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# Realism and Antirealism in Informational Foundations of Quantum Theory

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**Z**eilinger-Brukner's informational foundations of quantum theory, a theory based on Zeilinger's foundational principle for quantum mechanics that an elementary system carried one bit of information, explains seemingly unintuitive quantum behavior with simple theoretical framework. It is based on the notion that distinction between reality and information cannot be made, therefore they are the same. As the critics of informational foundations of quantum theory show, this antirealistic move captures the theory in tautology, where information only refers to itself, while the relationships outside the information with the help of which the nature of information would be defined are lost and the questions "Whose information? Information about what?" cannot be answered. The critic's solution is a return to realism, where the observer's effects on the information are neglected. We show that radical antirealism of informational foundations of quantum theory is not necessary and that the return to realism is not the only way forward. A comprehensive approach that exceeds mere realism and antirealism is also possible: we can consider both sources of the constraints on the information, those coming from the observer and those coming from the observed system/nature/reality. The information is always the observer's information about the observed. Such a comprehensive philosophical approach can still support the theoretical framework of informational founda-

tions of quantum theory: If we take that one bit is the smallest amount of information in the form of which the observed reality can be grasped by the observer, we can say that an elementary system (grasped and defined as such by the observer) correlates to one bit of information. Our approach thus explains all the features of the quantum behavior explained by informational foundations of quantum theory: the wave function and its collapse, entanglement, complementarity and quantum randomness. However, it does so in a more comprehensive and intuitive way. The presented approach is close to Husserl's explanation of the relationship between reality and the knowledge we have about it, and to Bohr's personal explanation of quantum mechanics, the complexity of which has often been missed and simplified to mere antirealism. Our approach thus reconnects phenomenology with contemporary philosophy of science and introduces the comprehensive approach that exceeds mere realism and antirealism to the field of quantum theories with informational foundations, where such an approach has not been taken before.

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## 1 Introduction

A century after the establishment of fundamentals of quantum mechanics, there is still no widely accepted interpretation of the results of quantum experiments and of the mathematical description of the quantum world. However, this does not mean that different interpretations of quantum mechanics have not contributed to the understanding of the world around us. As Avshalom C. Elitzur stated: “To be sure, physics would be very dull had these interpretations not been proposed in the first place. They teased researchers’ minds and stimulated experimentation and theorizing” [1, p. 4].

In the last decades, quantum information theories have been one of the most important mind teasers. They offered different theoretical frameworks explaining the characteristics of the quantum world and stimulated new experiments. As they based the explanation of the quantum world on the concept of information and considered the relationship between information, knowledge and reality, they opened some fundamental philosophical questions, previously considered as too theory-laden to be included in the formulation of fundamental theory: “Information? Whose information? Information about what?” [2, p. 34].

This also holds for Brukner’s and Zeilinger’s *informational foundations of quantum theory*, a theory based on Zeilinger’s foundational principle for quantum mechanics that the most elementary system has the information carrying capacity of at most one bit [3]. Brukner and Zeilinger manage to explain some seemingly problematic and unintuitive characteristics of the quantum world (e.g. entanglement, collapse of the wave function) by using simple theoretical framework based on a radical philosophical proposition that distinction “between reality and information, cannot be made” [4]. However, critics of informational foundations of quantum theory emphasize that this antirealistic move captures informational foundations of quantum theory in tautology [5] where (the system of) information is explained by (the characteristics of) information [5, 6]. Furthermore, if information is all we have, questions considering the nature of information: “Information? Whose information? Information about what?” [2], stay open and the philosophical basis of informational foundations of quantum theory is undefined. Consequently, the critics of the theory suggest return to realism [5, 6].

In the present paper we will analyze the philosophical standpoint of informational foundations of quantum theory, its problems and standpoints of its critics. We will consider the need for Zeilinger’s and Brukner’s philosophical radicalism, the justification of critic’s appeal to realism and propose the third option, which exceeds mere realism and antirealism.

## 2 Zeilinger-Brukner’s informational foundations of quantum theory

Zeilinger-Brukner’s theoretical framework is based on the concept of information. However, information is not understood in a technical sense as in classical information theory. Zeilinger and Brukner describe information as the result of the observation, as the answer about the property of the observed system. One bit of information represents one possible answer to the question about the property of the object of investigation. For example, to the question “Spin up?” there are two possible answers, “yes” (spin up) or “no” (spin down) [7]. Regarding information as the answer to the question about the measured property, Zeilinger equates the role of knowledge and information in several papers, when he describes knowledge or information about an object [3, 8] or of reality [4].

Exceeding the point of view of realism of ontic approaches, where the scientific knowledge about reality is taken as a direct manifestation of reality, while the influence of the one observing/measuring and the observation process/measurement are neglected, informational foundations of quantum theory follows the epistemic approach and closely considers the way we refer to reality, the form in which we grasp reality; as Zeilinger writes: “there is no way to refer to reality without using the information we have about it” [4]. Based on this observation, Zeilinger presupposes that: “it is important not to make distinctions that have no basis” and concludes: “the distinction between reality and our knowledge of reality, between reality and information, cannot be made” [4], therefore: “Wirklichkeit und Information sind dasselbe” (“Reality and information are the same”) [7, p. 317].

This equation between reality and information is the basis of the foundational principle of informational foundations of quantum theory. If we decompose “a system which may be represented by numerous propositions into constituent systems”, each “constituent system will be represented by fewer propositions” and

the limit is reached when an individual system finally represents the truth value to one single proposition only. Such a system we can call an elementary system. We thus suggest a principle of quantization of information as follows. An elementary system represents the truth value of one proposition. [...] We now note that the truth value of a proposition can be represented by one bit of information [...] Thus our principle becomes simply: An elementary system carries one bit of information. [3, p. 635]

However, regarding the antirealistic character of their theory, Zeilinger and Brukner emphasize:

the notions such as that a system “represents” the truth value of a proposition or that it “carries” one bit of information only implies a statement concerning what can be said about possible measurement results. For us a system is no more than a representative of a proposition. [9, p. 326]

Considering this, Zeilinger and Kofler describe the foundational principle as: “An elementary system is the manifestation of one bit of information” [8, p. 476].

On the basis of this simple foundational principle, Zeilinger and Brukner can explain the seemingly unintuitive fundamental quantum phenomena revealed by quantum experiments. The principle explains quantum randomness and complementarity: since an elementary system carries the answer to one question only, all other answers must contain an element of randomness.

The extreme case is when the measurement direction is orthogonal to the eigenstate direction. Then for the new measurement situation the system does not carry any information whatsoever, and the result is completely random. [...] The information carried now by the system is not in any way determined by the information it carried before the measurement. Thus we conclude that the new information the system now represents has been spontaneously created in the measurement itself. We finally remark that the viewpoint just presented lends natural support to Bohr’s notion of complementarity. This notion is well known, for example, for position and momentum or for the interference pattern and the path taken in a two-slit experiment; precise knowledge of one quantity excludes any knowledge of the other complementary quantity. [3, p. 636]

Furthermore, Zeilinger argues that the entanglement as another fundamental feature of quantum mechanics follows from a slight generalization of the foundational principle. In quantum mechanics, states are said to be entangled if for any composite system of two or more particles there exist pure states of the system (states that are as completely specified as the theory allows) in which parts of the system do not have pure states of their own [10].

*N elementary systems represent the truth values of N propositions. N elementary systems carry N bits. [...] After the interaction the N bits might still be represented by the N systems individually or, alternatively, they might all be represented by the N systems in a joint way, in*

the extreme with no individual system carrying any information on its own. In the latter case we have complete entanglement. [3, p. 637]

In the case of complete entanglement of two elementary systems, two bits of information are used to describe joint properties: e.g. should the spins of the two systems be measured along the  $z$  axis, they would be found to be identical and should they be measured along the  $x$  axis, they would be also found to be identical. These two propositions now uniquely determine the entangled quantum state, which does not contain any information about the individual systems. Therefore, any measurement performed on individual systems gives completely random results [3, 11].

The framework of informational foundations of quantum theory can also be used to explain the seemingly paradoxical collapse of the wave function:

There is never a paradox if we realize that the wave function is just an encoded mathematical representation of our knowledge of the system. When the state of a quantum system has a non-zero value at some position in space at some particular time, it does not mean that the system is physically present at that point, but only that our knowledge (or lack of knowledge) of the system allows the particle the possibility of being present at that point at that instant. What can be more natural than to change the representation of our knowledge if we gain new knowledge from a measurement performed on the system? When a measurement is performed, our knowledge of the system changes, and therefore its representation, the quantum state, also changes. In agreement with the new knowledge, it instantaneously changes all its components, even those which describe our knowledge in the regions of space quite distant from the site of the measurement. [9]

Based on equation between reality and information, the mathematical formulation describing the quantum world can be taken as a mere representation of our knowledge: with the measurement we gain, new knowledge and consequently the presentation of knowledge changes. The wave function and the measured property are just two different representations of different information. In informational foundations of quantum theory information is not information about reality, it is our only reality. Information is understood as not causally connected to anything it would be about. Consequently, the objectivity of information cannot be taken as self-evident on the basis of the common, from us independently existing outer world.

Any concept of an existing reality is then a mental construction based on these answers [(“yes” or “no”) answers to the questions posed to Nature]. Of course this does not imply that reality is no more than a pure subjective human construct. From our observations we are able to build up objects with a set of properties that do not change under variations of modes of observation or description. These are “invariants” with respect to these variations. Predictions based on any such specific invariants may then be checked by anyone, and as a result we may arrive at an intersubjective agreement about the model, thus lending a sense of independent reality to the mentally constructed objects. [9, p. 351]

Objectivity of the quantum world can be taken into account only on the basis of certain invariants and of the inter-subjective agreement about the gained information and its meaning. On this basis it is possible to exceed the solipsism and to conclude that a system of information, independent from us, forms, what we can call objective reality, so that the outer world (in that sense) exists [7].

In informational foundations of quantum theory we can speak about an inter-subjective world of information, however, we cannot speak about the outer world that this information is about and which would be a basis for scientific objectivity. As critics of informational foundations of quantum theory emphasize, if information and reality are the same [7], we can end up in tautology, where all the information describes is information [5], it only explains (a system of) information by (the characteristics of) information [6].

Zeilinger’s argument is based on sensible notion about the relationship between reality and information that we always refer to reality with the information we have about it [4]. However, by equating reality and information the sensible observation changes in tautology. The statement that the argument should support, destroys the sensibility of the argument itself. Now information only refers to itself.

By equating information and reality, the informational foundations of quantum theory loses the relationships outside the information with the help of which the mere nature of information would be defined. If information is all we have the answer to the question “Information about what?” cannot be provided. Despite the epistemic character of informational foundations of quantum theory, even the answer to the question “Whose information?” is not clear—if we can speak about a system of information independent from us, whose information it is then? It seems that the connection between information and the one get-

ting/possessing this information has been lost within the attempts to assure the objectivity of information. As the critics of informational foundations of quantum theory put it:

The very concepts of knowledge and information imply a special kind of relationship between different things, appropriate correlations between a knower and what is known. Thus “the distinction between reality and our knowledge of reality” not only can be made; *it must be made if the notions of knowledge and information are to have any meaning in the first place.* [5, p. 131]

### 3 Critic’s standpoint

Critic’s response to the problems in the epistemic approach of informational foundations of quantum theory and the radical antirealism of its authors is a return to the realism of ontic approaches. In the work by Daumer and colleagues [5] this can be seen in repeated praise of “Bohm’s simple deterministic” explanation of quantum mechanics and simultaneous criticism of “the convoluted indeterministic one of the Copenhagen view.” Timpson’s criticism [6], however, offers more direct insight into the problems faced by informational foundations of quantum theory. Timpson labels informational foundations of quantum theory’s epistemic position as immaterialist metaphysics, where results of measurement do not pertain to an externally existing mind-independent world and the object is just a useful construct connecting observations. He consents to Zeilinger’s point of view that the immaterialistic or antirealistic position in informational foundations of quantum theory is based on Copenhagen tradition and that it can be found in similar form in Bohr’s description of his own point of view. Commenting on supposedly similar Bohr’s and Zeilinger’s understanding of the relationship between physics, Nature and reality, Timpson’s own standpoint becomes clear:

The last sentence [of the statement famously attributed to Bohr by Petersen] is particularly pertinent: “Physics concerns what we can say about nature.” Compare again, another statement of Zeilinger’s, “...what can be said about Nature has a constitutive contribution on what can be *real*.” I think we find in these sentiments a crucial strand contributing to the thought that the rise of quantum information theory supports an informational immaterialism. If quantum mechanics reveals that the true subject matter of physics is what can be said, rather than how

things are, then this seems very close to saying that what is fundamental is the play of information across our psyche. [...] However, it is important to recognize that there is a very obvious difficulty with the thought that what can be said provides a constitutive contribution to what can be real and that physics correspondingly concerns what we can say about nature. Simply reflect that some explanation needs to be given of where the relevant constraints on what can be said come from. Surely there could be no other source for these constraints than the way the world actually is, it cannot *merely* be a matter of language. [6, p. 225]

Timpson criticizes the merely epistemic approach of informational foundations of quantum theory, which lacks consideration of the constraints coming from Nature. However, he replaces it with a merely ontic approach: for Timpson “there could be no other source for [the relevant constraints on what can be said] than the world actually is” [6, p. 225]. The informational foundations of quantum theory’s epistemic position—the consideration of the way we refer to reality, of the constraints coming from the observational/descriptive ability of the one observing/describing Nature—is now completely left out. For Zeilinger, reality and information are the same, we could say that reality is merely the manifestation of information, for Timpson reality is all there is to affect what can be said in physics, we could say that information is merely the manifestation of reality.

Antirealism of the epistemic approach taken in informational foundations of quantum theory leads to some serious philosophical problems: the argumentation on which the equation between reality and information and consequently the foundational principle for quantum mechanics are based is lost in tautology, while the mere nature of information cannot be comprehensively defined. But is the return to the realism of ontic approaches really the only way forward?

## 4 Exceeding mere realism and antirealism

On the one hand, informational foundations of quantum theory is based on radical antirealism, on the other hand, the critique of informational foundations of quantum theory is based on radical realism. However, despite very rarely used in the philosophy of quantum mechanics, a comprehensive view that would consider both constraints: those coming from the way nature actually is and those coming from the way we (can) observe, describe Nature, is also possible.

As Zeilinger pointed out, we always refer to reality with the information, we have about it. Or to put it otherwise, reality is always given to us in the form of information. We cannot grasp the reality as such, we observe the reality and get the information about it on the basis of this observation. This is always the information about the reality, or to be more precise, about *the observed system*, thus defining *the observed* as the part of reality we (the one observing) are focused on, as the object of the observation process. However, as information is always information about reality and not reality itself, the constraints defining the information cannot come just from the way *the observed system* is. The information is always information for (or to put it otherwise, according to) someone that receives this information, thus defining this someone as *the observer*: in the present article *the observer* is defined as the one receiving the information about *the observed*; based on our experiences we have an insight only into how human being’s receive and process the information, so, when not stated otherwise we will speak about a *human being observer*, though the term *observer* is a broader term. Information as *the observer’s* information is always co-defined by the way *the observer* (can) observe(s), measure(s), describe(s) and understand(s) *the observed*.

Following a comprehensive view that exceeds the radicalism of mere realism or mere antirealism and considers the complex relationships between information and other agents of the observation process, the fundamental philosophical questions about the nature of information: “Information? Whose information? Information about what?” [2], can be easily answered:

Information about what? It is information about *the observed*. In the case of the description of a particular measurement, we can say that information is the value of the position or of the polarization along a particular direction of the (observed) photon. However, this information only describes *the observed* in the context of that particular measurement. This knowledge cannot be generalized to *the observed* in all contexts, since *the quantum observed* is changed by the measurement. Information is causally connected with *the observed*; what we know is causally connected with what there is. However, information does not present *the observed* in itself, information is *the observed* as perceived by *the observer* in the context of the particular observation process.

Whose information? It is *the observer’s* information. It is always information of the one who observes *the observed*. Information is thus causally connected to *the observer’s* way of observation, context of observation and his ability to observe. We should not attribute *the observed* any a priori properties independent of *the observer* and context of description.

The question is, is such a comprehensive approach possible in quantum theory with informational foundations, or is the Zeilinger's and Brukner's radicalism, which makes informational foundations of quantum theory vulnerable to philosophical critique, necessary for the theoretical framework based on the concept of information.

Considering information as *the observer's* information about *the observed*, we can still base the foundational principle for quantum mechanics on relation (but not on equation) between reality and information about it: given that one bit is the smallest amount of information in the form of which the observed reality can be grasped by the observer, we can say that the elementary system (grasped and defined as such by the observer, on the basis of his observation of reality) correlates to one bit of information.

All the fundamental features explained by informational foundations of quantum theory can be then explained by quantum theory with informational foundations based on philosophical basis exceeding mere realism or antirealism. Such a comprehensive approach enables the insight into complex connections between information, *the observer* and *the observed* and thus a complex philosophical insight into the quantum world as described by quantum theory with informational foundations.

## 4.1 Connections between information, the observer and the observed

Information and *the observed* are both in two ways connected to *the observer*:

### 4.1.1 Ontic connection

Information and *the observed* are connected to *the observer* as to the one who, by trying to get information, already (necessary) has an influence on *the observed*, because the inclusion of *the observed* in the observation process already influences how *the observed* is. This connection is a precondition to get information about *the observed*.

When a quantum system is measured, it entangles with (*the observer's*) environment. This is described as decoherence, "the practically irreversible dislocalization (in Hilbert space) of superpositions due to ubiquitous entanglement with the environment" [12, p. 7]. However, to describe something, it is necessary to be outside the described set. If *the observer* is to describe this entanglement, he has to put the cut between the entangled system he is describing and himself. Usually the cut is put between the measurement apparatus and *the observer*, who thus describes the quantum system and the measurement apparatus as the entangled system and thus as *the quantum observed*.

The postulate that to describe something, it is necessary to be outside the described set, operationalistically explains the cut between quantum and classical in the process of measurement and is thus identical to Heisenberg's consideration of this problem known as "Heisenberg cut" [13]. This cut is a necessary condition for the possibility of empirical knowledge and is as such operationalistic, but not arbitrary; the choice depends on the nature of the experiment/approach and co-defines the way *the observer* describes *the observed*. However, since quantum description is universal, while classical physics can describe only complex classical systems, the cut cannot be shifted arbitrarily in the direction of the quantum system, but it can "be shifted arbitrarily far in the direction of *the observer* in the region that can otherwise be described according to the laws of classical physics" [14, p. 12].

When considering the connection between *the observer*, information and *the observed* from the ontic point of view, the answer to the question "what is changed at measurement?" would be—*the observed*. Of course, we cannot approach *the observed* directly, *the observed* by itself, we can only claim that what is changed is our information about *the (changed) observed* in the context of a particular measurement (that caused the change).

### 4.1.2 Epistemic connection

Information and *the observed* are connected with *the observer* as observer *per se*, as to the one for whom the information has a meaning. On the basis of the ontic connection the information becomes available, on the basis of the epistemic connection the information is grasped by *the observer*. Information has a meaning only as long as it is information for someone. Most probably the preconditions of our comprehension are those that determine information as the form, in which everything we comprehend is given. This epistemic connection can be described with the concept of projection postulate, describing the "collapse" of the state vector.

The cut between *the quantum observed* and *the classical observer* is now emplaced between the quantum system and the measuring apparatus; between both component systems of the total entangled system as defined within the description of the ontic connection.

When considering the connection between *the observer*, *the observed* and information from the epistemic point of view, the answer to the question "what is changed at measurement?" would be—our knowledge/our information. However, this knowledge is still causally connected to *the observed*. As we can see, the ontic and the epistemic connections between *the observer*, *the observed* and information are mutually dependent.

### 4.1.3 Fundamental features of the quantum world

Based on the insight into complex connections between information, *the observer* and *the observed*, some of the fundamental features of the quantum world, explained by informational foundations of quantum theory, can be explained in a more comprehensive and intuitive way. The wave function is still understood as *the observer's* knowledge, however, as *the observer's* knowledge about *the observed* that describes *the observed* before or after the measurement (or more correctly about *the potential future/past observed*). Thus it can describe *the observer's* knowledge only according to the potential (future) information about *the observed*, according to potential results of potential measurements. Therefore, the wave function can be understood by *the observer* only as a probability function.

Describing the quantum world as described by quantum theory with informational foundations, we can say that from the point of view of *the observer*, physical systems carry information and this informational content is behind quantum behavior. We always get particular information about *the observed* in the context of a particular observation. From the point of view of *the observer* (which is the only point of view we can have), *the observed* has the potential to give information even when not in the observation process. However, *the observed* is only defined by the particular information when in a relationship with another (observing) system and only for that observing system. Considering this, the quantum behavior, and entanglement and randomness as its main features, can be explained in a more comprehensive and clear way:

In entangled system, one of the component systems (one of the entangled particles) is defined only as a part of the total entangled system. It is completely specified from the point of view of the system it is entangled with, but unspecified for an “outer” observer:

one could prepare a pair of particles, *A* and *B*, in a superposition of the state “particle *A* is at position  $x_1$  and particle *B* is at position  $x_3$ ” and the state “particle *A* is at position  $x_2$  and particle *B* is at position  $x_4$ ”, formally written as  $(|x_1\rangle_A|x_3\rangle_B + |x_2\rangle_A|x_4\rangle_B) / \sqrt{2}$ . In such an entangled state, the composite system is completely specified in the sense that the correlations between the individuals are well defined. Whenever particle *A* is found at position  $x_1$  (or  $x_2$ ), particle *B* is certainly found at  $x_3$  (or  $x_4$  respectively). However, there is no information at all about whether particle *A* is at  $x_1$  or  $x_2$  and whether *B* is at  $x_3$  or  $x_4$ . [8, p. 472]

When particles *A* and *B* are entangled, particle *A* is completely determined from the point of view of particle *B* and vice versa, each of them is completely determined from the point of view of *the “inner” observer*, where *the observer* is not understood as a human being *observer*, but simply as a system “possessing” the information about the other (observed) system. What is fully defined, are not the particular properties as such, in the sense of objective reality for all *the observers*, but the relationship between both component systems. Therefore from the point of view of one of the component systems, with respect to himself as a reference system, the other component system is fully determined. A classical measurement apparatus can get only a random answer to the question about the position of the component system *A* or *B*. For an “outer” observer the relationship between component systems is determined, but not the component systems themselves (because a reference system of *the “outer” observer* cannot depend on *the observed component system*). In the same way, all our properties (and properties of other classical systems) are completely determined (from the point of view of an “inner” observer, e.g., an *observer* from our environment that considers himself as *the observer*, myself as *the observed* and places the cut somewhere between us), since in our classical everyday world we are completely entangled with our environment (different measurements are constantly performed on us).

Considering this, it seems that randomness is the basic “characteristic” of the world, while determinism is a consequence of decoherence. In the case of description of a measurement of a quantum system, the ontic connection between *the observer*, *the observed* and information about it, is a description from the point of view of *the “outer” observer*: the cut between *the observer* and *the observed* is placed between the measurement apparatus and the rest of our environment to describe the entanglement of the quantum system. The epistemic connection is a description from the point of view of the “inner” observer: according to us (as *the observer's*), *the observed quantum system* is now fully defined by the measured property.

## 5 Discussion

In informational foundations of quantum theory, seemingly unintuitive quantum phenomena can be explained using a simple foundational principle based on equation between reality and information. However, this radical antirealism makes informational foundations of quantum theory vulnerable to philosophical critique, which emphasizes that informational foundations of quantum theory ends up in tautology, where all the information describes is information, while the relationships outside the infor-

mation are lost and the answers to the questions “Information? Whose information? Information about what?” cannot be provided. Critic’s solution to these philosophical problems of informational foundations of quantum theory is a turn to mere realism, where informational foundations of quantum theory’s lack of consideration of the constraints coming from Nature is replaced with the lack of consideration of the constraints coming from the way the observer observes/describes Nature.

However, as we show in section 4, mere antirealism or realism are not the only available explanations of the relationship between reality and information, a comprehensive approach that considers all the constraints—those coming from the way Nature actually is and those coming from the way *the observer* observes/describes Nature—is also possible. The information can be understood as *the observer’s* information about *the observed*. There exist ontic and epistemic connections between information, *the observed* and *the observer*. When a quantum system is measured (and thus becomes *the observed*), it entangles with the measurement apparatus. Consequently, its ontic status is essentially changed and only now the information about *the observed* is available to *the observer*, thus leading to the epistemic connection. Now *the observer* can describe *the observed* by one of his concepts. However, all of *the observer’s* concepts are classical concepts, based on his experiences from his classical environment and applicable only to *the observed*, which is part of this environment (decoherence). The ontic and the epistemic connection are mutually dependent and both, *the observed* and *the observer* define the information.

Zeilinger’s and Brukner’s radical antirealism is not a necessary philosophical standpoint for the explanation of quantum behavior with the concept of information. In a context of the presented comprehensive philosophical approach, the foundational principle of informational foundations of quantum theory can still be formed, all the fundamental features explained by informational foundations of quantum theory still explained, while some of the fundamental features of the quantum world, like the wave function, entanglement and quantum randomness, can now be explained in a more comprehensive and intuitive way.

Considering the intuitiveness of such a comprehensive approach, the question arises whether, after a century after the establishment of fundamentals of quantum mechanics, such an approach really is something new. In continental philosophy a similar explanation of the relationship between reality and the knowledge one can have about reality has been offered by Husserl’s phenomenology, based on his understanding of the concept of phenomenon. Husserl’s phenomenon can be described as the thing as has been given/shown to me by itself, but

essentially to me, in my horizon, with the meaning it has to me [15]. As such, phenomenon is always essentially related to both, *the observer* (me) and *the observed* (the thing). Phenomenon is always intentional phenomenon, is phenomenon of something. The core of what we observe is *the observed* itself, but always within the horizon of the observation process and according to our own orientation. It is either an orientation towards thing itself or a specific interest, e.g. admiration, esthetical contemplation, practical interest, and this difference is essential for the observation. If things smell good or bad, these are not properties of things themselves. This is how they are given to *the observer*, because of his specific physical (bodily) interest, but these are always things given to *the observer* by themselves. Belief in the outer world, in reality, is Glaubengewissheit; it is belief in itself, because the connection between phenomenon and thing is based on certainty of reason, which is the foundation of any rational action in the world [16]. Husserl applied both the constraints, those coming from the thing (*the observed/reality*) and those coming from *the observer’s* way of observing, to the phenomenon and we could say that he considered phenomenon as *the observer’s* information about *the observed reality*.

Despite great relevance of Husserl’s work to quantum mechanics, Husserl’s phenomenology and quantum mechanics have only rarely been considered together [18–22], mostly due to the general separation between physics and philosophy during the so called “shut up and calculate era” [26] in the middle of 20th century and to the more personal “philosophical and political parting of the ways [between phenomenologists and philosophers of science] in pre-war Germany” [17]. However, according to [18, 20], Bohr’s personal interpretation of quantum mechanics, though not directly influenced by Husserl, also considered both constraints: those that come from Nature/reality and those that come from the way *the observer* observes/measures Nature. In the Introduction to the forth volume of his *Philosophical writings*, his position is described as ontological realism and epistemological anti-realism:

Bohr’s insistence that the description of nature involves the description of interactions between measuring instruments and the objects whose properties they are designed to measure [...] commits him to an ontological realism. [...] Not only did Bohr deny that atomic objects were purely constructions, but also he [...] distinguished] his view from those philosophers who regarded the measurement interaction as in some sense ‘creating’ the object of measurement. [...] At the same time, however, Bohr [...]



argues strongly against those forms of realism which would attempt to describe an objectively existing, independent reality in terms of concepts which are well-defined only in relation to ‘phenomena’, as he uses that term. Bohr’s ontological realism extends beyond the macro-realm to the atomic domain, nevertheless his epistemological anti-realism prohibits any attempt to carry the descriptive concepts of classical physics necessary for the description of phenomena beyond the phenomenal sphere to a world of things-in-themselves. [23, pp. 12–13]

Bohr’s position exceeds mere realism and antirealism: the information we get in the process of the measurement is information about *the observed*, about the measured object, however, it is *the observer’s* information and not a direct manifestation of *the observed*: *the observer* can describe *the measured observed* by one of his classical concepts, but this concept is not applicable to *the observed* in all contexts and cannot be taken as the property defining *the observed* independently from the context of particular observation.

Though comprehensive and influential, Bohr’s interpretation has been often misunderstood and simplified, especially after the so called “shut up and calculate” era, when a direct flow of knowledge especially between physicists and contemporary philosophers outside mere philosophy of science was broken. Partly integrated into the Copenhagen interpretation, where it was combined with common views of different quantum physicists mostly gathered around Bohr’s Institute of Theoretical Physics in Copenhagen, Bohr’s interpretation lost its complexity and sharpness. As we have shown in section 3, both, Zeilinger from his antirealistic point of view and Timpson from his realistic point of view, understand Bohr as immaterialist and antirealist and interpret the statement famously attributed to Bohr by Petersen accordingly:

It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature. [24, p. 8]

Simplifying Bohr’s point of view, Zeilinger and Timpson both limit themselves on “Physics concerns what we can say”. For Timpson this reveals the problematic immaterialism:

If quantum mechanics reveals that the true subject matter of physics is what can be said, rather than how things are, then this seems very close to saying that what is fundamental is the play of information across our psyches. [6, p. 225]

In contrast, for Zeilinger it directly supports his understanding of quantum mechanics as only indirectly a science of reality and predominately a science of knowledge and thus of information [25]. However, such understandings of Bohr’s view are only possible, because the second part of his statement is disregarded: “Physics concerns what we can say *about nature*” [24, p.8] (our emphasis). Exceeding mere realism or antirealism, Bohr’s statement considers both the constraints, those coming from *the observer*–“what we can say”–and those coming from *the observed*–“about nature”. Thus, Bohr’s statement is not implying that “the true subject matter of physics is what can be said” [6] and neither that quantum mechanics is predominately a science of knowledge [25]. It implies that the task of physics cannot be to describe nature as such, nature as it is, but nature as given to *the observer* in the form of phenomena (the expression used by Bohr, see the comparison between Husserl’s and Bohr’s usage of the term phenomenon in [18]).

As a dialog within the philosophical consideration of quantum theories with informational foundations is limited on opposition between realism and antirealism, the comprehensiveness of Bohr’s position is lost. The approach taken in the present paper is not completely new in philosophy or even in philosophy of quantum mechanics, but it is completely new within quantum information theory: it connects a comprehensive philosophical approach exceeding mere realism and antirealism with understanding of the relationship between reality and information, solves philosophical problems of antirealistic quantum theories with informational foundations, helps to better define the nature of information and shows the limitness of the realistic critique of antirealistic approach within informational foundations of quantum theory. Furthermore, it reconnects philosophical thought outside mere philosophy of science with contemporary quantum mechanics and shows that such a connection can definitely benefit our understanding of the world around us. Half a century after the so called “shut up and calculate” era their dialogue should finally be renewed. We believe that our study can serve as a model of a successful connection between philosophical aspects and new knowledge emerging in the field of quantum mechanics.

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