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Prediction, repetition, and erasure in quantum physics: experiment, theory, epistemology

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The article considers the epistemology of quantum phenomena and the quantum eraser experiments as reflecting certain essential features of these phenomena, and uses these experiments to introduce a new concept, that of 'erasure'. This concept is defined by the fact that a given quantum measurement destroys, 'erases', the usefulness of actual or even possible information associated with a given quantum system prior to this measurement, for the purposes of predictions concerning the experiments performed on this system after this measurement. The concept of 'erasure' allows one to capture certain fundamental aspects of quantum phenomena more sharply than previously, and to differentiate classical and quantum phenomena, and theories in a new way.

1. Introduction

This article explores the epistemological significance of the quantum eraser experiments, introduced by Marlan Scully and his co-workers [1] as reflecting some among the fundamental features of quantum phenomena, and uses these experiments to introduce a new concept, that of 'erasure'. This concept is defined by the fact that a quantum measurement destroys, 'erases', the usefulness of evidence or information associated with a given quantum system prior to this measurement, for the purposes of predictions concerning the experiments performed on this system after this measurement. This evidence may be actual, that is, evidence already obtained in previous measurements; or it may be possible, that is, evidence that, if actually obtained, would define our predictions in a particular way, and that can be changed by an 'erasure', as happens in the quantum eraser experiments. While, as I shall argue, in classical physics such an erasure requires extraordinary circumstances, every act of quantum measurement in effect performs this type of erasure. The concept of 'erasure' allows one both to capture certain fundamental aspects of quantum phenomena more sharply and to differentiate classical and quantum physical phenomena, and classical and quantum physics in a new way.

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I proceed as follows. First, I offer an outline of the interpretation of quantum phenomena and quantum mechanics that is, following Niels Bohr, adopted by this article and grounds its argument. Then I consider the delayed-choice aspects of the double-slit experiment. Finally, I discuss the quantum eraser experiments and develop the concept of 'erasure'.

2. Epistemology: quantum objects, phenomena, and events

The history of quantum physics suggests that a description of quantum *objects* and their behaviour is difficult and perhaps impossible to attain. This difficulty compelled Bohr to introduce his concept of (quantum) '*phenomenon*' in contradistinction to 'quantum object' [2, v. 2, p. 64]. 'Phenomena' in Bohr's sense are defined by the *effects* of the interaction between quantum objects and measuring instruments upon those instruments. Along with quantum objects themselves, the quantum aspects of this interaction are, in this view, not described by quantum mechanics, and may be beyond any description or even conception. On the other hand, those parts of measuring instruments where the effects of this interaction are manifest can be described by means of classical physics. Accordingly, we can also observe and describe these effects themselves in the same way we observe and describe *classical physical phenomena*, or indeed *objects*. In classical physics, objects and phenomena need not be sharply differentiated because the role of measuring instruments can, at least in principle, be bypassed, which circumstance also allows us to observe classical objects themselves, and to give them phenomenal representation and physical description, at least in principle or by way of idealization. This does not appear possible in quantum physics, which makes it difficult and perhaps impossible to consider quantum objects independently of their interaction with measuring instruments, and thus makes these instruments essential to the constitution of quantum phenomena.

Of course, even though classical physics can describe each effect in question, it cannot predict these effects or the numerical data associated with them. By contrast, quantum mechanics properly predicts these data, without (as least in the present interpretation) offering any description of the behaviour of quantum objects themselves. It is true that the quantum-mechanical predictions are in general statistical, even as concerns individual events, which may, however, be unavoidable, correlatively, it appears, to the impossibility of considering quantum objects apart from their interaction with measuring instruments [2, v. 2, p. 73]. The identical experimental set-ups are equally possible in classical and quantum physics, because, as just explained, we can handle the experimental arrangements used in quantum experiments classically, which allows us to control these arrangements and prepare them identically repeatedly. The fact, however, that identically prepared quantum experiments in general lead to different outcomes implies, in Bohr's words, that a 'logical approach cannot go beyond the deduction of the relative probabilities for the appearance of the individual phenomena under given experimental conditions' [2, v. 2, p. 73]. It follows that any theory properly predicting such phenomena is bound to be statistical.

In accordance with the interpretation just sketched, this article offers no *specific* ontological claims concerning quantum objects and their behaviour, apart from the *general* claim that they exist in a mode essentially different from that of classical physical objects and that they are responsible for the appearance of quantum phenomena by virtue of their interactions with the measuring instruments involved. On the other hand, this interpretation offers a logically consistent description of the key quantum experiments—in particular, the double-slit experiment, the delayed-choice experiments, and the quantum eraser experiments—based on our *knowledge* of the *effects* of the interactions between quantum objects and our experimental technology.

I would now like to introduce two postulates, which will ground the argument to follow. These postulates cannot be claimed to represent experimental facts. Nor would they be automatically adopted by physicists, or by philosophers of quantum theory. They are, however, consistent both with the experimental data pertaining to quantum phenomena and with quantum mechanics as a physical theory accounting for these data in (statistically) predictive terms. The first postulate is (weakly) ontological at the quantum level, even though in the present interpretation it is epistemology—what we can and cannot know concerning the impact of quantum objects upon our measuring instruments—that defines quantum *theory*. As explained above, in this interpretation, quantum theory deals in specific terms only with quantum *phenomena*, rather than with quantum *objects*, whose existence is assumed, but whose nature and behaviour is not described by quantum theory. The postulate itself may, however, be given a stronger ontological content in a different interpretation. The second postulate, which is, in some respects, close to Richard Feynman's view of the situation, may appear to be quantum-level ontological as well (indeed more strongly so than the first postulate) and is provisionally stated in these terms for the sake of economy. It need not, however, be seen in this way, and can be, and here will be, interpreted in accordance with the epistemology adopted in this article.

(1) There exist material physical systems, designated as quantum objects, whose behaviour, as manifest in their impact upon our measuring instruments, is different from that of the systems described by classical physics. It is also assumed that the ultimate constituents of nature, elementary particles, are quantum objects.

(2) In *certain specific respects* these objects, say, photons, individually behave physically *like* particles, while they do not *individually* behave physically like waves. (I shall explain the indicated qualifications presently.)

In particular, in the double-slit experiment a photon or any other quantum object never goes through both slits, regardless of the set-up (again, provisionally speaking about quantum objects themselves). Each photon only passes through one slit, whether we cannot know through which slit each photon has passed (which leads to the emergence of the interference pattern, once the experiment is repeated a large number of times) or whether we have, or can in principle have, such knowledge (which precludes the appearance of the interference pattern). The interference pattern itself reflects the statistical distribution of the traces left by photons in the first set-up, as opposed to a different distribution that is found in the second set-up. The mutual exclusivity or, in Bohr's language, complementarity of these two sets of events is correlative to the uncertainty relations, and both to the irreducible randomness of the outcome of quantum experiments.

Even though, in formulating the second postulate, I state more unequivocally that photons *never* individually behave physically like waves (this assumption is made sometimes), and make a qualified appeal to photons' particle-*like* individual behaviour, both statements require further qualification in view of the epistemology adopted here. For, in the present view, we do not observe the behaviour of quantum objects themselves, but only the effects of this behaviour upon our measuring instruments. These effects define individual quantum phenomena, such as a click in a detector or a trace on a silver screen. Accordingly, either type of characterization—particle-*like* (which can be both individual and collective) and wave-*like* (which is only collective)—only pertains to the effects of the interaction between photons or other quantum objects and measuring instruments. By contrast, neither concept, that of 'wave' or that of 'particle', applies to quantum objects themselves. The latter certainly do not behave in the way the particles do in classical physics, any more than in the way classical waves do; in particular, they cannot be simultaneously assigned both classical conjugate quantities of position and momentum, and hence trajectories. Nor can one apply to quantum objects other classical concepts, such as that of motion, or even words such as 'happens' or 'occurs', which, as Bohr and Heisenberg argue, can only apply at the level of observation manifest in measuring instruments, and not to quantum objects themselves or to what happens before an observation or between observations [3, pp. 51–58]. Hence, as I said, while the second postulate may appear to be quantum-level ontological and was provisionally stated in these terms, it need not be interpreted in this way and is not here. It may be noted that, although Feynman, to whose views this postulate is close, similarly states that 'light behaves like particles' and not like waves, his actual interpretation is close to the one adopted here [4, p. 15].

It follows that, in the present interpretation, the statement 'a photon passed through a slit' only means that a measuring device registered an event that is analogous to the outcome of a certain classical physical process, say, the hitting of a screen by a small classical object that passed through an opening in some diaphragm on its way. The statement 'a photon never passes through both slits' only means that no event corresponding to such a statement can be observed or registered. We can never register an individual event simultaneously linked to both slits, say, by placing a detector near each slit. Only one of these detectors registers individual events; both detectors never click simultaneously. Accordingly, although made sometimes, the assumption that a photon can pass through both slits poses difficulties, which are, as will be seen, amplified by the delayed-choice experiments. On the other hand, one could speak of a single photon as 'passing through a slit' in the sense that the corresponding event could have been registered by a which-path measuring device, if this device were installed, but only in this sense. It does not appear possible to conceive of the independent behaviour of individual photons, in part given the change in their behaviour depending on the measuring arrangement, or their 'propensity' to fit into collective patterns in some, but only some, arrangements, such as the interference pattern in the double-slit experiment or analogous patterns in other experiments, such as the beam splitter experiment (see [2, v. 2, pp. 50–51] and [4, p. 183]).

It is only in the sense just explained that the individual effects generated by photons are seen here as particle-*like* and not as wave-*like*. Collectively such effects may be wave-*like* in the sense of the interference patterns found when a large number of discrete traces, 'dots' accumulate in the absence of which-path measuring devices, and the 'propensity' in question (one might see it as wave-like, too) is only manifest 'collectively', which makes it all the more enigmatic. (These 'dots' appear as such only at a low resolution and actually comprise millions of atoms.) At least in the present view, it is not our knowledge of *the behaviour of quantum objects* themselves but our knowledge concerning *events registered in measuring instruments* that defines the absence or the appearance of the interference pattern in the double-slit experiment, or the outcomes found in the delayed-choice and the quantum eraser experiments.

3. The double-slit experiment as a delayed-choice experiment

I would like, before proceeding to the quantum eraser experiments, to briefly revisit certain delayed-choice features implicit in the double-slit experiment. The epistemological qualifications given in the preceding section should be kept in mind whenever I use (again, for the sake of economy) ontological language in referring to quantum objects. We may set up our equipment beforehand in either way—to enable or to disable the appearance of the interference pattern—by switching off or on the counters installed between the diaphragm with the slit and the screen in the two corresponding sets of runs of the experiment. We can, by means of suitable devices, also establish the possibility of knowing through which slit each photon passes even before each photon reaches the diaphragm and thus guarantee the absence of the interference pattern, as we do in quantum eraser experiments. In the case, however, of placing the detectors between the diaphragm and the screen, we can decide to switch the detectors on in each run of the experiment after the photon has passed through the slit and is on its way to the screen. Making our decision at this later point does not change the outcomes of the two respective sets of runs of the experiment, corresponding to each set-up, provided that the detectors are sufficiently far from the screen for us to have time to do so before the photon hits the screen. In this way, the double-slit experiment becomes the delayed-choice experiment.

It becomes apparent that the assumption that a single photon ever passes through both slits poses difficulties even beyond the fact that such an event cannot be registered, as explained above. (I leave aside Bohmian theories, to which my argument does not apply but which are manifestly nonlocal in any event.) For, by switching the counters on or off after a photon passes through the slits but before it reaches the screen, we can define the *past* event in two mutually exclusive ways—as that of the photon passing through one of the slits (like a particle would) or as that of the photon passing through both slits (like a wave would). This assumption is, however, not uncommon, and those who make it are in distinguished company. This company includes Einstein (at least at one point of his exchanges with Bohr) (e.g. [2, v. 2, p. 53]), John A. Wheeler [5], and, to give an example of a prominent popular exposition, Brian Greene [6, pp. 176–204]. In the case of Einstein, this view served his criticism of quantum theory, which would be justified were this assumption necessary. By contrast, both Wheeler and Greene embrace quantum theory and the strangeness of quantum phenomena, which they see as amplified by this assumption. The assumption itself leads Wheeler and, following him, Greene to speak of a kind of participatory universe, in which the past or, at least, the actualization of the past is defined by our subsequent participation in the measurement process. In Wheeler's cosmological-scale version of the delayed-choice experiment, this actualization can take place literally millions of years after the event. That Wheeler subscribes to the idea that a photon can pass through both slits (or both paths open to it in other quantum experiments) is especially intriguing because he is among the stronger advocates of Bohr's views, which appear to be in conflict with this idea. At least, no statement supporting it appears to occur in Bohr's writings.

In fairness, both Wheeler and Greene assume that the past is physically fixed in the case of such quantum events as well, and that the paradox arises only because our conventional ideas concerning temporality are not applicable at the quantum level. While they might be right on this last point, it does not appear to me that their conception of the past as an array of future possibilities is workable or in any event is sufficiently developed by them. Neither Wheeler or Greene, nor, to my knowledge, others who subscribe to the assumption that a single photon can pass through two slits or analogous assumptions in other experiments manage to find a satisfactory way of making such assumptions work. Could one assume that each photon is a wave-like object that always goes through both slits, if differently in different circumstances? Apart from the difficulties of explaining the particle-like aspects of photons' behaviour when they are registered by detectors or in other circumstances, this does not solve the problem of affecting the past by our subsequent actions. For, switching the detectors on or off would still change the way a single photon had propagated, as a wave, through the slits. Of course, if one believes that the past could be affected by the present, then the assumption that a photon can pass through both slits may be acceptable, even though such an event can never be observed.

We can make better sense of the situation by assuming that each photon only passes through one slit, while establishing at any point before or after this passage the *possibility* of knowing through which slit it passes destroys the possibility of the appearance of the interference pattern. It should be stressed, however, that, in the present view, one could speak of the 'fact' of a photon passing through a slit only in the sense that the corresponding observable event, a 'click', could, in principle, be registered by a measuring device, and that this fact would, again, destroy the possibility of observing the interference pattern. In this view, the two incompatible outcomes result from the fact that each of these two cases establishes a different measurement set-up, which is mutually exclusive with or complementary to the alternative set-up, and hence leads to the alternative predictions concerning the outcomes of the experiment and the correspondingly different statistical distributions of the traces on the screen. No concept of the independent behaviour, individual or collective, of photons needs to be assumed [2, v. 2, pp. 50–51]. The same considerations would also apply to analogous events recorded in other quantum experiments. Furthermore, as the quantum eraser experiments tell us, the situation is defined not only by what we actually know or don't know but also by what is in principle possible or impossible to *know* concerning our interactions with quantum objects. It is the possibility or impossibility of this knowledge that defines the kind of predictions we can or cannot make in each case, for example, whether an interference pattern will or will not appear on the screen in the double-slit experiment, or its delayed-choice and quantum eraser versions.

4. The Scully marking, quantum erasure, and quantum unrepeatability

At least in the present view, then, it is our *interaction* with quantum objects by means of our experimental technology (whose role is, again, irreducible, in contrast to the case of classical physics) that defines our knowledge concerning them or, again, more accurately, concerning the effects of this interaction upon the world that we can describe. The quantum eraser experiments, I argue, demonstrate this fact and amplify its significance. The marking of a photon, let us call it 'the Scully marking', is an act of measurement and, hence, interaction with a photon by means of our measuring devices, which allows for the possibility of knowledge that is incompatible with the appearance of the interference pattern, once a sufficient number of events is registered. Erasing such a marking is an alternative interaction with photons, which erases the possibility of such knowledge, and thus re-establishes the appearance of the interference pattern.

One should say *establishes*, rather than re-establishes, since in each case we deal with the two sets of disconnected and mutually exclusive—complementary—set-ups, and hence two sets of experiments that are completely disconnected from each other. We cannot perform both experiments on a single photon at the same time, or combine them in the way we can combine both the position and the momentum measurement in classical physics, which is what distinguishes it from quantum physics in view of the role of the uncertainty relations in quantum physics. The two corresponding experiments require two different photons, a fact that becomes crucial in the famous experiment of Einstein, Podolsky and Rosen (EPR) [7, 8]. The significance of this fact can also be seen as demonstrated by experiments approximating the EPR experiment for the continuous variables (the thought-experiment itself proposed by EPR cannot be realized as an actual experiment) [8–11]. Either a photon is marked or it is no longer marked, and the knowledge concerning through which slit it has passed is no longer available, which must lead to the interference pattern, once the experiment is repeated a sufficient number of times. The quantum eraser erases the (previously made) markings of the photons involved and not the outcome of the same experiment. The erasure of markings defines a new set of individual experiments. Nor, given the impossibility of repeating the identically prepared quantum experiments with the same outcome, can we repeat the experiment so as to guarantee that a single photon would pass through the same slit [8]. Erasing the marking after each photon passes through one slit or the other is analogous to switching the detectors off before a photon reaches them in the standard double-slit experiment (which assures the appearance of the interference pattern), and hence, it does not change anything in this respect. Similar considerations apply to the delayed-choice versions of the quantum eraser experiment, in which one encounters the alternative sets of patterns, discernable only when we know for which photons such knowledge is not available [1]. These experiments further demonstrate that it is the possibility of what we in principle can or cannot know (rather than only what we already know) that defines the outcomes of our experiments. Other recent versions of the quantum eraser experiment support this view as well, often more directly (e.g. [12]).

The quantum eraser experiments, thus amplify those features of quantum phenomena and quantum mechanics that have to do with the repeated and sequential measurements, and that thus fundamentally distinguish them from classical phenomena and classical physics, as was stressed by such founding figures as Bohr, Heisenberg, Schrödinger, Pauli, and von Neumann. In recent years, the question of the difference between quantum and classical physics has often been considered in the context of the EPR experiment and Bell's and related theorems, and the key experiments confirming them, especially those by Alain Aspect [13, 14]. As noted above, the question of the repeated measurements is relevant in this context as well [8]. Here, however, I would like to focus specifically on the concept of 'erasure'. According to Bohr: '[in quantum experiments] a subsequent measurement to a certain degree deprives the information given by a previous measurement of its significance for predicting the future course of the phenomena. Obviously, these facts not only set a limit to the *extent* of the information obtainable by measurements, but they also set a limit to the *meaning* which we may attribute to such information' [2, v. 1, p. 18; also pp. 67–68]. As Bohr acknowledges, Heisenberg makes the same point in his 1927 uncertainty-relations paper [15]. This point is equally crucial to Schrödinger in his paper best known for the 'cat paradox' it contains [16, pp. 152, 154]. According to Pauli, in quantum mechanics 'information obtained as a result of earlier measurements can be lost after *one* measurement', and in any event, it is no longer of any use for our future predictions [17, p. 220]. One might, then, speak of the 'erasure' of the data obtained or even potentially obtainable in a measurement by means of a measurement subsequent to this measurement for the purposes of our predictions concerning the outcome of the experiment following the second, *erasing* measurement.

From this perspective, the difference between classical and quantum phenomena and physics might be seen as follows. Suppose that one performs an experiment on a classical physical object, say, as Galileo did, by dropping such an object (a stone, for example) from a certain height. One can, at least ideally, always repeat the same experiment with the same outcome. Indeed, such a repetition is always, in principle, possible insofar as one retains a proper record of the experiment. This possibility of repeating the identically set up experiments is essential to the disciplinary nature of modern physics, classical or quantum, but with a crucial difference, stressed throughout this article: in quantum experiments we can only repeat the statistical data obtained in a given set of experiments, since in general the identically prepared experiments lead to different outcomes. In order to destroy this possibility of repeating a given experiment in classical physics, one literally has to erase the data in question entirely, to obliterate it without a trace. In the case of quantum phenomena, one encounters the *effects* accompanying this type of erasure of the preceding history in any given experiment. While the data necessary to repeat the experiment on an object, such as a photon, is identical to the one used in the previous experiment, it is, again, in general impossible to repeat any given experiment with the same outcome. Once a given quantum experiment is performed, specifically, once a measurement is made for the purposes of a prediction, the experiment is closed and the corresponding quantum object is no longer available for these purposes: it is as good as destroyed for the purposes of any future predictions compatible with this measurement. Conversely, any subsequent measurement establishes a new field of possible predictions. Accordingly, any given measurement 'erases' the information previously obtained in the sense of making it meaningless for the purposes of predictions, which are defined only by the last measurement performed.

A striking feature of the quantum eraser experiments is the erasure of the *determinate possibilities of knowledge* defined by the experiments involved rather than only the *actual knowledge* already obtained in such experiments, which gives a new and more radical meaning to our interactions with quantum objects.

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References

[1] M.O. Scully and K. Drühl, Phys. Rev. A **25** 2008 (1982).
[2] N. Bohr, *Philosophical Writings of Niels Bohr*, 3 Vols (Ox Bow Press, Woodbridge, Conn., 1988).
[3] W. Heisenberg, *Physics and Philosophy: The Revolution in Modern Science* (Harper & Row, New York, 1958).
[4] R. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton University Press, Princeton, NJ, 1985).
[5] J.A. Wheeler, in *Quantum Theory and Measurement*, edited by J.A. Wheeler and W.H. Zurek (Princeton University Press, Princeton, NJ, 1983), pp. 182–213.
[6] B. Greene, *The Fabric of the Cosmos: Space, Time, and the Texture of Reality* (Knopf, New York, 2004).
[7] A. Einstein, B. Podolsky and N. Rosen, in *Quantum Theory and Measurement*, edited by J.A. Wheeler and W.H. Zurek (Princeton University Press, Princeton, NJ, 1983), pp. 138–141; original work published in 1935.
[8] A. Plotnitsky, J. Mod. Opt. **53** 2293 (2006).
[9] Z.Y. Ou, S.F. Pereira, H.J. Kimble, *et al.*, Phys. Rev. Lett. **68** 3663 (1992).
[10] J.C. Howell, R.S. Bennink, S.J. Bentley, *et al.*, Phys. Rev. Lett. **92** 210403 (2004).
[11] M. D'Angelo, Y.-H. Kim, S.P. Kulik, *et al.*, Phys. Rev. Lett. **92** 233601 (2004).
[12] H. Kim, J. Ko and T. Kim, Phys. Rev. A **67** 054102 (2003).

[13] J.S. Bell: Physics **1** 195 (1964); also J.S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge University Press, Cambridge, 1987).
[14] A. Aspect, J. Dalibard and G. Roger, Phys. Rev. Lett. **49** 1804 (1982).
[15] W. Heisenberg, in *Quantum Theory and Measurement*, edited by J.A. Wheeler and W.H. Zurek (Princeton University Press, Princeton, NJ, 1983), pp. 62–86.
[16] E. Schrödinger, in *Quantum Theory and Measurement*, edited by J.A. Wheeler and W.H. Zurek (Princeton University Press, Princeton, NJ, 1983), pp. 152–167; original work published in 1935.
[17] W. Pauli, A Letter to Born 31 March 1954, in *M. Born, The Born–Einstein Letter*, translated by I. Born (Macmillan, New York, 2005).