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Simões, Eduardo

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# EINSTEIN'S LOCAL REALISM VS. BOHR'S INSTRUMENTAL ANTI-REALISM: THE DEBATE BETWEEN TWO TITANS IN THE QUANTUM THEORY ARENA

**Eduardo Simões**[1]
Universidade Federal do Tocantins (UFT)
https://orcid.org/0000-0001-7375-8574
E-mail: eduardosimoes@uft.edu.br

**ABSTRACT:**
The objective of this article is to demonstrate how the historical debate between materialism and idealism, in the field of Philosophy, extends, in new clothes, to the field of Quantum Physics characterized by realism and anti-realism. For this, we opted for a debate, also historical, between the realism of Albert Einstein, for whom reality exists regardless of the existence of the knowing subject, and Niels Bohr, for whom we do not have access to the ultimate reality of the matter, unless conditioning it to the existence of an observer endowed with rationality, position adopted in the Interpretation of Complementarity (1927) – posture that was expanded in 1935 when Bohr assumed a "relationalist" conception, according to which the quantum state is defined by the relationship between the quantum object and the entire measuring device. This is an extremely important debate, as it further consolidates the results of nascent Quantum Mechanics, guaranteeing Bohr the leadership of the orthodoxy based on the interpretation of complementarity. Here, when dealing with Quantum Theory, we will not make any distinction between the terms Quantum Physics, Quantum Theory or Quantum Mechanics. The entire discussion will be held under the name "Quantum Theory". Theory that tries to analyze and describe the behavior of physical systems of reduced dimensions, close to the sizes of molecules, atoms and subatomic particles. We hope that the reader will appreciate the genius of these two titans in this field of Physics when they magnificently formulate the arguments that support the object of their defenses.

**KEYWORDS**: Einstein; Bohr; Realism; Anti-realism; Quantum Mechanics.

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[1] Doutor em Filosofia pela Universidade Federal de São Carlos (UFSCAR), São Carlos – SP, Brasil. Professor da Universidade Federal do Tocantins (UFT), Palmas – TO, Brasil.

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## Introduction

The history of realism and anti-realism in twentieth-century Physics is, in fact, the unfolding of older discussions in Philosophy, which involve a debate between materialists and idealists about the nature of reality. Such discussions ended up promoting developments of other doctrines under the aegis of nomenclatures that defend different ideals, such as: naturalism, determinism, reductionism, positivism, empiricism, fideism, skepticism, sensualism, solipsism, agnosticism, etc. All of these doctrines are in some way involved with the question of the ultimate nature of reality and they compose the initial debate fostered by materialistic and idealistic schools of thought within the history of Philosophy.

In short, materialism defends the idea of recognizing the existence of the *objects themselves*, outside the mind, and those ideas and sensations are copies or reflections of these objects. On the other hand, idealism conceives reality as existing dependently on the human mind. Objects do not exist *outside the mind*, they are nothing more than *combinations of sensations*. It is noticeable, therefore, that for the idealist the absence of the conscious observer, who captures and reflects about reality, makes the existence of reality itself unfeasible.

On the philosophical field, the debate about materialism vs idealism goes back to disputes in Greek Antiquity that involve characters like Plato[2] and Epicurus and that deal with the question about the relationship between thinking and being or about that, which could be the originary: is it the nature or the spirit? As it was said, this issue had acquired philosophical relevance for centuries and from time to time, it reveals itself stronger in materialistic shades (Leucippus, Democritus, Epicurus, Lucretius, Mettrie, Holbach, Gassendi, Feuerbach, Marx, Engels, Lenin, etc.) sometimes in idealistic shades (Plato, Berkeley, Kant, Fichte, Schelling, Hegel, etc.). On the materialism of Epicurus, this, one way or another, shows the orthodox materialistic positions of Classical Physics. On the other hand, theories such as Quantum Mysticism and those that give emphasis to the subjectivity in the understanding of reality, they can also be linked to philosophical idealism when defending that the mind has an essential role in the constitution of reality. In Philosophy, who radicalizes this type of idea is the subjective idealism of George Berkeley (1685-1753).

Berkeley in his *Principles of Human Knowledge* (1710) and in *Three Dialogues* (1713) defends his immaterialism sustained in the denial of the reality of any object in the outside world that was not perceived by *the spirit* or *the mind*. For him, *to be is to be perceived (esse percipiti)*, that is, things only exist if, and while, someone perceives them. The starting point of his philosophy, however, is too well known: his ideal is the defense of religion against the threats of the atomist philosophy (Gassendi, Galileo, Basson and Bérigard) and against all ideas that could lead to materialism and skepticism. A corpuscular philosophy conflicts with religious principles, because if all events are determined by physical conditions, we are forced to assume a materialistic conception of the "human spirit". As a result, in the mind of Bishop Berkeley, it is necessary to destroy the skepticism provided by the new materialistic science, since its "truths" are totally incompatible with revealed religion. The philosopher says: "For as we have shown the doctrine

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[2] Most of Plato's philosophy interpreters agreed that their thinking defends a type of realism, namely, the "realism of ideas", because, according to them, the Platonic "idealism" refers to the Idea, to the *Eidos*, and not to the primacy of the mind as the ultimate foundation of reality and this reading seems to me correct. However, even so, I maintain the reading of Platonic thought, in agreement with Heisenberg, as being a type of idealism, idealism of pure forms. To this end, I take into account that "pure forms" or "mathematical entities" are not realities that exist independently of the mind, and are therefore real. In *Problems of Modern Physics*, when referring to symmetries as the "pure forms" of matter, Heisenberg calls this position "Platonic idealism" for conceiving the elementary particles of matter as expressions of formal principles of symmetry, which would be the *eidos* of matter. For him, modern physics would be closer to Platonic idealism than to Epicurus' materialistic atomism.

of matter or corporeal substance, to have been the main pillar and support of *skepticism*, so likewise upon the same foundation have been raised all the impious schemes of *atheism* and irreligion" (BERKELEY, 1996, § 92).

To summarize, what Berkeley's immaterialism defends is that things are a *set of ideas*. Objects do not exist outside the mind and reality is what we perceive, that is, *combinations of sensations*. According to Berkeley (1996, § 5), "the object and the sensation are the same thing, and cannot therefore be abstracted from each other". Space and all the things that exist in it (houses, mountains, rivers, valleys, trees, etc.) are themselves impossible, simple imaginations.

> [...] If the word *substance* be taken in a philosophic sense, for the support of accidents or qualities without the mind: then indeed I acknowledge that we take it away, if one may be said to take away that which never had any existence, not even in the imagination. (BERKELEY, 1996, § 37)

With this stance, Berkeley inaugurates the school of thought of dogmatic immaterialist idealism, whose reflections will present themselves, *with particular nuances*, in the philosophies of science by Ernst Mach, Richard Avenarius, Karl Pearson, P. Duhem and Henri Poincaré and, consequently, they will reflect on some interpretations of reality in 20th century Physics. On the other hand, philosophical materialism will present itself, in the form of scientific realism, in all strands of contemporary classical physics. It is our duty, however, to present what is expected with the use of the terms materialism and idealism for Physics of the 20th century, which, it is reinforced, is not a *literal translation* for the term realism and anti-realism. Much more than that, it is an appropriation of terms for the field of Physics as specific nuances that is very close to the original use in Philosophy.

What we present as materialism in Philosophy here will be translated into the field of Physics with the terminology of *realism*. We would therefore like to reinforce that if all materialism is realism, not all realism is materialism. That is why, in order not to get involved in the conceptual confusions of the esoteric taxonomy of realisms and anti-realisms promoted by the philosophy of physics, which would provide, for example, that the same thinker could very well be realistic in relation to "p, q, r" and anti-realist in relation to "x, y, z"[3], we will restrict our analysis only to what concerns the realism of entities or substances which involve the debate between Einstein and Bohr. To summarize, the underlying thesis is that everything that exists can be reduced to physical realities, such as matter, energy, entropy, fields, etc. In the limit, such conception is also fixed on the idea of the existence of objects themselves, which are real, and whose reality is independent of our mind. In this case, the epistemic subject can be eliminated and the reality will remain as it is. Ideas and sensations are copies or reflections of these objects. Such realistic approach cannot be confused with positivism, which is a different conception. Positivism, in scientific thinking, has as its fundamental task the positive description of natural phenomena from the data of experience. The positivist fixes himself on the observations, on the *positive data* obtained by the scientific instruments and declares as *metaphysical* any theory that recognizes the existence and the cognoscibility of objective reality based on non-observable premises. It should be noted, however, that, unlike positivism, scientific realism, in the context of discovery, can maintain a realistic perspective of non-observable entities.

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[33] "Heisenberg was an anti-materialist, that is, he denied the elementary particle of matter as the ultimate reality from which all things are made, and he assumed a deeper level of reality, of which matter would be the phenomenon. It is, therefore, against the ontology of substance realism that the philosopher physicist opposed. It assumes a nomological or unsubstantialized mathematical realism, but it denies the materialistic realism that postulates elementary particles as constituents of ultimate physical reality" (DA SILVA, BRANCO, 2019, p. 268).

We will replace, on the other hand, the term idealism with scientific *anti-realism*. Here, again, we reinforce that "unfolding" does not mean "identity". We are not claiming that anti-realism is a type of idealism. Even if it is accepted that the collapse of the wave function occurs due to the observer's mind, this does not mean that the observer is an idealist in the Berkeley sense who admits that there are no material objects and that *only the mind* (and the God) *is real*. In this type of anti-realism, however, two positions stand out: I) that there is no reality that is independent of mind; II) that the mind, the subject, has an essential role in the constitution of the world. Such postures are very common in physical theories in which mysticism takes over the theory, leaving margin for counterintuitive and overly strange assertions, such as those in which the mind plays an essential role in the developments of quantum phenomena. We will also circumscribe in the field of anti-realist theories, including some quantum orthodox theories, those that are based on the ideal that mathematical formalism should account for a supposed reality, but does not ensure that such equations relate to reality itself, that is, it does not assume the realistic perspective of non-observable entities. This type of anti-realist theory ends up working much more as a fabrication of reality, since formalism provides intelligibility and universality to the theory, but, in an *ad hoc* way, introduces additions that are impossible to test, which serve to solve what is evident as problematic. What is asked, however, is whether, in these cases, a research program when faced with some difficulties, or with some recalcitrant phenomena, should be abandoned? Alternatively, is it worth the creation of *ad hoc* elements for the maintenance of the program, even if they may not be able to account for the real phenomenon? Or if, in the end, an adjustment to the "protective belt"[4] would suffice, even against the reality, for physicists to "move on with life"?

In view of the purposes of this article, we will address two interpretative behaviors of Quantum Physics in the 20th century that fit under the label of realist and anti-realist, namely, those of Albert Einstein and Niels Bohr. Einstein is known for the realistic posture that he has always defended in his scientific career. He believed that the universe had its own existence and it was independent of the existence of the cognizant subject and, as a result, he did not allow passive acceptance of the uncertainties of Quantum Mechanics that, in his conception, represented symptoms that something was wrong with the theory and its interpretations. Bohr, on the other hand, believed that we have no access to the ultimate reality of matter except in a conceptualized way, therefore, there is no way to represent a reality independent of us - reality is conditioned to the existence of the observer endowed with rationality. The symptoms of Bohr's anti-realism, however, will appear in his interpretation of the complementarity, which became known as the Copenhagen interpretation and which became the target of Einstein's criticism. Such interpretation is part of what is known as the orthodox interpretation of Quantum Mechanics, which is broader than it, and whose defense Bohr was an astute debater. It is in the debate between these two titans and about their philosophical developments in their perspectives, that this article intends to be founded, presenting to the public of Philosophy how the versions of philosophical materialism and idealism extended to realistic and anti-realist features in the field of Quantum Theory.

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[4] Fundamental thesis by I. Lakatos where the protective belt refers to a series of auxiliary theories that protect the firm core and prohibit falsehood (negative heuristics) of the research program.

## 1. The Interpretation of complementarity of Niels Bohr

Two interpretations emerged in the years 1926 and 1927 that were compatible with each other in terms of describing quantum phenomena, but competing in popularity among physicists of that time. Heisenberg's matrix mechanics took a while to get popular and raised many controversies, since it was in a mathematical language that physicists were not used to. It explained very well discontinuous phenomena, with discrete movements of finite dimension, and asserted that it does not matter if it used a representation in terms of particles or a wave, since both provide the same experimental predictions. On the other hand, Schrödinger's wave mechanics which, precisely because it is wave-based - based on the notion of continuity, on the notion of gradual transition - it quickly got the sympathy among physicists because it was based on the use of differential equations, very common for them. Because it is similar to the classical fluid mechanics, the image was easily visible and suggestive. The central point that marks the difference between these two representations of physics and that required an answer - which occupied many years in Bohr's life - are the antinomies that exist between two equally experientiable, logical or coherent positions, but that come to diametrically opposite conclusions: continuity vs. discontinuity, causality vs. indeterminacy, locality vs. non-locality, action by contact vs. action at a distance (immediate action that violates the speed of light). It was precisely by trying to reconcile these antithetical positions that Bohr reached in his interpretation of complementarity, also called the Copenhagen interpretation.

It was in September of 1927, in Como, Italy, during the *International Physics Congress* held in commemoration of the centenary of Alessandro Volta's death (1745-1827), that Niels Bohr, for the first time, presented his formulation of the complementarity. Most of the founders of Quantum Theory were gathered, except for Einstein and Ehrenfest who would meet Bohr at the *5th Solvay Conference*, in Brussels, in the following month, where Bohr's lecture would be repeated. In a lecture entitled *The Quantum Postulate and the Recent Development of Atomic Theory*, Bohr gives a summary of the state of the art of Quantum Theory discussing about its contemporary problems: the uncertainty principle, the development of matrix mechanics, the wave mechanics, the problems of Schrödinger's interpretation, the stationary states of an atom and about the future perspectives of Quantum Theory.

Bohr deals with all themes, emphasizing the basic differences between the classical and quantum descriptions of physics: he discusses the discontinuity characteristic of quantum processes, which is unfamiliar to classical theories; he deals with the renunciation that the quantum postulate makes about the spatiotemporal coordination of atomic processes; he addresses the interaction between the observation agent and atomic phenomena; he expresses his anti-realism by stating that it makes no sense to attribute reality to the physical object independent of an observer: "(...) an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation" (BOHR, 1928, p. 580); he discusses the inherent irrationality in the quantum postulate when the possibility of cutting between the subject and the quantum object at any point in the chain that joins the two[5]; he discusses about a physical system that requires the elimination of all external disturbances, in this case, about the Schrödinger equation or other type of unitarity evolution that applies to closed systems; he also deals with the system in which there is an interaction with the measuring device, where a deterministic equation is not applied but a projection postulate: "(...) in order to make observation possible we permit certain interactions with suitable agencies of measurement,

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[5] Thesis of psychophysical parallelism that was formally developed later by von Neumann.

not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word" (BOHR, 1928, p. 580). Here Bohr introduces his first statement of complementarity:

> The very nature of the quantum theory thus forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively. (BOHR, 1928, p. 580)

It is a statement that involves Bohr's first type of complementarity between a pair of characteristics that are consistent in classical physics, namely, space-time coordination and causality - which in this quote should be understood as "determinism" - or between *observation* and *definition*. "Indeed, in the description of atomic phenomena, the quantum postulate presents us with the task of developing a 'complementarity' theory the consistency of which can be judged only by weighing the possibilities of definition and observation." (BOHR, 1928, p. 580).

> An isolated system preserves energy and momentum, and therefore it is possible to say that it satisfies the *causality*. However, as it cannot be observed, it is not possible to associate a spatial position and temporal instant to it. On the other hand, when observed, a system starts to have a *spatiotemporal coordination* (given by the result of the measurement), but its state (after the reduction) did not evolve from the previous state according to the law of causality (that is, in a determinist way). (PESSOA JR., 2019, p. 94)

Bohr later abandoned the first formulation of complementarity, since, for an anti-realist position such as his, this notion made a distinction between an atom while existing and the same atom while known, which did not make sense. "Only from a realistic point of view is possible to give meaning to this 1st type of complementarity" (PESSOA JR., 2019, p. 94).

Bohr presents a second type of complementarity and this one involves the question of *complementarity between particle and wave*. This type of complementarity occurs against the grain of classical physics in which wave and particle are mutually exclusive elements. Bohr says:

> The problem of the nature of the constituents of matter presents us with an analogous situation. The individuality of the elementary electrical corpuscles is forced upon us by general evidence. Nevertheless, recent experience, above all the discovery of the selective reflection of electrons from metal crystals, requires the use of the wave theory superposition principle in accordance with the original ideas of L. de Broglie. Just as in the case of light, we have consequently in the question of the nature of matter, so far as we adhere to classical concepts, to face an inevitable dilemma, which has to be regarded as the very expression of experimental evidence. In fact, here again we are not dealing with contradictory but with complementary pictures of the phenomena, which only together offer a natural generalization of the classical mode of description. (BOHR, 1928, p. 581)

In Bohr's opinion, the wave aspects (superposition principle in wave theory) and corpuscular aspects (energy conservation and momentum) of a quantum object, although mutually exclusive, are complementary. The definition by the wave or particle aspect will depend on the type of experiment carried out by the observer: if he opts for the double-slit experiment, for example, it will show the wave nature; if it is the photoelectric effect experiment, on the other hand, nature will become corpuscular. This duality constitutes an "exhaustive" description of the quantum object, because they exhaust their possibilities of description, that is, there would not be any way more complete of representing a quantum entity. What Bohr does is to associate the *wave aspect with the definition* (the wave function with the unobserved). Later, he will define the *wave phenomenon* in the scope of observation (when interference occurs), as the *corpuscular phenomenon* (when it is possible to infer trajectories) (PESSOA JR., 2007-11). What will be defined is that, for systems existing on the atomic scale, there is no predetermined value for physical quantities, it is the measurements that create reality.

The third type of *complementarity is the one among the incompatible observables*, as it is the case with position and movement. According to Bohr (BOHR, 1928, p. 581):

> The difficulties with which a causal space-time description is confronted in the quantum theory, and which have been the subject of repeated discussions, are now placed into the foreground by the recent development of the symbolic methods. An important contribution to the problem of a consistent application of these methods has been made lately by Heisenberg *(Zeitschr. f. Phys.*, 43, 172; 1927). In particular, he has stressed the peculiar reciprocal uncertainty which affects all measurements of atomic quantities. Before we enter upon his results it will be advantageous to show how the complementary nature of the description appearing in this uncertainty is unavoidable already in an analysis of the most elementary concepts employed in interpreting experience.

We saw that Heisenberg's uncertainty principle advocated the impossibility of accurate and concurrent knowledge of the position and amount of movement of a particle and, for Heisenberg, it is possible to use either the corpuscular or wave representation, since both provide the same experimental predictions. The third type of complementarity proposed by Bohr incorporated Heisenberg's physics into his own as a synonym for uncertainty. Here, complementarity occurs through the thesis that two conjugated quantities are complementary to each other in the sense that both are mutually exclusive, since the more precise determination of the value of one of them results in greater uncertainty with respect to the complementary quantity. Only according to the experiment, can we use either a corpuscular description, or a wave, but never both at the same time. According to Bohr, the use of a corpuscular or wave picture depends on the experiment in question and a "phenomenon" is the description of what must be observed and the equipment used to obtain the observation, since they are complementary. The dismemberment of representations is merely a sign of the fact that, in the normal language available to us to communicate the results of our experiments, it is only possible to express the unity of nature through a complementary model of description.

> What Bohr was pointing to in 1927 was the curious realization that in the atomic domain, the only way the observer (including his equipment) can be uninvolved is if he observes nothing at all. As soon as he sets up the observation tools on his workbench, the system he has chosen to put under observation and his measuring instruments for doing the job form one inseparable whole. Therefore, the results depend heavily on the apparatus. (HOLTON, 1970, p. 155)

In short, this notion of complementarity states that, in a sense, the unmeasured atom is not real: its attributes are created or defined in the act of measurement.

> When you ask, "What is light?" the answer is: the observer, his various pieces and types of equipment, his experiments, his theories and models of interpretation, and whatever it may be that fills an otherwise empty room when the lightbulb is allowed to keep on burning. All this, together, is light. (HOLTON, 1970, p. 156)

This type of interpretation is characteristic of a typical anti-realism professed by Bohr[6] and Heisenberg who maintain that the object has no existence that is independent of the subject who observes it. The case of light is a typical example of what is stated here: even if there are the room, the equipment - with its various parts and types -, theories, models and everything else that could fill the room, even so, without the existence of the subject who observes, which is complementary to everything else, the existence of the light object would definitely be compromised. Therefore, the philosophical developments of this notion of complementarity are directed in three ways: I) it professes a type of anti-realism where words like "particle" or "wave" do not designate anything about material objects or material properties of such objects, that is, they have no ontological *status*, they are only a description of certain experiments; II) it sacralizes the measuring instruments to the point that the act of observation and the figure of the observer become an integral part of the instrument itself, that is, it perverts the so-called scientific concept of dissociation between subject, object and scientific instruments, in addition to making measurement the alpha and the omega of knowledge, since there is nothing being observed besides observation itself; III) it compromises the notion of "scientific objectivity", since the foundation of scientific knowledge shifts from the protagonism of the "object" to that of the "subject". In fact, the obsolete distinction between subject and object is no longer valid in the view of the complementarists.

According to Schrödinger (1951, p. 154), what Bohr and Heisenberg "mean that recent discoveries in physics have pushed forward to the mysterious boundary between the *subject* and the *object*, which thereby has turned out not to be a sharp boundary at all". Bohr, on the other hand, reinforces his hope that "the idea of complementarity is suited to characterize the situation, which bears a deep-going analogy to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object" (BOHR, 1928, p. 590). However, the idea of complementarity, despite being the foundation for the orthodox line of Quantum Theory, has nonetheless been an object of criticism by many of its contemporaries, as well as by recent scholars.

> [...] One may say that the concept of complementarity introduced by Bohr into the interpretation of quantum theory has encouraged the physicists to use an ambiguous rather than an unambiguous language, to use the classical concepts in a somewhat vague manner hi conformity with the principle of uncertainty, to apply alternatively different classical concepts which would lead to contradictions if used simultaneously. (HEISENBERG, 1958, p. 179)

According to Bunge (2000, p. 237), when we look at the concept of complementarity, we see that it "is not a physical doctrine, but philosophical, because it does not refer to matter in motion, but to concepts and their verbalizations". It is precisely in positions like these that Einstein sustains his realism, not admitting the obscurantism underlying to some notions of Quantum Theory and opposing interpretations that demonstrate fragility in the use and application of terms. Bohr was his main debater.

## 2. The Einstein-Bohr debate on the fundamentals of Quantum Mechanics

To say that Einstein was an enemy of Quantum Mechanics is a huge mistake, because he was one of its founders. However, Einstein's realism did not agree with the uncertainties and anti-

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[6] In the case of Bohr, anti-realism has been followed by a positivist background for placing in the measuring instrument full confidence in deciphering of reality, that is, by sacralizing the measuring instruments.

realism of Quantum Mechanics and, precisely because of his set of classical beliefs, Einstein sometimes fought in the arena of Quantum Physics and Bohr was one of his main intellectual opponents.

The interpretation of complementarity proposed by Bohr argues that the act of measurement influences a quantum system that makes it adopt characteristics that are observed *a posteriori*. For example, the manifestation of light, either as a wave or as a particle, depends on what the experimentalist makes it to be. While it does not manifest itself as one thing or the other, it is as if it were in a kind of limbo. Until they are observed, quantum systems remain as if in a state of superposition, that is, in a mixture of all possible states.

Three moments mark the history of the debates between Einstein and Bohr regarding the truths of Quantum Mechanics: *the 5th Solvay Conference on Physics* in 1927; *the 6th Solvay Conference on Physics* in 1930; and the study published in 1935 that became known as the Einstein-Podolsky-Rosen paradox (EPR paradox).

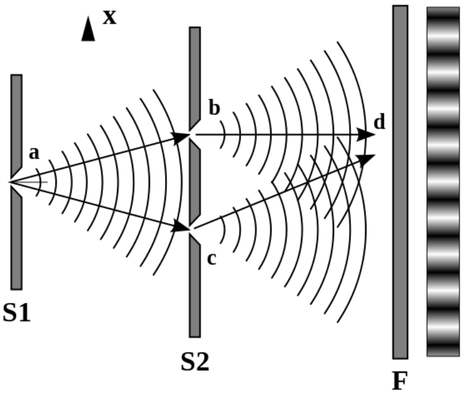
*The 5th Solvay Conference on Physics*, held in 1927 in Brussels, brought together the biggest names in physics of that time. The official photo of the event alone contained 19 Nobel Prizes (won before and after of Conference). The 5th Solvay Conference was dedicated to the theme "Electrons and Photons" and was marked by the big names who debated about the *status* of Quantum Mechanics, as well as by Einstein's struggle against the growing orthodoxy led by Bohr and embodied in the Copenhagen interpretation, whose fundamentals were based on the concept of complementarity developed by Bohr himself.

According to Brown (1981, p. 60), "before 1927, Einstein devoted considerable energy to an attempt to reconcile quantum conditions with the causal description of field theory, that is, with the use of differential equations for equations of motion". The attempt failed, but not Einstein's desire to base the Quantum Theory on a causal theoretical field language.

In April 1927, Einstein received a letter from Bohr containing a copy of Heisenberg's analysis of the uncertainty relations. The uncertainty principle forbade that a particle had the exact position and velocity values measured at the same time. Likewise, Bohr's principle of complementarity, based on the concept of uncertainty, prevented a wave phenomenon from confirming the claim that the detected *quantum* would follow a well-defined trajectory when passing through a well-determined slit and that "the operational limits imposed by relations ensure awareness of duality, because 'the different aspects of the problem never manifest simultaneously'" (BROWN, 1981, 60).

> Well, it is one of the two essential themes of Einstein's "opposition" that these "different aspects of the problem", meaning that, the spatiotemporal and causal considerations, should not be seen in Quantum Mechanics as necessarily incompatible with each other, as claimed Bohr (...). If Bohr were right, the causal theory program would be futile. Einstein's so-called attempt to "discredit" the new mechanics after 1927 was primarily motivated by this central consideration. (BROWN, 1981, 60)

We see that the classic theme of the causality and spatiotemporal relations was strong in Einstein and that quantum uncertainty was a permanent nuisance, since "God does not play dice" (*... ob der liebe Gott würfelt*). It was precisely to deny this notion that Einstein presented a thought experiment as a challenge to uncertainty and complementarity. Let us see the example of the slit experiment:



**Ref.**: aminoapps.com/c/tudo-sobre-ciencia

Here we saw that a quantum entity (a photon, for example) followed its path and was detected as a point at position *d*. Behind the detector screen *F* we have an interference pattern formed by the accumulation of thousands of these points. The question that remains is: through which slit did the particle went through?

> Bohr stated that his question did not have an answer. On this wave phenomenon (that is, one that exhibits interference fringes), it did not make sense to attribute trajectory to the detected quantum. It is not about ignorance: it is not that the quantum goes through one of the slits and we will never know which one. It is more than that! On the propagation, the quantum does not behave like a particle! It goes through both slits! (PESSOA JR., 2007-11, p. 34)

Furthermore, in an experiment in which at each moment one, and only one, of the slits *b* and *c* is open, it is known that the interference fringes are not obtained in *F*. The obvious conclusion of this is that, if the particles have defined trajectories that they cross a single slit, then the particle's behavior when crossing the slit in question would seem to depend on whether the other slit is open or closed! Bohr would call this conclusion "paradoxical" and avoided it through the complementarity thesis[7]. However, Einstein was not satisfied with this position and, as "paradoxical" as the physical implications were, he wanted to show the possibility of the approach. In a simple thought experiment, he suggested that *S2* would be *disconnected* from the rigid support, to allow it movement as a result of the particle colliding with the slits. To the particles that are recorded by *F* at non remote points from the axis of symmetry of the arrangement, an "upward" rebound by *S2* indicates that the particle came from *b* and a "downward" rebound by *S2* indicates that the particle came from *c*. In this way, the measurement would not cause any disturbance in the particle, but would give us the necessary information to determine through which slit it went. The interpretation of complementarity would be refuted!

During the Conference, Einstein usually came to breakfast at the hotel, where the participants of the conference were, with his objections; at dinner, Bohr communicated his answer. On that day, "poor Bohr must not have paid much attention to the official sections

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[7] Complementarity occurs, in this sense, through the thesis that two conjugated quantities are complementary to each other in the sense that both are mutually exclusive, since the more accurate determination of the value of one of them results in greater uncertainty regarding the complementary quantity. In terms of radiation, the wave and corpuscular aspects, for example, are not contradictory, but complementary. The definition by the wave or particle aspect will depend on the type of the experiment carried out by the observer: if he opts for the double slit experience, it will show the wave nature, however, if the experience is that of the photoelectric effect, nature will show up by corpuscular. For systems existing on the atomic scale there is no predetermined value for physical quantities, it is the measurements that create reality.

during the day" (BROWN, 1981, p. 61). In simple terms, Bohr considers *S2* - despite its macroscopic size - as a quantum object, also subject to uncertainty relations.

> The key to his answer was that the bulkhead (where the slits are) should be subject to the uncertainty principle. If this bulkhead was suspended in springs, in a way it was possible to measure its speed (upward or downward) after the passage of the quantum, then, by the uncertainty principle, its position would not be well-determined (the uncertainty principle says that the speed is well-defined and exact, the position will have to be ill-defined; or vice-versa). In other words, the position of the slits could not be controlled with exactitude. Even if we insisted that an interference pattern would form, such pattern would dislocate (upward or downward) each new quantum (since, according to the uncertainty principle applied to the bulkhead, the position of the slits would be different each new quantum). Therefore, it is like these interference patterns would be trembled, blurring the result that is visible on screen, after thousands of quanta pass through the system. According to Bohr's relatively simple calculations, the uncertainty in the position of the slits would be sufficient to blur the interference pattern completely. That is, even this idea of Einstein, of measuring the momentum (or speed) of the bulkhead after the detection of the quantum, would end up eliminating the interference fringes. We would know the trajectories, but we would lose the wave fringes. Exactly as required by the complementarity principle of the Danish physicist. (PESSOA JR., 2007-11, p. 35)

Thus, it can be seen that the uncertainty relations are an integral part of the "quantum conspiracy" - because, to obtain the fringes, the measurement of location cannot be carried out - and reinforce the complementarity, making Bohr the winner in this debate, which contributed much for the acceptance of the Copenhagen interpretation.

The Einstein-Bohr debate took on other dimensions at the *6th Solvay Conference on Physics* in 1930. Once again, Einstein and the representatives of the Copenhagen line of thought engaged in discussions on the fundamentals of Quantum Mechanics. This time, the discussion involved the uncertainty principle for energy and mass, "in particular, the general relationship between energy and mass, expressed in Einstein's famous formula $E = mc^2$ should allow, by means of simple weighing, to measure the total energy of any system and, thus, in principle to control the energy transferred to it when it interacts with an atomic object" (BOHR, 1949, p. 225).

For his realistic thesis, Einstein used the photon in a box experiment. It is a thought experiment that Einstein tried, through the relativistic consideration of the relation between energy and mass, to show how to prepare a set of photons whose energy and time of arrival are simultaneously fixed.

> As an arrangement suited for such purpose, Einstein proposed the device (...), consisting of a box with a hole in its side, which could be opened or closed by a shutter moved by means of a clock-work within the box. If, in the beginning, the box contained a certain amount of radiation and the clock was set to open the shutter for a very short interval at a chosen time, it could be achieved that a single photon was released through the hole at a moment known with as great accuracy as desired. Moreover, it would apparently also be possible, by weighing the whole box before and after this event, to measure the energy of the photon with any accuracy wanted, in definite contradiction to the reciprocal indeterminacy of time and energy quantities in quantum mechanics. (BOHR, 1949, p. 225-226)

If Einstein's experiment is consistent, it indicates that Heisenberg's energy-time relationship is inconsistent!

Einstein did not expect, however, that Bohr would get an answer to his provocation and, this time, using Einstein's own General Theory of Relativity. According to Bohr, "Einstein's

General Theory of Relativity indicates that there is an indeterminacy at the instant of the photon production in the arrangement, which is directly linked to the indeterminacy in the measure of energy. And the product of these indeterminations is consistent with the Heisenberg's relation!" (BROWN, 1981, p. 68). Thus, the debate seemed to be closed for good. However, the anxiety that always accompanied Einstein when facing his inherent problems in explaining reality would make him take another step, this time, with the presentation of an article published in 1935, with his colleagues Boris Podolsky and Nathan Rosen.

With the title *Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?* Einstein, Podolsky and Rosen's article (known as EPR), published on the *Physical Review* (1935), became bombastic by questioning the orthodox postulate according to which "*when the momentum of a particle is known, its coordinate has no physical reality*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 778). According to Leon Rosenfeld, a friend of Bohr, "this onslaught came down upon us as a bolt from the blue" (ROSENFELD, 1967 *apud* WHEELER; ZUREK, 1983, p. 142).

As it is well known, the realistic attitude of Einstein, who believed that the universe has its own existence, did not allow passive acceptance of the uncertainties of Quantum Mechanics that, in his conception, represented symptoms that something was wrong with the theory and with its interpretation. According to Herbert (1985, p. 201), Einstein argued that "the belief in an external world independent of the perceiving subject is the basis of all-natural science". On the other hand, Bohr "responded by comparing Einstein to the critics of his own relativity theory. He pointed out that thanks to Einstein's work, physicists have come to realize that space and time are not absolute but relative to an observer's state of motion". It should be noted, however, that, in Einstein's view, the problem was not with the correction of the theory[8], since it is resolved that the formalism of Quantum Mechanics is correct and that the statements underlying this formalism are consistent. What bothered Einstein - and this we have seen since the 1927 debate - was the question of the completeness of Quantum Theory, object of EPR questioning in the article in question.

> EPR do not contest quantum theory's competence to describe phenomena; Einstein, Podolsky, and Rosen claim, however, to have demonstrated the existence of certain "elements of reality" (in Einstein's words), parts of the world *not directly observable* which quantum theory simply leaves out. (HERBERT, 1985, p. 209-210)

For the authors, the *completeness condition* of a theory presupposes that "*every element of the physical reality must have a counterpart in the physical theory*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 777). That is, there must be a correspondence between physical theory and objective reality in order to build a complete picture of the reality in question. In addition, the *criterion of reality* says that: "*If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding lo this physical quantity*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 777). The condition is necessary, but it is not enough to determine the completeness of a physical theory, since, by itself, it does not guarantee that the theory is complete in fact, for example, "two different elements of reality could have the *same* counterpart in a physical theory, so that the theory would not be complete, despite satisfying **C**[9]. The **C** condition also allows the theory to postulate non-existent entities" (PESSOA JR., 2019, p. 206). Copenhagen's interpretation of

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[8] "The correctness of a theory is judged by the degree of agreement between its conclusions and human experience" (EINSTEIN; PODOLSKY; ROSEN, 1891, p. 90).

[9] **C** = *completeness*, in the words of Pessoa Jr.

Quantum Mechanics, therefore, would be a correct interpretation in its formalism, but incomplete. This is what the EPR paradox tries to demonstrate.

The EPR argument is based on the attempt to deny the completeness of Quantum Mechanics through the notion of correlated systems. We saw that in Quantum Theory the superposition of quantum states was seen as real: until a quantum system was measured, it remained in a state of superposition of all states. This points to the requirement of the correlation between the quantum system and the observer, since the existence of the quantum system (its exit from limbo) depends on the observer who proceeds to the measurement. As the observer measures a particle, the probabilities of the wave function of both particles collapse to consolidate the result. The wave function of the second particle collapses at exactly the same moment as the other, no matter how far apart the particles are. It was this type of conception that bothered Einstein's realism that he complained with assertions that "he could not imagine that a mouse could change the universe drastically simply by looking at it" (HERBERT, 1985, p. 174).

As it is conceived in Quantum Mechanics, this wave function collapse occurs instantly, at a distance and non-locally way. This suggests that the information of what was measured in $A$ was transmitted instantly to $B$. Therefore, the question that remains is: would this type of action at a distance be possible, which causes two particles to interact instantly and non-locally, even though these particles are thousands of kilometers apart from each other? If such "entanglement", in Schrödinger's language, is possible, the notion that no signal carrying information can be sent faster than the speed of light (300 thousand km/s) falls apart.

EPR introduced a *locality* hypothesis in which it would be *impossible* for the measurement of a particle at one point $A$ to have instantaneous reflections on another particle, at another point $B$, with a speed greater than the speed of light. "(...) Since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 779). That is, if we decide to measure $A$'s position, we would find that $B$ has a well-defined position and if we measure $A$'s speed, we would find that $B$ also has a well-defined speed. As the particles are separated by a great distance, the measurement in $A$ cannot influence the position and speed values of particle $B$. In other words, $B$ should initially have a well-defined position and speed at the same time. "The two particles in the imaginary experiment must already know what states they are in when they separate, he said. They carry this knowledge with them, instead of changing states simultaneously over remote distances" (BAKER, 2015, p. 78). Thus, EPR instituted a paradoxical situation of the existence of two contradictory notions: *locality* vs. *non-locality* - the first was admitted by most physicists of that time and the second was then embedded in the formalism of Quantum Mechanics. With the paradox in place, it was not difficult for EPR to present arguments that concluded that, by virtue of what has been demonstrated, Quantum Mechanics is incomplete.

> Let us go over the argument with a little more detail. On Earth, I *can* measure an observable $A_1$, and with that the state of particle nº 2 would reduce itself to a self-state of $A_2$. However, on Earth, I also *could* measure an observable $B_1$ that is incompatible with $A_1$ (in other words, whose associated operators do not commute), and so on the Moon the state of particle nº 2 would reduce to a self-state of $B_2$ (that is compatible with $A_2$). Now, check this: by the hypothesis of *locality*, nothing I do on Earth can instantly affect (or a speed bigger than the light) the *reality* on the Moon. But as I can measure both $A_1$ and $B_1$, on Earth, so both an $A_2$ self-state or a $B_2$ self-state have a simultaneous reality on the Moon, contrary to what Quantum Mechanics says (since $A_2$ and $B_2$ are incompatible). Thus, it would not be able to handle all the details of reality, it would be *incomplete.* (PESSOA JR., 2019, p. 205-206)

The EPR conclusion spells out an argument in a disjunctive form that is easy to analyze[10]. It is, in fact, an "exclusive disjunction", involved in the following premises of the authors: "Previously we proved that **either** (1) the quantum-mechanical description of reality given by the wave function is not complete **or** (2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 780 – emphasis added). The truth table of an exclusive disjunction involving the premises (1) and (2) of the EPR conclusion, in propositional logic, is as follows:

| 1 | 2 | 1 ∨ 2 |
|---|---|---|
| T | T | F |
| F | T | T |
| T | F | T |
| F | F | F |

This means that:

a) Because it is an exclusive disjunction, it is impossible for (1) and (2) to be true (T) at the same time, hence the result of the operation of disjunction will be false (check the first line of the table). This means that, if it is true (T) that "(1) the quantum-mechanical description of reality given by the wave function is not complete", then the proposition "(2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality" cannot be true;
b) The propositions are mutually exclusive. This means that, because they are exclusive, affirming one of them presupposes denying the other. Thus, if it is true (T) that "(1) the quantum-mechanical description of reality given by the wave function is not complete", then, it is false (F) that "(2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality" or vice versa - or one thing, or the other, but not both - this is evidenced in the second and third lines of the table;
c) Finally, the negation of (1) implies the negation of (2), which forces EPR to state that (1) is true (T):

> Starting then with the assumption that the wave function does give a complete description of the physical reality, we arrived at the conclusion that two physical quantities, with noncommuting operators, can have simultaneous reality. Thus, the negation of (1) leads to the negation of the only other alternative (2). We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete. (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 780)

It is an interesting logical formulation, but it ends up revealing Einstein's discomfort with the intelligibility of this type of quantum entanglement. For him, as a convict realist, it was difficult to imagine the universe wrapped in a web of quantum connections, with an unknown number of particles communicating with its distant twins. Even so, for many, EPR would have been wrong: according to some, due to the defense of the principle of locality; according to others,

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[10] Contrary to the amount of logical analysis, using classical (natural deduction proof) and non-classical (modal logic) analyzes, which have been presented as "deciphering" the EPR argument, which, many times, due to the degree of complexity in the understanding, it is preferable to read the original authors' own article (see, for example, McGRATH, 1978).

due to their defense of the realistic position of the existence of reality independent of measurement. "As soon as the paper was published, he [Einstein] received quite a number of letters from physicists 'eagerly pointing out to him just where the argument was wrong. What amused Einstein was that, while all the scientists were quite positive that the argument was wrong, they all gave different reasons for their belief!'" (JAMMER, 1974, p. 187).

Despite the comments, criticisms and refutations to the EPR paradox, no answer was given shortly after the publication of the work. Everyone expected a manifestation from the father of the Copenhagen interpretation and that happened five months after the EPR article, when Niels Bohr published his response to the paradox, with the same title as the EPR article, and in the same journal where it was published. Much of Bohr's response is a reiteration of what he had already presented in response to Einstein's provocation in 1927 – "the trend of the argumentation was in substance the same as that exposed in the foregoing pages (...)" (BOHR, 1949, p. 232). Thus, there were no surprises, since Bohr's strategy was to question the reality criterion of EPR. Bohr argues, therefore, that the EPR's criterion reality criterion contains an ambiguity that makes it inapplicable in the considered case, since a physical influence *from the measurement* of one particle to the other particle *is excluded*. According to the Danish physicist, it is impossible for a quantum entity to have a property without being measured, that is, such property does not exist, it is not hidden waiting for a measuring device or any interference from the observer. Thus, "from our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by Einstein, Podolsky and Rosen contains an ambiguity as regards the meaning of the expression 'without in any way disturbing a system'" (BOHR, 1935, p. 700).

We saw that the expression "without in any way disturbing a system" had been used by EPR (1935, p. 777). Bohr considered, however, that the choice of measuring $A$ or $B$ constituted an influence on the very conditions that define the "phenomenon", since different experimental arrangements would have to be used (PESSOA JR., 2019). Something that had already been anticipated by EPR when they claimed that "indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality only *when they can be simultaneously measured or predicted*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 780).

According to Pessoa Jr. (2019), Bohr would not, indeed, reject the "element of reality" of EPR, but the locality notion itself through a notion of totality of the phenomenon. However, "by ruling out a 'mechanical disturbance', Bohr seems to accept the principle of locality **LOC,** but soon after he states that the 'definition' itself of the system compound of two particles depends on the choice made by the experimentalist in relation to one of the particles, which is a way to reaffirm the *non-locality* character of Quantum Mechanics" (PESSOA JR., 2019, p. 212).

It is certain that, as Bohr himself said, "the discussions with Einstein which have formed the theme of this article have extended over many years which have witnessed great progress in the field of atomic physics. Whether our actual meetings have been of short or long duration, they have always left a deep and lasting impression on my mind (...)" (BOHR, 1949, p. 240). The impasse, however, was broken by the theoretical physical efforts of John Bell, in 1964, who created a test with which he *rejected* all models of reality with the property of locality. But this will be the subject of an upcoming article.

## Final Considerations

We saw that Bohr's interpretation of complementarity, in the early days of Quantum Mechanics, altered the development of atomic theory, since, unlike Heisenberg and Schrödinger's theories, his interpretation proposed the inclusion of the observer in the description of reality itself, which led physics to add a pragmatic dimension to the image of scientific knowledge. Therefore, form and content became fundamental factors in the anti-realist critique of atomic theories, because, in explaining the question of how individuality appeared in objects composed of non-individual elements, it was necessary to clarify the boundaries that delimited the difference between form and configuration. What is seen, in this context, is that there is a flagrant bias towards anti-realism among many of those who dialogue with Quantum Physics. For them, dealing with electronic orbits, material waves, charge densities, energy and linear momentum or the elementary particles that make up the atom is to deal with theoretical terms that occur in accepted scientific theories, but that do not refer to real entities (FRAASSEN, 1980). It is clear that most physicists of the 20th century stood out for the experimental character of the theory, which forced them to constant laboratory work. However, within the theoretical work, the dependence on the inclusion of *ad hoc* elements in the "explanation of reality" is also guaranteed, based on the creation of models that seek to adequately anticipate this same reality. This is the case, for example, of the principle of complementarity between subject, measuring device and object in Niels Bohr's theory that, even though it is labeled positivist (PESSOA JR., 2001), it is a view that does not fit with reality material, therefore, of a pure anti-realism. It was precisely a position against the type of conception that was proposed to deal with this article and Einstein is, for us, the main representative of the realistic posture[11] willing to face any anti-realism. His great productions in Theoretical Physics, which include works on General and Special Relativity, the Brownian motion, the photoelectric effect, the mass-energy equivalence, the field equations, the Bose-Einstein statistics and the EPR paradox, demonstrate the realist character of his work, which contributes to his vision becoming a "thorn in one's side" for the orthodoxy of Quantum Theory. If his advances are correct and if it is possible to admit, without realism being considered naive, that there is a reality independent of the mind, that only Physics can answer.

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[11] For other representatives of realism in Quantum Theory, see: De Broglie, David Bohm, John Bell, Taketani, Jordan, Zeh, Cramer, Everett, Zurek, Giraldhi and Landé.

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**Autor(a) para correspondência / Corresponding author:** Eduardo Simões. Avenida NS 15, Quadra 109 Norte, Sala 32 B, Bloco II, Campus de Palmas. Plano Diretor Norte, 77001-090, Palmas – TO, Brasil. eduardosimoes@uft.edu.br