Why Bohm was never a determinist

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Abstract
Bohm's interpretation of quantum mechanics has generally been received as an attempt to restore the determinism of classical physics. However, although this interpretation, as Bohm initially proposed it in 1952, does indeed have the feature of being deterministic, for Bohm this was never the main point. In fact, in other publications and in correspondence from this period, he argued that the assumption that nature is deterministic is unjustified and should be abandoned. Whereas it has been argued before that Bohm's commitment to determinism was connected to his interest in Marxism, I argue for the opposite: Bohm found resources in Marxist philosophy for developing a non-deterministic notion of causality, which is based on the idea of infinite complexity and an infinite number of levels of nature. From ca. 1954 onwards, Bohm's conception of causality further weakened, as he developed the idea of a dialectical relation between causality and chance.

Keywords: Determinism; chance; levels of nature; dialectical materialism; David Bohm

Introduction
If David Bohm is known for one thing, it is for developing a fully deterministic interpretation of quantum mechanics.[1] His interpretation of quantum mechanics has generally been understood as an attempt to restore determinism in physics, and he has been praised for showing that a common sense, deterministic account of quantum mechanics is possible, as well as criticized for being conservative and unwilling to accept the revolutionary features of modern physics (Van Strien, 2020). In the 1950s, he was mostly criticized: for example, Rosenfeld argued that Bohm's theory was motivated by a "metaphysical prejudice" of determinism (Rosenfeld 1958), and Pauli described it as a "classical-deterministic myth" of atomic physics (Pauli to Fierz, 1952, in Von Meyenn 1996, 500).

However, a closer look at Bohm's writings from the 1950s shows that his views were not at all conservative (Van Strien 2020; Oldofredi 2023). Bohm emphasized the complexity of nature and the interconnectedness of everything, and from the beginning he emphasized the holistic and nonlocal aspects of his interpretation of quantum mechanics.[2] And as I want to argue in this paper, he was in fact never a determinist. That for Bohm, restoring determinism was never the central aim, has already been argued in Del Santo (2019) and Van Strien (2020); here I want to defend the stronger claim that Bohm was in fact always opposed to determinism.[3]

[1] But see Landsman (2022).
[2] These consist in the fact that the momentum of a particle depends on the system as a whole, and the motion of particles is guided by a quantum potential which does not vanish at large distances.
[3] See also Del Santo and Krizek (2023), in which the same claim is made; this paper and the present paper were written simultaneously and independently of each other.

It will be useful to have a definition of determinism. Determinism, roughly, is the view that any natural process can be fully described through a specification of initial (and boundary) conditions and a set of laws of nature: the laws of nature always yield a unique solution, such that they fully specify future states. This implies that given the state of a perfectly isolated system at an instant, it is in principle possible to derive the state of the system at all later times (and generally also at all earlier times). Or: given the state of the universe at an instant, it is in principle possible to derive the state of the universe at all later (and earlier) times. This is an *in-principle* argument: it does not need to be possible in practice to give exact predictions, and in fact this is almost never possible. But the determinist view is that in some way a complete specification of states and laws of nature exists or is possible, such that later states can be derived from earlier states plus the laws of nature. I will argue that in this sense, Bohm was never a determinist.

Determinism relies on the assumption that a physical system is always in a definite state, which can be specified through a number of variables. Furthermore, determinism can only hold in a non-trivial way if you allow for a limited number of laws of nature, which hold absolutely and are of limited complexity: if you allow for an unlimited number of laws of nature or for laws of unlimited complexity, determinism holds trivially, because then for every conceivable sequence of events, one can find laws of nature describing exactly this sequence. Finally, either it must be possible to consider a system in perfect isolation, or determinism can only hold for the universe as a whole.

Generally, a lot of confusion has been caused by the fact that ‘causality’ is often equated with ‘determinism’, but that it can have other meanings as well. The term ‘causality’ can be used for example to refer to the principle that nothing happens without a cause, that the same cause is always followed by the same effect, or that there is no action at a distance; and none of these principles is equivalent to determinism. As we will see, also for Bohm, ‘determinism’ and ‘causality’ did not have the same meaning, and therefore the fact that Bohm named his interpretation of quantum mechanics the *causal* interpretation does not necessarily mean that he was committed to determinism.

In the next two sections, I will describe the development of Bohm’s views on determinism and causality during the 1950s, and how they were embedded in Marxist philosophy. This account is based on Bohm’s published work as well as on his correspondence during this period. I will end with some brief notes on the later developments of Bohm’s views.

Determinism Versus Causality

In 1951, Bohm published a textbook titled *Quantum Theory*, which provides a general introduction to quantum physics. The book was finished in the summer of 1950. Through writing this book, Bohm tried to make sense of quantum physics himself, but after finishing it he was not convinced that the standard interpretation, as he had presented it here, could be correct. This then motivated him to develop an alternative interpretation, which he managed to do already in the spring of 1951. One may therefore suspect that *Quantum Theory* does not yet present Bohm’s own views, but merely his understanding of the consensus at the time. However, his treatment of quantum physics is not standard in every way: it is oriented towards Niels Bohr’s account of quantum mechanics, but is also based on an underlying assumption of realism, which is visible for example in Bohm’s ontological interpretation of Bohr’s notion of complementarity (Freire 2019). The book also reveals Bohm’s views on determinism at the time. If Bohm merely wanted to present a standard account of quantum physics, he could just have written that the theory is indeterministic; but he made a point of arguing that determinism had never been plausible and that there is no reason to expect a physical theory to be deterministic (Bohm, 1951, 150-53). He argues that the rise of determinism in classical mechanics had been connected with the development of the science of mechanics and the growing importance of machines, which led to a mechanistic worldview. But indeterminism is in fact closer to everyday experience, since what we experience is that a cause "produces a tendency to an effect" but "does not guarantee the effect" (Bohm 1951, 150). That Bohm was already critical of determinism when writing *Quantum Theory* can also be seen from a letter which he wrote to Miriam Yevick in 1952; here, Bohm writes that when he started working on the book, he tended towards Bohr's views because Bohr "tried to explain the physical meaning of the theory" and also because

> …there was an element of dialectics in Bohr's point of view which attracted me. It seemed progressive because it broke the old mechanist materialist determinism, which left no room for growth and development of something new (Bohm to Yevick, 1952, in Talbot ed., 2017, 235).

Thus, Bohm was definitely not a determinist when he wrote *Quantum Theory.* Moreover, the fact that Bohm saw Bohr's break with determinism as dialectic suggests that already at this point, there was a connection between Bohm's rejection of determinism and Marxist philosophy.

On December 4, 1950, at the height of the cold war and the McCarthy era, Bohm was indicted for contempt of Congress, because of his affiliations with communism and his refusal to testify for the House Un-American Activities Committee (HUAC) (Freire 2019, 56-62). This led to a suspension from his job at Princeton University. Bohm had been a member of the communist party for a brief period in 1942, and although he had quickly become disappointed with the party, he had remained a Marxist. During the months he was suspended, Bohm had a lot of free time, which he used to develop an alternative interpretation of quantum physics (Bohm to Schatzman, 1952, in Besson 2018, 335).

By July 1951, Bohm had sent his article, "A suggested interpretation of the quantum theory in terms of 'hidden' variables", to *Physical Review,* where it was published in early 1952. In Bohm's interpretation, which is similar to an earlier proposal by de Broglie, particles have a well-defined position and momentum at all times and thus a well-defined path, and their movement is guided by a quantum potential which is derived from the Schrödinger equation. This interpretation yields exactly the same predictions as the standard interpretation. It is indeed deterministic; however, the fact that Bohm proposed an interpretation that had the feature of being deterministic does not necessarily imply that he was committed to determinism at this point. He saw this interpretation as preliminary: it showed that an alternative interpretation of quantum physics was possible, but it should still be developed further, and Bohm in particular wanted to modify it in such a way that new predictions could be derived from it (Bohm 1952, 179). And from the paper, it does not seem that restoring determinism is Bohm's main motivation. Bohm's main concern is with the intelligibility of nature, the possibility to describe and understand natural processes and the possibility to give a realist account of quantum physics. He writes that the interpretation he proposes "provides a consistent alternative to the usual assumption that no objective and precisely definable description of reality is possible at the quantum level of accuracy" (Bohm 1952, 188). Bohm does object to the present quantum theory that "it requires us to give up the possibility of even conceiving precisely what might determine the behavior of an individual system at the quantum level" (Bohm 1952, 168). According to the usual interpretation of quantum mechanics, the theory can only yield probabilities for measurement outcomes, and more than this is not possible; in contrast, Bohm wants to be able to say what determines the behavior of an individual system. This is of course closely related to determinism, but does not necessarily have to take the form of a full-blown determinism, and it is not clear from the paper that it does. In the conclusion, Bohm argues that we should assume that the world is objectively real; furthermore, he proposes the hypothesis that the world "can correctly be regarded as having a precisely describable and analysable structure of unlimited complexity" (Bohm 1952, 189). This idea of unlimited complexity seems already in tension with determinism, since it implies that we can never arrive at a deterministic theory which gives a complete description of physical reality.

Overall, this paper by itself does not provide conclusive evidence of whether Bohm was committed to determinism at this time. However, additional evidence makes it very implausible that he was ever committed to determinism. We have already seen that he rejected determinism not long before writing the paper in spring 1951, namely in *Quantum Theory*, which he finished in summer 1950. Furthermore, in his correspondence we find explicit rejections of determinism shortly after. In May 1951, Bohm was acquitted from the charges of contempt of congress. However, his contract at Princeton University ended in June, and the university decided not to prolong his contract; although not officially stated, it was clear that this was for political reasons, and it was clear to Bohm that he would not be able to find a job at another university in the US. In October 1951, Bohm therefore moved to Brazil, where he got a professorship at the University of São Paulo (Freire 2019). Shortly before moving to Brazil, Bohm wrote a letter to the physicist Evry Schatzman in France, in which he discusses his interpretation of quantum physics. He added: "there are probably an infinite number of levels of reality, so that a *complete* theory will never be obtained" (Bohm to Schatzman, in Besson 2018, 310).[4] From São Paulo, Bohm sent letters to friends in the US. His letters to three female friends, namely Hanna Loewy, the physicist Melba Phillips, and the mathematician Miriam Yevick, have been published in the volume *David Bohm: Causality and Chance, Letters to Three Women* (ed. Talbot, 2017). In these letters, Bohm frequently discusses the conception of an infinite number of levels of nature. Our description of nature at the quantum level is very different from that at the classical level, and Bohm was convinced that in order to get a fuller understanding of certain phenomena we will need to go to a sub-quantum level, which will again look very different. The elements at each level emerge from elements at a lower level, from which they are qualitatively different. Bohm thought that the total number of levels of nature must be assumed to be infinite; thus, nature is infinitely complex.

In November 1951, Bohm writes to Yevick: "Because of the existence of an infinite number of levels, the deterministic laws of order at each level probably follow only as a result of conditions of chaos existing at lower levels" (Talbot 2017, 205). The laws of thermodynamics arise from the unordered motions of the molecules and atoms at a lower level; Bohm thinks that something similar holds for all laws of nature. In March 1952, shortly after the article with his deterministic interpretation of quantum mechanics came out, Bohm describes the idea of a mechanically determined universe as a *nightmare*:

> I think that the explicit recognition of a limitless number of levels would be a big step forward in science. Most of the errors of both the positivist and the 19th century 'mechanical' materialists spring from an implicit assumption that the laws of nature will some day finally be understood in terms of a limited number of hypotheses. From this comes the nightmare of a mechanically determined universe that follows an inevitable course. (Bohm to Yevick, March 1952, in Talbot 2017, 254).

A bit further on, Bohm writes that with the notion of an infinite number of levels of nature, "the nightmare of complete determinism is avoided" (Talbot 2017, 254).

[4] The letter is undated, but he writes that he is about to move to São Paulo, where he arrived on October 10 (Freire 2019, 63).

This does not mean that Bohm argued in favor of indeterminism at this point. In fact, he writes that positivists and idealists have tried to avoid the nightmare of determinism by assuming that there can be spontaneous, uncaused events, but according to Bohm, this is equally unfounded. Bohm argues that both the assumption of absolute determinism and the assumption of indeterminism obstruct the progress of science: a determinist assumes that one already knows all causes at play, while an indeterminist assumes that there are no causes to be found, and therefore both views "discourage a search for 'deeper' causes than those already known" (Talbot 2017, 254).

Bohm chose the term 'causal interpretation' for his interpretation of quantum mechanics because it enables a causal account of quantum phenomena. In an article published in 1953, Bohm argues that the assumption that certain events can take place purely by chance is unscientific, since to assume that something is uncaused means giving up on trying to understand it:

> …when we face a new and as yet unexplained phenomena, the most fruitful attitude is always to assume they have a cause, which we must discover. Even if there really were no cause, no error could come from the assumption that there was one. All that would happen would be that our efforts to find the cause would not be successful. But if, as is much more likely, there really is a cause, and we assume there is not, then we may be led to overlook important new factors that are needed in the theory. (Bohm 1953a, 284).

By assuming that events at the quantum level may be genuinely uncaused, "the usual interpretation relegates real physical phenomena to a domain that is by definition forever beyond the possibility of scientific investigation" (Bohm 1953a, 284). In fact, "the domain of causality defines the domain of science itself" (Bohm 1953a, 284). And in another paper published in 1953, Bohm argued that if uranium nuclei decay at different times, it is only reasonable to suppose that there must be a difference between them: "the most elementary scientific procedure would suggest that if two objects are observed to act differently, this should be regarded as *a posteriori* evidence that there must in fact be some physical difference between them" (Bohm 1953b, 465). He argues that whereas according to the usual interpretation of quantum mechanics there is no difference between two uranium nuclei which decay at different times, according to the causal interpretation there indeed is a difference: the time of decay is determined by the exact positions of the particles within the nucleus, and these positions must thus be different for the two nuclei (Bohm 1953b, 465-66). In this way, Bohm's interpretation indeed offers a causal account of radioactive decay.

Thus, Bohm argues that we must assume that every event has a cause and that it is in principle possible to find this cause. At the same time, he describes determinism as a 'nightmare'. How to understand this? Can one accept that everything has a cause without being a determinist?

Although causality has often been equated with determinism, Bohm in fact makes an explicit distinction. In his correspondence from the early 1950s, Bohm equates determinism with mechanical determinism, according to which nature consists of fixed basic elements which move according to fundamental laws of nature. With this conception of determinism, nature is conceived of as a machine, in which there is only quantitative change, which consists in the rearrangement of basic elements. Causality, in contrast, can describe qualitative as well as quantitative change. Bohm argues that there is an emergence of qualitatively new behavior at higher levels of nature, and this can be described with causal laws (Bohm to Phillips, 1953, in Talbot 2017, 164). However, whereas Bohm sees determinism as mechanical, one may object that also non-mechanical conceptions of determinism are possible.

But Bohm draws further distinctions between causality and determinism. Determinism is about the possibility to predict events, and if determinism holds, the future determines the past as well as the past determines the future. Causality is additionally about the possibility to change the course of events: by changing the causes, we can change the effects (Bohm to Yevick, 1952, in Talbot 2017, 255). Thereby, causality also involves a temporal element: we can change the causes and thereby change the effects, but not vice versa (Bohm 1953a, 285). Bohm argues that causality is in fact incompatible with determinism: if determinism holds, it is not possible for us to actually change anything. If determinism holds, then rather than an event having a specific cause, it is determined by the entire earlier state of the universe. Therefore, Bohm writes that if we accept Laplacian determinism, "causality itself loses all meaning" (Bohm 1953a, 285).

According to Bohm, this problem is avoided because we don't have to accept Laplacian determinism. The latter only follows if we take the laws of Newtonian mechanics to be absolutely valid; but the history of science teaches us that we should never assume that we have found a final theory which holds absolutely. As soon as we accept that Newton's laws only hold within a limited domain and only with good approximation, it no longer follows from these laws that the universe as a whole is deterministic. Thus, Newtonian mechanics is deterministic, and the causal interpretation shows that also a deterministic theory of quantum mechanics may be possible; but neither of these hold absolutely, and neither of these can be taken to be a final theory. Therefore, neither of these imply a universal, Laplacian determinism (Bohm 1953a, 285).

We may ask if Bohm's conception of levels of nature could nevertheless allow for an ontological conception of determinism of the universe as a whole: could one argue that, given the state of the universe as a whole, including all levels, at an instant, only one future development is possible? In his correspondence, Bohm argues that as long as we assume the number of levels of nature to be finite, we do arrive at the conclusion that nature as a whole must be deterministic. However, if there is an infinite number of levels of nature, no complete analysis is possible, since we cannot conceive of the state of the universe as a whole:

> Although each level is causal, the totality of levels cannot ever be taken into account. Thus, as a matter of principle, we say that complete determinism could not even be conceived of, yet, each level can be determined (Bohm to Yevick, 1952, in Talbot 2017, 254).[5]

With an infinite number of levels of nature, there can always be an emergence of genuinely new behavior "because the effects of the limitless number of lower levels can always surge up into a higher level (and vice versa)" (Bohm to Yevick, 1952, in Talbot 2017, 255). Furthermore, what happens at a certain level does not only depend on lower levels but can also depend on a higher level, and therefore we cannot obtain exact knowledge of what happens at a certain level by analysing only the lower levels:

> …the higher levels will also always help determine the character of things that may exist at the lower levels. Thus, every level is in a sense, just as real as every other, since the "whole picture" cannot be deduced by starting at the "lowest level" and working upward. (Bohm to Yevick, 1952, in Talbot 2017, 246; see also p. 171).

Therefore, according to Bohm, "if we have a finite number of causal levels, then the future is already contained logically in the present, but not if we have an infinite number" (Bohm to Yevick, 1952, in

[5] In a letter to Charles Biederman in 1961, Bohm writes that we could say that every event is determined if we consider the totality of the world, but that this would be a trivial determinism (Bohm to Biederman, 1961, in Pylkkänen 1999, 164). This is related to the point that the concept of determinism is only meaningful if it is based on the idea that there is a limited number of laws of nature which hold absolutely.

Talbot 2017, 255); "It is the unlimited number of levels which give matter its 'non-mechanical' aspects" (Talbot 2017, 254).

Bohm's views imply that we can never arrive at a theory which is deterministic as well as fully accurate. A specific level of nature may be described by a deterministic theory; however, since levels are never fully independent from each other, this can only be an idealization. No complete description of nature is possible, not even in principle: it is principally impossible to fully specify the state of a system, and therefore, Bohm is not a determinist according to the definition given in the introduction. In this way, Bohm can argue that in principle, it is always possible to find a cause for any event, without implying that nature as a whole is deterministic.

There is a Marxist element in Bohm's conception of infinite levels of nature: Bohm himself directly connects it with dialectical materialism (Talbot 2017, 255).[6] In an interview, Bohm said:

> I remember also, before leaving the United States, I picked up something in the Princeton library, some Soviet publication which mentioned Lenin saying that the electron was inexhaustible. (…). That sort of struck a chord because I said, 'Well, not only the electron, but everything, all matter is inexhaustible'.[7]

This refers to a passage from Lenin's book *Materialism and Empirio-criticism*, in which Lenin argues against positivism. Lenin writes: "The electron is as *inexhaustible* as the atom, nature is infinite, but it infinitely *exists*" (Lenin 1947, 243). Also for Lenin, this meant that our knowledge of nature can never be complete. Bohm's view of an infinite number of levels of nature was probably also influenced by Friedrich Engels, who also proposed a view according to which there are different levels of nature, with qualitatively new properties emerging at higher levels (Sheehan 1985, 34). Engels' materialism is not a crude materialism but rather organicist and emergentist: there is always an emergence of qualitatively new properties.

Determinism and Randomness

An issue with Bohm's interpretation of quantum mechanics is how to account for the Born rule: the probability density for the position of particles must be equal to $P=|\Psi|^2$ (with Ψ the wave function) in order to agree with experimental results. In the standard interpretation of quantum mechanics, this is simply postulated, but in Bohm's interpretation, particles have well-defined trajectories and equations of motion, and one has to account for the fact that the probability density is given by the above equation. It can be proven that once the probability density satisfies the Born rule, this is stable and will continue to hold, but how is this situation reached when you start with an arbitrary configuration of particles? Here, Bohm brought in the idea of random or chaotic movements. In a manuscript which Bohm sent to de Broglie in 1951, he argues that the Born rule can be explained through "the chaotic character of the particle motion (resembling Brownian motion), which arises whenever the particle interacts with other systems" (Bohm, in Drezet and Stock 2021, 171). There are deterministic laws which determine the trajectories of particles, but there is also always some deviation from these trajectories due to chaotic motion resulting from the interactions with other systems, and after a while this results in a convergence of the probability density to $P=|\Psi|^2$. Also in (1952), Bohm points at the "chaotically complicated character" of the coupling between the particle

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[6] On Marxist elements in Bohm's early work, see also Kojevnikov (2002).

[7] Interview of David Bohm by Maurice Wilkins on 1986 December 22, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA, www.aip.org/history-programs/niels-bohr-library/oral-histories/32977-6.

and the surrounding systems with which it interacts to explain the Born rule. And in (1953b), Bohm provides a demonstration of how an arbitrary initial probability distribution approaches $P=|\Psi|^2$ as a result of random collisions.

In 1953, the French physicist Jean-Pierre Vigier, an assistant of de Broglie, came to Brazil to work with Bohm for a few months. Their work resulted in a joint paper, in which they explain the claim that any initial probability density will develop to the probability density $P=|\Psi|^2$ through random fluctuations in the quantum potential. Bohm and Vigier use a hydrodynamic model and argue that there exist fluctuations in the quantum potential like in any other physically real fluid or field, and that these can originate from motions at a sub-quantum level. The fluctuations in the motion of particles can be compared to Brownian motion, the random motion of particles suspended in a fluid which results from their collision with molecules in the fluid (Bohm and Vigier 1954). Thus, Bohm and Vigier appeal to a lower level of nature in order to solve an issue in Bohm's interpretation of quantum mechanics.

This appeal to random motion is not necessarily incompatible with determinism. Though Brownian motion itself is random, it arises as a result of the motion of molecules in a fluid, and it is possible that these molecules move according to deterministic equations, although their motion is too complex to be tractable. In this way, Brownian motion may be seen as an example of how random behavior can emerge from underlying determinism; and analogously, Bohm's and Vigier's claim that random fluctuations arise as a result of motions at a sub-quantum level does not necessarily exclude the possibility that there is a deterministic theory for the sub-quantum level. However, Bohm and Vigier do seem to understand their derivation of the Born rule as an introduction of randomness and as thereby going against determinism. In (1957, 116), Bohm notes about his work with Vigier: "in our model we have not insisted on a purely causal theory, for we have also utilized the assumption of random fluctuations originating at a deeper level". And in a letter to Popper in 1984, Bohm writes:

> It is true that I first used a determinist version of (…) quantum theory. But later, (…) a paper was written, in which we assumed that the movement of the particle was a stochastic process. Clearly that is not determinism. (Bohm to Popper, 1984, quoted in Del Santo 2019).

Thus, from the beginning, Bohm thought that random or chaotic processes played a role in his interpretation of quantum mechanics, and by 1954 he had supplemented the deterministic account given in his 1952 paper with an element of randomness arising from a lower level of nature, which for him meant that his interpretation of quantum mechanics was no longer deterministic.

Causality and Chance

Although as we have seen, it seems that Bohm was never committed to a complete determinism, until around 1954 he held on to the idea that chance must always be taken to arise from underlying causality and seems to have regarded causality as more fundamental. Furthermore, his correspondence shows that around 1952-54, he was working on models in which deterministic laws give rise to chaos and randomness, and thought that "all chaos comes from causality" (Bohm to Yevick, 1953, in Talbot 2017, 317). He also argued that probability distributions can be derived from causal laws. He developed these ideas in particular through his correspondence with Miriam Yevick, who later also published on this topic (Yevick 1957). Bohm saw it as problematic if we need two different accounts of probabilities: in statistical mechanics, we need to use probabilities because we cannot specify the exact state of the system for practical reasons, though probabilities would theoretically be eliminable if could give a full specification of the system, whereas in the standard account of quantum mechanics, there are probabilities which are fundamental and irreducible (Bohm 1953b, 466). Bohm thought that an advantage of his theory of quantum mechanics was that with this theory, probabilities could be interpreted in the same way as in statistical mechanics, thus no second notion of probability is needed. Thus, even though Bohm rejected absolute determinism, he thought that there always needs to be a causal basis for chance and probability.

At some point in 1954, however, his views seem to have shifted: where before, he thought that causality was more fundamental than chance, he now argued that there is a dialectical relation between causality and chance and that both are equally objective (Talbot 2017, 49-62). Here he was influenced by the Brazilian physicist Mario Schönberg, with whom he worked in São Paulo, as well as the Argentine physicist Mario Bunge (Talbot 2017, 56). Both were also Marxists and interested in dialectical materialism. Soon after his arrival in Brazil, in November 1951, Bohm mentioned in his correspondence that he was reading Friedrich Engels' *Dialectics of Nature* in Portuguese, "borrowed from the collections of Schönberg" (Bohm to Yevick, 1951, in Talbot 2017, 200–203) – apparently, Bohm used Engels' work for learning Portuguese. Engels' *Dialectics of Nature*, which remained unfinished and fragmentary and was published only after his death, contains remarks on the relation between chance and necessity. Here, Engels objects to the view that some things are necessary and other things are purely accidental: there is always an interplay of both. He also objects to the deterministic view according to which everything is necessary and nothing is accidental: for Engels, this is an "empty phrase" because it is not verifiable in any way, and because in practice, chance always continues to play a role (Engels 1954, 219). Engels appeals to Hegel's dialectical views on causality and argues that causality arises from chance and chance from causality, and that what is necessary from one perspective becomes accidental when seen from another perspective and vice versa. Also Schönberg thought that there was a dialectical relation between causality and chance. Bohm had a difficult relationship with Schönberg but became more receptive to his views after a while (Peat 1997, 155; Talbot 2017, 351, 404). In an interview, Bohm says that Schönberg "helped to show me that I had been approaching the thing in a narrow way, by just looking at causality, without bringing into the opposite side of chance".[8] And:

> I had been discussing causality and essentially through discussions with Schönberg had turned into more a dialectical direction. That is he was very interested in dialectic. He used to say that Lenin had said communists should read Hegel, and very few did.[9]

Bohm took up Schönberg's advice to read Hegel. He became very interested in the philosophy of Hegel, an interest which remained strong throughout his life (Kožnjak 2022; Peat 1997).

Also Mario Bunge regarded causality and chance as dialectical opposites. In 1953 Bunge came to work with Bohm in São Paulo for six months. Two years before, he had published an article titled "What is chance?", in which he argued that "chance and necessity convert one into the other according to the general laws of dialectics" (Bunge 1951, 231). As science develops, we find that what seemed to be necessary in fact arises from chance events, and what seemed to be chance events in turn arise from necessity (Bunge 1951, 218). Bunge argued that the dilemma between determinism and indeterminism is a false one: these are both unfounded metaphysical positions. The

[8] Interview (footnote 7).
[9] Interview of David Bohm by Maurice Wilkins on 1986 October 3, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA, www.aip.org/history-programs/niels-bohr-library/oral-histories/32977-5

article is explicitly written from a Marxist perspective, including quotes from Engels. Bohm found this article very interesting: it was part of his motivation to invite Bunge to São Paulo (Bunge 2016, 90).

By 1954, Bohm had adopted these views of a dialectic relation between causality and chance, as can be seen from his correspondence from this period. Whereas before he was concerned with showing how randomness can arise from causality, he now argued that causality and randomness are "equally real, and both are inter-dependent and interconnected" (Bohm to Yevick, 1954, in Talbot 2017, 382). Causal laws and statistical laws are both needed in our descriptions of nature and have an equally objective validity.

Thus, during his time in Brazil, Bohm's interest in dialectical materialism deepened. Forstner (2008) has analyzed the changes in Bohm's thought in this period in terms of the concept of thought-collectives developed by Ludwik Fleck, arguing that after moving to Brazil, Bohm became detached from his former community of physicists in the US and departed from the thought-style of that community, and dialectical materialism became more central to his thought.

In early 1955 Bohm moved to Israel. In 1957, he published his book *Causality and Chance in Modern Physics*, about which he later said: "I just about finished most of it when I got out of Brazil. I finished it finally in Israel, but the basic thing was done in Brazil"; "I think that book was basically a result of Brazil. I think in Brazil the main thing that happened was that my ideas transformed a great deal".[10] In *Causality and Chance in Modern Physics*, Bohm argues that causality and contingency are both abstractions which offer opposite views of the same object. "Each view, then, limits the other, corrects the other, and through its relationship with the other enables us to form a better concept of what the object is" (Bohm 1957, 3). Bohm argued that the assumption of determinism and the assumption of fundamental chance are equally unsupported. Whenever one has deterministic laws of nature, a closer study may reveal that these laws arise through averaging over chance fluctuations; and similarly, whenever one has statistical laws of nature, which merely ascribe probabilities to future events, a more detailed study may reveal how these laws arise from underlying determinism. Thus, wherever one finds determinism, there can be underlying chance and vice versa.

Bohm objects to the standard interpretation of quantum mechanics that it takes chance to be fundamental and excludes the possibility of ever being able to describe the exact trajectories of particles. However, he also argues against a strictly determinist picture, since it relies on the assumption that our current theory is final and its laws hold absolutely. This, according to Bohm is unjustified: scientific theories always have a limited domain of validity, and even within this domain they don't hold absolutely, since different levels of reality are never fully isolated from each other. Since our laws of nature never hold absolutely and can never give a complete description of nature, they generally do not determine the future uniquely: "Rather, they make possible only a one-to-many correspondence between cause and effect, in the sense that a specification of certain causes will in general limit the effect to a certain range of possibilities" (Bohm 1957, 16). In an isolated mechanical system, we can have something close to deterministic laws, but true determinism remains an idealization: no system is ever perfectly isolated, which means that there are always some external disturbances, and even in a perfectly isolated mechanical system,

> …there would still exist disturbances coming from motions at the molecular level. Of course, one could in principle try to take these into account by applying the laws of motion to the molecules themselves, but then one would discover still further disturbances coming from the quantum-mechanical and other deeper-lying properties of matter (Bohm 1957, 20).

[10] Interview (footnote 9).

Bohm argues that the assumption that the indeterminacy of quantum mechanics is final is just as unjustified as the assumption that classical determinism holds absolutely – in both cases, the possibility that future developments will lead to changes in the theoretical framework is excluded (Bohm 1957, 102). Though Bohm speaks about an infinity of levels of nature, he notes towards the end of the book that as science develops further, we may find that this structure of levels breaks down at some point, and instead of describing nature at smaller and smaller scales we may "disclose a still more general pattern of organization of things" (Bohm 1957, 140). But what Bohm is sure of is that nature is inexhaustibly rich and that science will never be finished.

Bohm's *Causality and Chance in Modern Physics* does not mention the names Engels, Marx, Lenin, Hegel, or the word 'dialectical', but it is very clearly based on dialectical materialism. In fact, during his time in Brazil he mentioned in his correspondence that he was working on a book on dialectical materialism, which is probably this book (Talbot 2017, 291). It is of course understandable that Bohm did not make the dialectical materialist basis of his work explicit, since this would not have helped the acceptance of his ideas. However, various elements of dialectical materialism can be recognized in *Causality and Chance in Modern Physics*. First, the idea that nature is inexhaustibly rich is, as we have seen, also expressed in Lenin's statement of the inexhaustibility of the atom and in Engels' views on the levels of nature. Furthermore, Bohm writes that everything is interconnected, and that everything is always in transformation and nothing remains constant; these ideas can be found in Engels' natural philosophy as well (Sheehan 1985, 36-44). Bohm also writes that quantitative change leads to qualitative change, giving the example of phase transitions: if the temperature of a gas is lowered, the gas condenses and enters a liquid phase, and thereby new qualities appear (Bohm 1957, 52). This derives from Engels' formulation of Hegel's first law of dialectics, "the law of the transformation of quantity into quality and vice versa".[11] According to Engels, this is a natural law which is based on our study of nature, and Engels also gives phase transitions as an example. Finally, as we have seen, Bohm argues for a dialectic relation between causality and chance.

Freire (2015, 52; 2019) has argued that in the early 1950s, Bohm was committed to determinism, and that this was connected to the fact that he was a communist during this period. He writes furthermore that in the second half of the 1950s, Bohm abandoned determinism, and that it is plausible that this development is connected to his break with communism in 1956, "following the revelations of Nikita Khrushchev, the Soviet leader, at the 20th Congress of the Soviet Communist Party, about the crimes in the Stalin-era, and the Soviet invasion of Hungary", which deeply shocked Bohm (Freire 2019, 105; and see Talbot 2017, 67-75).

However, the opposite seems to be the case. Rather than motivating a determinist view, Bohm's interest in Marxist philosophy helped him develop an account of causality that was not deterministic, and then to arrive at the idea of a dialectic relation between causality and chance. His break with communism took place before the publication of *Causality and Chance in Modern Physics*, but after he had developed the central ideas presented therein: we have seen that according to Bohm, the book was mostly written when he arrived in Israel in 1955.

Marxism is often associated with determinism, and especially with the idea that there are laws determining the development of society. But there are different schools in Marxist philosophy. Freire himself has pointed out that there was a variety of Marxist views on quantum physics, and has

[11] The second law of dialectics, in Engels' formulation, is "The law of the interpenetration of opposites": there are contradictory tendencies in everything. The third law of dialectics is "The law of the negation of the negation", which means that everything carries within itself the conditions for its annihilation (Engels 1954).

in fact discussed a few cases of physicists who adhered to a dialectical materialist philosophy and rejected determinism, including Paul Langevin in France and Mituo Taketani in Japan (Freire 1997).[12] A further example of a Marxist physicist rejecting determinism is the Russian physicist and historian of science Boris Hessen (Talbot and Pattison, 2021). And in the 1950s, the Belgian physicist Léon Rosenfeld and the Soviet physicist Vladimir Fock argued against determinism from a Marxist perspective. They both argued that Bohr's notion of complementarity could be understood in a dialectic way (see Jacobsen 2007, Cross 1991, Freire 1997, Martinez 2019). Rosenfeld and Fock were in fact among Bohm's strongest critics: they both saw Bohm's interpretation as a step back to an outdated mechanistic determinism (although, as I have argued, this perception was not entirely correct). We have already seen that both Bunge and Schönberg also rejected determinism from a dialectical materialist point of view. Vigier, who was a member of the communist party in France, initially rejected Bohm's conception of an infinite number of levels of nature, but by 1954 he had become convinced of the idea and argued that it was in agreement with dialectical materialism (Besson 2018, 165). He argued that for this reason, Bohm's interpretation should not be understood as a return to Laplacian mechanical determinism (Vigier 1956, 125), and in a lecture in 1957, speaking about the approach of Bohm and himself, he said: "We do not wish to return to Laplacian determinism and to reduce all laws to causal laws" (Vigier in Körner (ed.) 1957, 77). In 1961 Vigier published an article titled "Théorie des Niveaux et Dialectique de la Nature" in the communist journal *La Pensée*, in which he expressed ideas closely resembling those of Bohm in *Causality and Chance in Modern Physics,* but with the dialectical materialist foundations made explicit (Vigier 1961).

So even if, especially in the Soviet Union, there were also Marxist physicists who sought for a deterministic physics, it seems that in many (if not most) cases, an adherence to Marxist philosophy was instead connected to a rejection of determinism in physics. In this respect, it is not surprising that Marxist philosophy in fact helped Bohm develop non-determinist views.

Later Years

After the late 1950s Bohm rarely mentioned dialectical materialism again, and this is probably indeed connected with his disillusionment with communism. Hegel, however, remained a strong influence throughout his life: Bohm endlessly read and reread Hegel (Kožnjak 2022). The dialectic elements of his view on causality and chance are also expressed in his correspondence with the artist Charles Biederman in the early 1960s. Here, Bohm argues that chance and contingency have as much objective existence as causality, and writes: "Every time we have a regularity, we must have some limit to this regularity. (…) Wherever there is law, there must be lawlessness." (Bohm to Biederman, 1960; in Pylkkänen 1999, 34). Therefore, "the future is not fully determined by the past" and there can be genuine freedom (Bohm to Biederman, 1960; in Pylkkänen 1999, 14).

Already in the 1950s, Bohm remarked that his 1952 interpretation of quantum mechanics was preliminary and in some respects unsatisfactory, but he thought that it showed the possibility in principle of alternative interpretations of quantum mechanics and that it was a promising starting point for further development (Bohm 1957, 127). By the early 1960s, Bohm had abandoned his causal interpretation in search of a more radically new theory of quantum physics. However, there seems to be little evidence that this should be understood as a result of a change in his views on causality; rather, he seems to have been disappointed by the reception of his theory and by the lack

[12] On Marxist approaches to quantum mechanics, see e.g., Cross 1991, Freire 1995.

of concrete results. He did move further away from mechanism in this period, arguing that also our conceptions of space and time may have to be revised.

In the 1970s Bohm took up his (1952) interpretation of quantum mechanics again, after some of his students became interested in it. In *The Undivided Universe* (1993), Bohm and his co-author Hiley give a detailed account of Bohm's interpretation of quantum mechanics, although with some differences from Bohm's work from the 1950s. In the introduction, they write that they prefer the term 'ontological interpretation' over 'causal interpretation'; however, I think it is not clear that this indicates a weakening of Bohm's commitment to causality. Bohm and Hiley write that the theory they propose does not have to be deterministic: "The question of determinism is therefore a secondary one, while the primary question is whether we can have an adequate conception of the reality of a quantum system, be this causal or be it stochastic or be it of any other nature" (Bohm and Hiley 1993, 2). When they discuss causality and determinism later in the book, the views expressed are similar to those in Bohm's *Causality and Chance in Modern Physics*: whenever there is determinism, there can be underlying chance and the other way around, and "ultimately our overall world view is neither absolutely deterministic nor absolutely indeterministic" (Bohm and Hiley 1993, 324).

Conclusion

To summarize: in *Quantum Theory* (finished in 1950), Bohm wrote that there is no reason to expect a physical theory to be deterministic. In the period 1951-1953, he argued in correspondence that we must assume that everything has a cause, and that chance reduces to causality, but he explicitly distinguished causality from determinism and rejected a fully deterministic account of nature, even referring to determinism as a 'nightmare'. Although the interpretation of quantum mechanics he proposed in 1952 was indeed deterministic, it was not motivated by a commitment to determinism, and Bohm in fact suggested from the beginning that an element of chaos or randomness had to be added in order to account for the Born rule. From ca. 1954, Bohm argued that there is a dialectic relation between causality and chance: causality and chance always transform into each other and both are equally objective.

Nevertheless, Bohm's theory of quantum mechanics has almost universally been received as an attempt to restore determinism in physics. This makes him part of a more general pattern. Beller (1999) has pointed out that there has been a tendency to interpret all opposition to the standard interpretation of quantum mechanics as a metaphysical attachment to classical determinism, and that in this way, opposition has been portrayed as conservative and dogmatic (Beller, 1999, 281). Other examples of this tendency are Schrödinger and Einstein. Schrödinger's objections to the standard interpretation of quantum mechanics have often been interpreted as a refusal to accept indeterminism, despite the fact that Schrödinger already argued that we should give up on determinism before the introduction of an explicitly indeterministic theory of quantum mechanics in 1925-26, and despite the fact that Schrödinger's objections were in fact different (Ben-Menahem 1989). Also Einstein's concerns with quantum physics have often been thought to stem from an attachment to outdated classical determinism: his objections are often summarized by his statement that "God does not play dice". However, also in the case of Einstein, it has been argued that indeterminism was actually never his main concern and that his actual concerns with quantum mechanics went deeper (see e.g. Fine 1986, Howard 1993, Paty 1995).

Like Schrödinger and Einstein, Bohm was primarily after an *understanding* of quantum mechanics. Bohm was not satisfied with the standard account of quantum mechanics because it implied that there is a hard limit to the possibility to describe and understand natural processes. This is related to causality, but it does not mean that he was committed to determinism.

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