mathematically) idealizes the corresponding physical configuration in nature. One might say that the real physical cause for any determination, including that of the initial state that defines a given situation, is the gravitational field defined by the Sun and other corporeal objects or fields in the Solar system. From this viewpoint, a given state of any single object can only be seen as a *physical* cause of its future states insofar as the whole configuration of bodies and forces involved, which determines the law of motion and hence of causality, is considered as part of this state. On the other hand, one might see these factors as built into the state of an object as defined by its position and momentum, at each point. Then one might say that each given state is a cause of all subsequent states, as effects, with the *law* of causality defined by the laws of motion and forces for this system.

In addition, the history of a classical system, thus considered, only goes so far in a given representation, and thus, as indicated above, involves the suspension of the ultimate cause or even many more remote causes. Newton bracketed the physical nature of and hence the causes of gravity and was (wisely) content to merely take its force into account in his law of gravity. This bracketing allows one to apply this law, including as a law of causality, as part of the overall "legislature," as it were, of causality for a given classical system, defined by Newton's law of gravity and other laws of Newton's mechanics. While this application is only possible within those limits where we need not be concerned with the physical nature of gravity itself, these limits are very broad and allow us to consider a large number of physical systems. In most applications of classical physics, the earlier history of a given system, say, that of the emergence of the Solar system, is bracketed as well, although some cases assume large spatial and temporal frames, all the way to the scale the Universe, at least up to a point. For, once one gets closer to the Big Bang, the practical use of the model become difficult, even if one remains within the classical scheme, but at least once galaxies are formed, one can have good, albeit limited, approximations and assessments, even by using Newton's theory of gravity.

Einstein's general relativity has, to some degree, resolved the problem of the nature of gravity, but only to some degree, since the ultimate nature of gravity may be and generally is assumed to be quantum. In this case, our theory of gravity may and, on the view adopted here, would require the suspension of classical causality at the ultimate level. Just as in classical physics, however, for many practical cases in which we use relativistic gravity, the *ultimate* nature of gravity is not crucial. On the other hand, the difference between general-relativistic and Newtonian laws of gravity is crucial, even in explaining the behavior of the motion of planets, such as, famously, Mercury, in the Solar system. Classical causality, however, applies, with certain qualifications, in general (or special) relativity as well.

It is, again, also usually assumed that there is no backward-in-time physical influence, even though the equations of classical physics are mathematically symmetrical with respect to time reversal. In addition, these equations or those of relativity do not provide for the concept of now, defined only from the outside by the clocks we use and our consciousness, a circumstance much pondered by Einstein throughout his life. This assumption, along with the historical framing just defined, makes classical causality related to, but not quite the same as the temporal division of past and future. Causes always precede effects: bodies, such as planets, move in a gravitational field, such as that of the solar system, because of the earlier history of this field, even though these bodies contribute to this field. Relativistic considerations, again, impose further restrictions by limiting causes to those occurring in the backward (past) light cone of the event that is seen as an effect of this cause, while no event can be a cause of any event outside the forward (future) light cone of that event.

It is argued sometimes that general relativity and quantum mechanics suggest and even imply the possibility of retroaction in time and backward-in-time causality (e.g., [9, p. 188]). I do not find these arguments sufficiently compelling in either case, first of all, because there is, thus far, no experimental evidence for retroaction in time or backward-in-time causality. It is true that there are certain legitimate (hypothetical) arguments for the possibility of retroaction in time and, by implication, for the corresponding concept of causality. Among them is the existence of close time loops in K. Gödel's

solutions of the equations of general relativity ("Gödel's metric"), K. Thorne's wormhole "time-machines," the hypothetical existence of tachions (particles that travel only faster than light in a vacuum, which is not forbidden by relativity), and a few others. It is a different question *how* compelling these arguments are and to whom. For, while most arguments against retroaction in time do not altogether rule it out, the problems of the assumption remain serious on well-known logical and physical grounds. In addition, there is, again, no experimental evidence supporting the idea. Its main *physical* appeal appears to be that it may "solve" certain actual or sometimes perceived problems of the current quantum theory, from quantum mechanics to quantum field theory to (as yet not developed) quantum gravity. Its main *philosophical* appeal is that physics, or rather certain physicists, entertain the idea on the grounds just stated. Since retroaction in time cannot be completely ruled out by our current theories, one could of course explore the corresponding notions of causality. It is also true that both relativity and quantum theory taught us that we should not trust our general (everyday) or even philosophical intuition in fundamental physics. Accordingly, one might agree with P. Dowe's *general* contention that "it will not do for the philosopher to rule out a priori what the scientist is currently contemplating as a serious hypothesis" [9, p. 188]. It does not appear to me, however, that there are sufficiently compelling physical reasons (mostly those mentioned above) to pursue the possibility of retroaction in time, which Dowe has *specifically* in mind here, while there are more compelling reasons against this possibility.[7] In other words, *how seriously* this particular hypothesis is contemplated by scientists is not altogether clear, and I would argue that it is not very seriously entertained widely. Given that our current fundamental theories are manifestly incomplete, it is of course possible that retroaction in time or that backward-in-time causality might in one way or another be shown to be a feature of nature. For now, however, although the equations of classical physics or relativity are mathematically symmetrical with respect to time reversal, the assumption that there is no retroaction in time and no corresponding causal influence is reasonable and, within a wide range, workable within in the idealization of classical or relativistic physics.

In sum, classical causality is workable in classical mechanics or, with certain qualifications (not fundamental in nature) elsewhere in classical physics and relativity. However, it only applies to the idealized (mathematical) models used by these theories; and, moreover, the application of these models is limited by spatial, temporal, and other frames, although one might also see these frames as parts or parameters of the model. In other words, in accordance with Heisenberg's argument with which I began, although by connecting classical causality to other concepts of classical physics we can define this concept and its limits more sharply, we still do not know, at least not completely, how far classical causality ultimately extends in physics.

It does appear, however, that classical causality is likely to have a limited domain of application in physics. In particular, it may not apply at all either on very small scales, in view of quantum physics, or on very large scales, for a complex set of reasons, which, however, include the apparently quantum origins of the universe and the ultimately quantum character of gravity. In other words, a kind of causal or deterministic picture that Laplace and others envisioned for the universe is unlikely to apply. The idea of an overall causal universe, including one based on the classical concept of causality, is by no means completely abandoned, however. It was, for example, recently advocated by G. 't Hooft, for the reasons

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[7] Dowe's argument for backward-in-time causality in quantum mechanics is primarily motivated by a philosophical discontent (which is common) with certain interpretations of the Copenhagen type and certain attempts to address the problems posed by the famous Einstein, Podolsky, and Rosen (EPR) experiment and Bell's theorem [9, pp. 182-183]. To the present author, these reasons, again, do not appear to be sufficient to resort to backward-in-time causality, given the difficulties of applying it in physics, as explained above. Besides, Dowe's gloss of the Copenhagen interpretation hardly does justice to the views of most followers of the Spirit of Copenhagen, and specifically those of major figures, such as Bohr, whose position on the subject is, as I have discussed elsewhere, nothing like the gloss offered by Dowe [2, pp. 237-278]. Also, Dowe's argument is shaped by a rather limited view of the history of the question of causality in physics or philosophy, a view, by and large, restricted to the Anglo-American analytic philosophical tradition, and a few earlier authors, such as Hume. In particular, remarkably, Kant is not considered. Nor are Nietzsche or the American pragmatists, C. H. Peirce and William James, who offered important critiques of the idea of causality. None of the founding figures of quantum theory is discussed either.

having to do with the EPR-Bell type experiments [18]. 't Hooft certainly does not think in terms of anything like classical mechanics in considering the behavior of individual quantum systems, even though he does want to depart from the standard quantum mechanics. Similarly, while Bohmian and other causal quantum theories are different from classical mechanics, they are classically causal. So are certain interpretations of standard quantum mechanics.[8] It appears difficult to sustain such interpretations, especially if one wants to avoid certain, at least in the present view, undesirable consequences, most especially the violation of relativity (nonlocality) or the extension of classical causality to backward-in-time causality. It is notable that most such extensions, for example, Dowe's concept of causality, which he, again, sees as enabling a better approach to explaining the EPR-Bell correlations than more standard alternatives, are essentially classical in their conceptual architecture (in Dowe's case, refined via Hans Reichenbach's fork mechanism [9, pp. 192-209]). The only difference is that backward-in-time causation is now allowed. This difference is of course crucial *physically*. Once again, however, in my view, there do not appear to be sufficiently compelling reasons to adopt retroaction in time and backward-in-time causality, indeed even in contrast to the standard view of classical causality, which is compelling for many reasons and which is manifestly workable within large limits.

On the other hand, it appears to me that there are good reasons to ask the following question. Assuming an interpretation of quantum mechanics, such as the one adopted here, in which quantum mechanics or quantum phenomena themselves do not obey classical causality, and assuming both locality and the absence of retroaction in time or backward-in-time causality, is it possible to introduce a concept of causality that is different from the classical one? The answer, I would argue is yes, and I shall propose such a concept in the next section.

4. Quantum Physics and Quantum Causality

It will be helpful to revisit, first, some of the main reasons for why quantum physics makes it difficult to maintain classical causality. Arguably, the single most defining circumstance responsible for this situation is that, as noted earlier, identically prepared quantum experiments (in the sense of the state of the measuring instruments involved, which we can control classically) in general lead to different outcomes. This difference is ineliminable and automatically implies the irreducibly probabilistic nature of our quantum predictions. Also, unlike in classical physics, we cannot neglect this difference so as to have an idealized nonprobabilistic model of quantum phenomena, because we cannot even in principle improve the probabilities of our predictions, at least after a certain point (defined by Planck's constant, h), regardless of how much we improve the precision of our measuring instruments. This can also be expressed by saying that this would remain the case even if we had ideal instruments. The uncertainty relations, $\Delta q \Delta p \cong h$, which, too, would apply even had we ideal instruments, are correlative to this situation and establish the same limit quantitatively. Strictly speaking, the situation is subtler. In any single run of a given experiment (the double-slit experiment, for example), the emission of an object, such as an electron, is never assured. Nor, at the other end of the experiment can a given event, marked, say, by a spot on the screen, be guaranteed to have resulted from the collisions between the screen and an electron emitted from the source. Statistically, however, such events can be neglected, since we do know that in a vast majority of cases traces on the screen can be correlated with, and in this respect are "caused" by, particles emitted from the source, and thus with events of emission. The outcome of each run of the experiments (in the same setup) is, again, different each time (a spot on the screen is found in a different place), while the condition of each emission is the same as concerns the state of the apparatus that makes the emission possible. To return to Pauli's formulation, there is no law that comprehends *the outcome of individual experiment*s, even if we have a causal theory, say, along Bohmian lines, of *quantum processes*

[8] I shall leave these interpretations aside. Although it would be difficult to rule them out, they, at least those I am familiar with, are, in my view, difficult to sustain, as I argued in [2, pp. 191-211]. Also, unlike those interpretations that are not classically causal, such interpretations, or Bohmian theories, tell us little new about causality, even if one adopts backward-in-time causality, since the latter, again, has an essentially classical architecture.

themselves. For, to properly correspond to the data in question the predictions of the theory must still be probabilistic or statistical, as they are, in the proper correspondence with the data, in Bohmian mechanics, which is, accordingly, causal (again, at the expense of nonlocality and hence in conflict with the requirements of relativity) but is not deterministic. In the present view, the emission of an electron or its interaction with a measuring device does not have a physical (mechanical) explanation, which also prevents us from being able to explain why the differences in the outcome of identically prepared experiments arise (cf., also [4, pp. 89-90]). In view of these circumstances, it is indeed remarkable and enigmatic that there can exist algorithmic procedures, such as the one provided by quantum mechanics (cum Born or related rules for deriving probabilities from the formalism), that allow us to make correct probabilistic estimates, *under specified experimental conditions*. This last qualification is important, as Bohr often stressed (e.g., [16, v. 2, p. 57). Thus, in the double-slit experiment, the outcomes are different, depending upon whether we can or cannot know, even in principle, through which slit each electron involved had passed, since it is only in the second case that we observe the interference pattern of traces on the screen. Quantum mechanics gives correspondingly different probabilistic estimates for each case.[9]

It follows, then, that we can, ideally, *identically prepare* a given experiment in the sense of the state of our equipment in both classical and quantum physics. This identical preparation is essential for the very functioning of physics as science, since we must be able to repeat our experiments, *in this sense*, to maintain this functioning. However, unlike in classical physics, in the case of (individual) quantum experiments we can, rigorously, speak only of the identical preparations of such initial set-ups, but given different outcomes of these experiments, not of identically repeating the experiment in the sense of the behavior of quantum objects. In other words, there is never a guarantee that two quantum *objects* could ever be identically prepared under the identical conditions of the apparatus, and in general they are not. There is no experiment that would allow us to ascertain the identical initial physical states of quantum objects themselves in identically prepared quantum experiments. As a result, what we can repeat in terms of experimental outcomes are only observed probabilities and statistics of these outcomes, and these probabilities are well predicted by quantum mechanics, thereby properly confirmed experimentally as a theory of quantum phenomena. In classical physics, we can, in principle, simultaneously ascertain both the position and the momentum of the object under investigation because we can observe this object without disturbing or interfering with it appreciably and thus apply the (idealized) realist and causal model of classical mechanics. It is the possibility, at least, again, in principle, of this definition at any point by determining *both* the position and the momentum that enables the (classically) causal character of classical mechanics as a proper theory of the individual behavior of classical objects. By contrast, in quantum physics, it is never possible to observe quantum objects independently of their interactions with measuring instruments, which thus always *interfere* with the behavior of quantum objects or disturb them. The uncertainty relations, which do not depend on quantum mechanics (although the latter is of course consistent with them) may be seen as a correlative to this impossibility or, at least, interpreted accordingly, as they indeed were by Heisenberg, who discovered them. Quantum mechanics, again, reflects this situation and the difficulties of applying classical causality under these conditions.

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[9] It is true, of course, that the rules for counting probabilities or, one might say, the "calculus" of probability in the case of quantum phenomena is different from those of classical statistical physics, as Max Planck was the first to discover. Quantum mechanics is able to predict quantum probabilities correctly by, famously, changing the procedure from adding probabilities themselves to adding "probabilities amplitudes" and by applying Born's rule accordingly. For a classic account, see [19, v. 3, pp. 1-11]. The relationships between different interpretations of probability itself and different interpretations of quantum mechanics are significant, and they have led to stimulating debates concerning the mathematical aspects of quantum probability. There are numerous arguments regarding what kind of probability theory—such as frequentist, Bayesian, Kolmogorovian, or contextual—is best suited to quantum theory. On some of these issues, see [20]. I shall, however, bypass the subject, since it does not change my main point here and in my overall discussion of "quantum causality," given that, as things stand now, quantum predictions are irreducible probabilistic on experimental grounds regardless of how we calculate or interpret the probabilities involved. Accordingly, "quantum causality" is defined by quantum phenomena themselves, rather than only by quantum mechanics in whatever interpretation.

As Bohr, who eventually preferred to speak of *interference*, came to realize, the language of disturbance is hardly suitable here [16, v. 2, pp. 63-64]. For, although it technically applies, it may suggest that the independent behavior of quantum objects may be classical-like and specifically (classically) causal, and that it is only the interference of measuring instruments that introduces probability into our account of the situation. This view, often accompanied by the view that the formalism of quantum mechanics describes this classically causal behavior has not been uncommon even in standard quantum mechanics, and is found also in the work of several founding figures, including, although only briefly, Bohr [2, pp. 191-211]. There is, however, no particular reason to adopt this view, especially given that (as is often acknowledged by those who hold it) that this independent causal behavior is in principle unobservable. Nobody has ever observed a quantum object, say, a moving photon, as such, apart from its effects on measuring instruments. There are quantum macro objects, such as Josephson's junctures, whose quantum behavior we can ascertain experimentally, as opposed to most other macro objects, which behave classically, although their ultimate constitution is quantum (or at least is generally assumed to be). However, engaging with the properly quantum behavior of such objects, that is, observing the corresponding quantum effects, requires proper measuring instruments. In other words, quantum macro objects are no more observable as quantum than are quantum micro objects. Observable quantum events or phenomena (which are physically classical) cannot be rigorously connected, even probabilistically or statistically, to any quantum-level sequence of events that preceded it, or that will follow it. Statistical correlations only pertain to the data found at the classical level of observable phenomena. It does not appear possible, at least in the Copenhagen-type of view, to know or ultimately even to conceive of what happens between quantum experiments. In Heisenberg's words: "There is no description of what happens to the system between the initial observation and the next measurement" [4, p. 47].

We can measure and, in some cases, such as those of the EPR measurements, predict any single physical quantity involved, say, the position, exactly, as we do in classical physics, that is, as exactly as our instruments allow us, and we can improve on this precision by using better instruments, so as to consider such measurements as ideally exact.[10] However, in view of the uncertainty relations, if we do so, the other quantity, the momentum, becomes entirely undetermined, which inhibits and, in the present view, disables the possibility of a realistic and, as a consequence, classically causal description of quantum objects and behavior. For, this description depends on defining the state of the system at any given point so that one can also predict it at any other point (or track its behavior in the past), at least, again, ideally. By the same token, in the case of classical mechanics, the theory is deterministic insofar as we can make exact predictions concerning the future behavior of classical objects. By contrast, the uncertainty relations are, as I said, correlative to the irreducible probabilistic character of our quantum predictions. Quantum mechanics responds to this character, in part by virtue of properly correlating its formalism with the uncertainty relations, which can be established and verified experimentally, apart from quantum mechanics or any theory, and hence may be seen as a law of nature. In other words, it appears difficult (and, in the present interpretation, impossible) even to apply the concept of state as conceived in classical physics to quantum objects and processes, a circumstance that is correlative to Heisenberg's uncertainty relations *in the corresponding interpretation*. As Schrödinger noted (with some dismay), "if a classical state does not exist at any moment, it can hardly change causally" [21, p. 154].

In both classical and quantum physics we need a measuring device to determine a given quantity, such as the momentum or the position of the object under investigation. The difference is defined by the possibility in classical physics and, in view of the uncertainty relation, the impossibility in quantum physics to simultaneously determine both conjugate quantities. In classical physics, we can do so, at least, again, ideally or in principle, because, as just explained, whatever the effects our measurement has on the

[10] This claim requires further qualifications. In particular, in Bohr or the present view, these quantities (even single ones, rather than only jointly those that are subject to the uncertainty relations) pertain only to certain parts of measuring instruments, rather than quantum objects themselves. This would make developing causal or, to begin with, realistic theory of quantum behavior even more difficult. These qualifications may, however, be put aside here, since my main argument applies even without them.

behavior of the object in question can in principle be neglected or compensated for. In quantum measurement, the measuring device used in the experiment irreducibly affects the behavior of the quantum object under investigations in such a way that the simultaneous determination of both conjugate quantities is never possible at the same time.[11] The two situations of measurements or correspondingly predictions concerning the future behavior of a given quantum object are, thus, mutually exclusive or, in Bohr's terms, complementary. This is the proper physical content of Bohr's concept of complementarity, in turn correlative to the uncertainty relations. In any individual experiment, we can only predict, either probabilistically or sometimes (as in the EPR type of experiments) exactly, either one of these conjugate quantities or the other, but never both together, in the way we can in classical physics.[12]

One could argue (and many have argued, beginning, again, with Einstein) that these circumstances in themselves do not exclude the possibility that the underlying (quantum) physical processes that connect such quantum phenomena (this connection is of course essential) are ultimately causal. Indeed, given how such concepts as causality (or reality, to begin with) and determinism are defined, in particular via idealized physical models, this may be possible in principle. If, as I noted earlier (note 10), such were the case, insofar as it correctly predicts the outcome at the level of phenomena and measurement, quantum mechanics would be a merely correct but incomplete theory of this ultimately causal underlying dynamics, which is what Einstein believed, under the assumption of locality. Alternatively, Einstein argues, quantum mechanics would be nonlocal [22]. It may be shown, however, following both Heisenberg and Bohr, who responded to Einstein accordingly, such does not appear to be the case, and quantum mechanics can still be seen as complete without giving up locality [23][2, pp. 236-278].

Insofar as it does not appear possible to causally connect the "dots" observed (also in the literal sense of the term) in quantum experiments, quantum mechanics may be seen as "nonlocal" in the following, very different sense, correlative to the lack of classical causality. Unlike classical physics or relativity, quantum mechanics does not make its predictions by means of algorithms based, at least in principle, on (mathematically) descriptively following the infinitesimal continuous (causal) changes in the state of the system in question, which changes are described by the equations used, again, at least in principle and in idealized way. This kind of local tracking, or again, any physical description of quantum behavior appears to be impossible in quantum theory, at least in the standard version and in the present interpretation of it. Instead, quantum mechanics makes predictions concerning certain future events spatially separated from the events on which these predictions are based.[13] While it does not appear possible to explain how these predictions come about, in other words, to offer a physical description of quantum objects and processes,

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[11] As indicated earlier, in Bohmian theories, where the underlying classical-like causal behavior of quantum objects is assumed and both position and momentum assigned to them at any point, no undistorted *description* of this behavior is possible. Accordingly, the uncertainty relations and (at the level of measurement) complementarity still hold, along with the same (correct) statistical predictions that are given by the standard quantum mechanics.

[12] It is sometimes argued, beginning with Einstein, that one could, in the EPR-type experiments, ascertain the precise value of both the position and the momentum of a given object, and thus de facto (although not in practice) circumvent the uncertainty relations. Accordingly, Einstein contended, quantum mechanics is either incomplete or else nonlocal. I would argue, following Bohr, that it is never possible to bypass the uncertainty relations in this way. This allows one to counter-argue Einstein's and related arguments in the case of continuous variables, and thus avoid the alternative of either nonlocality or incompleteness of quantum mechanics. One could also *analogously* responds to the arguments of the same type around Bell's theorem, which applies to discrete variables, which, while it introduced additional complexities and nuances, does not change the epistemology of the situation. While it is not possible to pursue the subject here, the reasons for the possibility of such counterargument are epistemologically similar those given here for the difficulties of offering a classically causal or realist account of the quantum-mechanical situation. I have considered the case in detail in [2, pp. 236-278]. As noted throughout this article in more general terms, the debate concerning the subject remains as intense as ever, and the opposing sides are still often inspired by the respective arguments of Einstein and Bohr, who, to his great disappointment, failed to convince Einstein.

[13] The situation is, thus, the opposite of that of Bohmian theories, where such tracking is in principle possible, although we displace the actual state of the system in the process. Bohmian theories are, thus, *local* in this sense, but are *nonlocal* in the sense of implying an instantaneous physical action at a distance.

the situation need not involve nonlocality in the sense of the instantaneous physical connections, forbidden by relativity, whether these connections are expressly manifest or not. Accordingly, one might speak of spooky predictions at a distance, but without any "spooky actions at a distance," which troubled Einstein. But then, Einstein would not like the idea of such spooky predictions at a distance either, since his vision of physics was defined by both forms of locality in question. Indeed, it might appear that both require each other. However, as quantum mechanics tells us, such may not necessarily be the case.

One might look at the epistemological situation of quantum mechanics in the present interpretation from yet another perspective. Quantum mechanics extends classical physics insofar as it is, just as classical physics, from Galileo on, and then relativity have been, the experimental-mathematical science of nature. However, quantum theory, at least, again, in interpretations of the type discussed here, breaks with both classical physics and relativity by establishing new relationships between mathematics and physics, or mathematics and nature. The mathematics of quantum theory is able to predict correctly the experimental data in question without offering and even preventing the description of the physical processes responsible for these data. Taking advantage of and bringing together both main meanings of the word "experiment," I would argue, that, while not without some, indeed indispensable, help from nature, quantum mechanics was the first physical theory that is both, and jointly, truly experimental and truly mathematical. It is (I am indebted to G. Mauro D'Ariano on this point) truly experimental because it is not, as in classical physics, merely the independent behavior of the systems considered that we track, but what kinds of experiments we perform, how we *experiment* with nature, that defines what happens. Of course, we experiment, often with great ingenuity, in classical physics as well. There, however, our experiments do not define what happens, but essentially track what would have happened in any event. In quantum physics, for the first time, we can do something in *defining* the world by our experiments, and our experiments *cannot avoid* doing so. This last qualification is crucial because some of our classical experiments may also change the world if our interference is sufficient to significantly disturb the classical configuration involved. By the same token, quantum mechanics is truly mathematical because the mathematical formalism of the theory is not defined and hence constrained by this tracking of what would have happened anyhow, but is concerned with predictions defined by our experiments.[14]

It is this determination, probabilistic though it is, of what can and conversely cannot happen by virtue of our experimental decisions that defines what I call "quantum causality." Or rather, since quantum events or phenomena may occur without our staging of quantum experiments, this determination is an instance of quantum causality in the case of human quantum experiments. This instance, however, provides a model of the more general definition, which may be formulated as follows. *Whatever happens as a quantum event and is registered as such (thus providing us with the initial data) defines a possible set of, in general probabilistically, predictable outcomes of future events and irrevocably rules out the possibility of our predictions concerning certain other, such as and in particular complementary, events*.

At the same time, for the reasons explained earlier, each such event completely erases any data obtained in any preceding events as meaningful for the purposes of our predictions concerning future events from this point on. There is nothing that can help us to improve the probabilities of our predictions, neither the information previously obtained by measurements on the same object, nor a repetition of the same experiment with another quantum object of the same kind with the identical preparation, in the way it can be done in classical physics. On the one hand, no determinate connection to any past event can ever be guaranteed in the case of individual quantum events (again, no mechanical cause of any quantum event can be found) and no exact repetition that establishes classical-like regularity of events is possible. This situation clearly excludes both classical causality and, automatically, backward-in-time causality of any kind. On the other hand, quantum events do define future quantum events in strong, even if probabilistic, terms. In this sense the language of causality as referring to probabilistic correlations is appropriate,

[14] Indeed, it follows that we experiment with mathematics as well, in any event more so than in classical physics, since we invent mathematical schemes unrelated to any reality rather than refine our phenomenal perceptions or representations, which constrain us in classical physics.

especially because, as thus defined, quantum causality, while irreducibly probabilistic, does refer, closer to Bayesian lines of thinking, to individual events, rather than only to statistical multiplicities of event.

The Bohr-Einstein debate concerning quantum mechanics may be considered from this perspective as well. Bohr saw quantum mechanics as a probabilistic theory of *individual* quantum processes, or more accurately, individual quantum phenomena or events, manifested in measuring instruments, since in his interpretation quantum mechanics does not describe quantum objects and behavior, but only probabilistically predicts the outcome of relevant experiments, in accord with quantum causality, as defined here. Einstein would prefer to see quantum mechanics as a statistical theory of multiplicities, on the model of classical statistical mechanics, under the assumption that a realist and classically causal theory, a proper mechanics, of individual quantum processes could eventually be developed. Accordingly, in Bohr's view, even though quantum mechanics did not describe quantum processes themselves, quantum mechanics would be a complete, as well a local, theory of these processes and observable phenomena and events they lead to, at least, as complete as nature allows our theory of quantum phenomena to be (e.g., [23], also [2, pp. 237-278]). In Einstein's view, quantum mechanics would not be a complete theory of individual quantum processes, of the type classical mechanics is, although he acknowledged that, as such a theory, quantum mechanics could be seen as local [15, p. 205]. As noted earlier, considered as a theory of individual quantum processes, quantum mechanics could only be seen as either incomplete or nonlocal in Einstein's view based in his analysis of the EPR-type experiment [19]. Einstein is correct in arguing that quantum mechanics, at least if viewed in the Spirit of Copenhagen, is not a theory of individual quantum processes and events of the (realist and causal) *type* classical mechanics is. The question is whether such a more complete (by Einstein's criteria) and local classical-like theory of quantum phenomena is possible, as Einstein hoped, or whether, as Bohr thought to be more likely, nature allows us only as much as quantum mechanics (within its proper scope) and higher-level quantum theories (within their scope) deliver. In this case, these theories would be complete (as well as, again, local), albeit in the sense different from that of Einstein, whose concept of completeness was modeled on classical mechanics. This question is still with us, and Einstein's view has continued to serve as an inspiration for many physicists and philosophers, Schrödinger, Bohm, J. S. Bell, and Roger Penrose, among them, ever since, and it still does. Bohmian mechanics, for example, was in part inspired by this view, although the theory did not satisfy Einstein, because of its nonlocality (as strong a requirement for Einstein as for Bohr) and because it was, in his view, too close to the standard quantum mechanics, in part by virtue of making exactly the same predictions as the latter. Einstein appears to have preferred to see quantum mechanics to be proven wrong one day on experimental grounds. Thus far, however, it has been amply confirmed experimentally and appears to have withstood all experimental attempts to disprove it.

As explained earlier, in order to effectively apply classical causality with the identical preparation of our measuring instruments as part of our mathematical descriptive-predictive machinery, we impose artificial frames, most especially spatial and temporal ones, but also others, for example, by bracketing the atomic or quantum constitution of the physical objects considered. In some cases, our spatiotemporal frames may extend quite far, for example, in the history of the solar system or even in the known universe itself, nearly to its origin, some 14 billion years ago—nearly, but not quite, because the very early, pre-Big-Bang, history of the universe may be quantum. If such is the case, however, *in the present view* (assuming the same epistemology applies) our mathematical machinery will not be able to provide us with the description of this early quantum history as a quantum process. This does not of course mean that there is nothing that we can say about these early stages of the Universe as quantum events. Our classical observations of the traces of these early processes may be established as configurations of quantum phenomena, like the traces of the screen found in the double-slit experiments. These traces can give us information, again, physically classical but organizationally quantum (just as in the case of the double-slit experiment), concerning this earlier history, similarly, again, to the double-slit experiment, where the presence or conversely the absence of an interference pattern tells us something about the earlier conditions of the overall arrangement. A number of currently available (albeit still hypothetical) theories of the early Universe, such as various versions of the "inflation" theory or the "cosmic landscape" theory, depend on an effective use this type of data. The *very* early history of the Universe, which likely to have

been purely quantum, might well have been erased without a trace and hence is altogether beyond our reach. The available traces might also enable us to meaningfully relate, probabilistically, different successive (classically manifest) stages of the Universe as quantum phenomena. They may even enable us to make predictions, again, probabilistic in character, concerning the future state of the Universe, by writing (which has been attempted), a Schrödinger-like equation for the state defined by these traces, once again, however, without enabling us to say anything about the quantum aspects of the process itself that will lead to this future state. We can only trace classical or (classically) relativistic aspects of this process, without, however, being able to connect or predict the corresponding events under these circumstances, that is, given the quantum nature of the processes that link these events.

It is also possible, however, that the epistemological argument offered here may only apply to quantum mechanics as a theory operative within its particular scope and limits, just as classical physics is operative within its scope and limits, or various quantum field theories are within their respective scopes and limits. Indeed, the epistemology of quantum field theory, beginning with quantum electrodynamics, may well require still more radical renunciations of our classical epistemological ideas and ideals [2, pp. 353-368]. The prospects are far less certain for more comprehensive theories that are necessary (as our theories at present are manifestly incomplete) but yet to be developed. As we haven't heard their last word (which is to say their next word), one cannot be sure. Nature might show itself to be less mysterious at the next stage of our, it appears, interminable and interminably inconclusive encounter with it, or, just as it did in the case of quantum phenomena in the last century, it might confront us with something more mysterious than we can imagine now.

5. Nanophysics, Nontechnology, and Causality

In spite of a great deal of attention and sometimes hype in science and engineering, or popular press (where most hype is generated), nanoscience and nanotechnology received little *philosophical* attention of the kind classical physics, relativity, and quantum physics received. They have received considerable attention in sociological studies of science and technology, where certain philosophical questions have been raised, but mostly of social, cultural, and ethical character rather than of the fundamental epistemological nature, where such questions as those of reality and causality belong. In some respects, this is understandable. The primary concerns of nanoscience and nanotechnology appear to be more technically or practically oriented, rather than aligned with fundamental physics and foundational concerns, which more readily invite epistemological inquires of this kind. Not only in the sociological literature just mentioned (or again, popular literature and press), but also in such journals as *Nature* and *Science*, nanotechnology tends to dominate nanoscience. On the other hand, given the significant immediate impact of nanotechnology on our life, social, political, and ethical concerns or related philosophical issues are to be expected to enter current discussions and debates. That need not mean, however, that nanoscience, and specifically nanophysics, or nanotechnology cannot serve as a source of important philosophical reflections on fundamental nature. That includes the questions of reality and causality in physics, classical and quantum, since nanophysics involves both and combines them in new ways. Indeed, while technical articles on nanophysics do not usually reflect on foundational questions, their content suggests the possibility of such reflections.

Quantum information science provides an instructive parallel here. Its initial concerns were more practically oriented by the tasks of establishing theoretical grounds for and directly pursuing such projects as quantum cryptography and computing, and in some respects these concerns still primarily shape the field. At the same time, however, the field provided a strong impetus for new research into quantum foundations and has actively pursued this research, indeed to the point of rethinking the very nature of quantum theory in terms of quantum information.[15] Importantly, these two lines of pursuit have been in reciprocal and mutually enabling interactions throughout the history of this new field. Indeed, it is not only a matter of a parallel but also of the connections between both fields, since nanophysics provides

[15] Literature on the subject is extensive. See, for example, [24],[25], and [26] and references there.

new theoretical possibilities for quantum information theory and new practical venues for building workable quantum computing devices, the greatest task of quantum information technology.

Accordingly, it would not be surprising if nanophysics offered new possibilities for physical and philosophical investigations into foundational questions in physics, and I would like, in closing, to briefly discuss two instances of nanophysics and nanotechnology that suggest such possibilities. As throughout this article, I adopt the view that these are specific experimental and theoretical features of physics that reveal its deepest philosophical aspects and, thus, should guide our philosophical thinking about physics. Although, I can do no more than indicate some of these features, this will allow me to support my philosophical point here, which is as follows. Nanophysics provides an important juncture in which classical and quantum microphysics come together. As a result, it may enable us to elucidate their relationships, for example, the deeper aspects of quantum measurement as the interactions between quantum objects and quantum aspects of measuring instrument, the interaction that, in Bohr's language, is (irreversibly) "amplified" to the classical level [16, v. 2, p. 51]. At least in some respects, this amplification is unavoidably nanophysical.[16] Reciprocally, our investigations of foundational questions regarding reality and causality may help us to gain deeper insights into nanophysics.

My first example comes from nanooptics, and it concerns the possibility of "a single-molecule optical transistor," which, among other things, may have applications in both optical and quantum computing [27][28][29]. Important as the practical aspects of such a device may be, given, for example, that photons are especially robust against decoherence (although the difficulties of controlling photons on nanometers scale are formidable), it is the (quantum) physics behind this possible technology that is of most interest in the present context. Although the argument of Zumofen *et al* in [25] is essentially limited to a more or less classical treatment, its arguably most interesting point is what happens if their treatment is extended, as it can be, to the case of a quantized electromagnetic field and a possible extension of their formalism "in the context of QED [quantum electrodynamics]." According to the authors: "The modal formalism developed in this Letter can be extended in the context of QED to analyze such phenomena and will be the subject of a future study. Furthermore, it would be interesting to investigate the photon autocorrelation function since photon bunching or antibunching is generally expected when there is destructive or constructive interference, respectively" [28, pp. 3-4]. This type of investigation would bring into play more specifically quantum features of the interactions between photons and two-level systems, such as quantum interference and quantum probability and statistics [28, p. 4]. My philosophical point, accordingly, is as follows, and it would equally apply to quantum information processing, to which the articles just cited relate, since their investigations might open "new doors for quantum information processing using photons as information carriers" [25, p. 4]. Indeed this point would apply to all quantum-based technology, such as lasers, for example. Those features of quantum phenomena and quantum mechanics that pose great difficulties as concerns reality and causality are also responsible for extraordinary possibilities of both new physics and new technology. At the same time, new physics and new technology, including nanophysics and nanotechnology, shed new light on these philosophical problems and offer new ways of thinking about them.

My second example has to do with graphene sheets, the single atomic layers of crystalline carbon in which carbon atoms are arranged in honeycomb patterns. Working with graphene brings together physics, chemistry, fluids mechanics, mechanical engineering, electronics, behavior of proteins, and other fields, and is sometimes referred to as the hottest new material of nanotechnology, as well as electronic physics [31][32][33]. This is the case on both scores (nanophysics or nanotechnology and electronic physics) because graphene has remarkable electronic properties, beginning with the fact that it remains stable and conductive on the molecular scale, which of course offers great possibilities for electronic technology and nanotechnology. More remarkable are those properties of graphene that are associated with the so-called fractional quantum Hall effects, when (Dirac) electrons behave collectively as a particle carrying a charge that is a fraction of an electron charge [31][32][33]. In addition, when travelling through graphene,

[16] Bohr is often misunderstood on this point [2, pp. 329-331]. This amplification is often associated with decoherence, which may be seen as yet another juncture of quantum physics and nanophysics.

electrons behave as quasi-particles of a mass zero and (unlike the case of their behavior in other materials) can be treated quantum-field-theoretically. As a result, graphene may help us conduct small-scale experiments that test quantum theories all the way to the standard model.

First, then, as in my first example, we deal with both a manifestation of the potential of quantum behavior of matter in spite of epistemological difficulties of explaining this behavior. Actually, in both cases, we deal with quantum-electrodynamic effects, which may take us beyond quantum mechanics, epistemologically as well as physically [2, pp. 353-368]. Secondly, however, the remarkable properties of graphene and other new materials enable nature's and our own quantum experimentation, as discussed above. This experimentation changes the future in accordance with the law of *quantum causality* rather than, as in classical physics, merely track down what is bound to happen, according to the law of *classical causality*. Nanophysics and nanotechnology can and, I would wager, will play a significant role in thus shaping the "dark materials" of nature into new realities of the world.

I borrow the language of "dark materials" from John Milton's famous description of chaos in *Paradise Lost*:

> ... Into this wild Abyss,
> The Womb of Nature, and perhaps her grave,
> Of neither Sea, nor Shore, nor Air, nor Fire,
> But all of 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.
>
> John Milton, *Paradise Lost*, Book II, 910-916

This extraordinary description is presciently close to the understanding of the ultimate (quantum) constitution of nature adopted here, insofar as the ultimate character of these constituents and this behavior are "dark" beyond our knowledge or even conception. And yet, these "dark materials" allow nature and, by experimenting with nature and with its help, ourselves to create new *configurations* of technology and even of nature itself. Of course, only nature could create new Worlds on the ultimate scale, new Universes. It is prudent to leave God aside or to leave God to Milton. It is certainly more than merely prudent not to assume a god-like role in our experimentation. This is one of many lessons of twentieth-century quantum physics, or indeed of all science throughout its history, from Galileo on, reminding us that the philosophy of physics is sometimes also moral philosophy. Nanoscience and nanotechnology will do well to heed this lesson. Our experimentation, however, need not depend on and be measured by assuming such a role. The commitment itself to creative experimentation may well be imperative; or in the language of (Kant's) moral philosophy, this commitment may be seen as the categorical imperative of all good science. This is certainly a point on which classical and quantum physics converge: creative experimentation, physical, mathematical, or philosophical, is the categorical imperative and the primary force of *causality* of both, whatever the nature of this causality (a difficult problem in its own right) may be.

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