Quantum Physics: Ontology or Epistemology?

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The year 2005 was declared by the United Nations General Assembly as the "World Year of Physics" in celebration of the centenary of Albert Einstein's *annus mirabilis*, his miraculous year of 1905. Einstein had published five groundbreaking papers in this year, including his theory of relativity and the most famous equation in physics: $E = mc^2$.

The first paper to be published that year, "Über einen die Erzeugung und Verwandlung des Lichts betreffenden heuristischen Gesichtspunkt" ("On a Heuristic Viewpoint Concerning the Production and Transformation of Light"), was concerned with Einstein's proposal that light consists of quanta. Although the title conveys a tone of cautiousness, the content itself was bold, suggesting that real light particles existed, moving around and behaving in a manner similar to that of gas particles. It is apparent that Einstein did have some insight into the revolutionary nature of the papers. In correspondence with his friend Habicht, in the same year the papers were published, Einstein wrote in anticipation of their very important nature, referring to the first paper as "truly revolutionary." It has been suggested that this is the only paper Einstein ever called revolutionary, and it therefore seems fitting that it is for this work that he received the Nobel Prize, rather than for his theory of relativity.

Einstein's particles of light are today called photons, coined by the American chemist Gilbert N. Lewis. It has become commonplace in many laboratories around the world to experiment with individual photons and with many different kinds of more complex varieties of photon states. It is unsurprising, therefore, that the concept of photons has been experimentally verified with extremely high precision.

Regardless of this level of experimentation and precision, a unique discussion within the history of science continues to this day, and can be simply reduced to the question of "What is light?"—a question that even Einstein was unable to unravel within his lifetime. In a deeper sense the question is concerned with how quantum mechanics should be interpreted; this is a contentious issue and one on which there is still an ongoing debate.

We should remark here that, like most physical theories, there are at least two levels of interpretation of quantum mechanics. The first, lower level of interpretation deals with the question of how the constituent parts of a theory translate into experimental observation. This is by no means a simple and obvious question. On the contrary, relating a mathematical theory to experimentation at best involves large sets of explicit and implicit (although sometimes implicit alone) assumptions, agreements, procedures, and rules, concerning what an experimenter must do to establish a link between observations and theoretical prediction. For example, the simple symbol x usually refers to position. For the experimenter, it is not enough to realize that an object sits at position x; he/she must also ensure that measurements are made of that position. This requires at least two factors. First, a definition of scale is needed, and second, the position of the object can only be defined relative to positions of other objects. The definition scale for distance, as it is currently understood, is directly connected to the definition of time, since distances are only defined through time and the velocity of light. More interesting in terms of the present discussion, however, is the second observation: that any given position is only defined in *relation* to the position of other objects in the universe. Following this line of reasoning, position per se does not make any sense at all. In fact, this can be taken even further; making the assumption that a single object existing in an otherwise empty universe has a position, is a concept devoid of meaning. One consequence of this, according to Mach's principle, is that all dynamics must be explicable in terms of the relative positions of objects and any changes to these relative positions. For example, when a pail full of water is rotated the centrifugal force observed is the result of the pail moving relative to the fixed stars. To return to the interpretation of quantum mechanics, while there are certainly complicated rules on this lower level, there also appears to be general agreement among physicists about what the symbols of quantum mechanics mean. Ultimately, the quantum state gives the probability of observing a certain predicted result, where the registered result is simply some property of the classical apparatus used.

Beyond this primary level of interpretation there is a secondary level, which might be called a metalevel. On this level, it is not satisfactory merely to connect the constituent parts of our theory with the results obtained from observation. Rather, we want to understand what the meaning of the theory is: what it tells us about the inner structure of the world, our position in the world, and whether we play any significant role in it. It is clear that within the twentieth century some of these questions have been considered as unanswerable and have therefore fallen into neglect, but that is not to say that humanity has ceased to ask deep questions about meaning and its role in the universe.

For most participants in the debate, this interpretational question does not represent a criticism of quantum physics. Such a position would be rather difficult to maintain in view of the immense accuracy of quantum mechanics. The debate, however, focuses essentially on questions about the deeper meaning of the theory, specifically, the consequences that quantum theory has on our worldview.

An alternative stance would be to take the view that, at present, the conceptual foundations of quantum mechanics have not been settled. This does not imply that the mathematical axioms normally put forward are incorrect. Rather, it raises the question of the exact nature of the general underlying physical principles upon which quantum theory is built. Such underlying principles are known to form the foundations both of special and of general relativity theory; namely the relativity principle stating that all laws of physics must be the same for all inertial observers, and the equivalence principle of general relativity theory.

This chapter suggests that the foundational debate in quantum physics might gain new momentum by having its basis in real experimentation. While gedanken experiments have been very instrumental to the early debate, many of the community at large today fail to notice the incredible detail in which it is possible to perform experiments with individual quantum systems. These experiments have not only confirmed all predictions of quantum mechanics, but they have opened doors for new technologies — for example, new quantum information technology, including concepts like quantum teleportation and the quantum computer.

The nature of the reality to which quantum mechanics refers is one question that must be addressed, and to which a broad spectrum of responses have been given. At one end of this spectrum lies the assumption that quantum physics refers to a reality whose existence is independent, prior to observation of any of its observed aspects. This position, for example, was upheld by Albert Einstein. It is found in its most succinct formulation in the desideratum expressed in the celebrated Einstein-Podolsky-Rosen paper; namely, that every element of physical reality must have a counterpart in a complete physical theory. Exploring the EPR-definition of elements of reality led to the development of theorems by John Bell as well as Kochen and Specker, asserting that the assumption of the existence of such elements of reality, independent of observation, is in contradiction to quantum mechanics.

At the other end of the spectrum is the position held by Niels Bohr, according to which the equations of quantum physics do not describe reality *per se,* but only what we can know about the world. According to this position, the concern of quantum mechanics is epistemological. The ontological question then arises: What is the object of this epistemology? What is *it* that we know something about?

It is interesting to note that in some recent experiments using quantum entanglement in general, but particularly in those specifically concerned with quantum teleportation, these questions have had direct experimental relevance. For example, why is it that systems can perfectly correlate with each other over large distances, yet it is wrong to assume that this correlation is due to the individual properties of the system?

We shall briefly discuss the situation of entanglement using a rather simple futuristic "example." Consider a pair of entangled "quantum dice." These quantum dice, which might become a favorite Christmas present for children at some time far in the future, behave as follows: If we throw the two dice, they will always show the same number. Unpack the next pair of dice, throw them — again they will each show the same number. This number might vary from one pair of dice to the next, but for each pair, the first throw always specifies what that number will be.

Next, we might ask ourselves if this magic connection, which Albert Einstein calls "spooky," continues to exist over large distances. To investigate this, we might take our pair of dice, throw one here and the other at some far-off distance. We will find that we observe the same result: the two dice continue to show the same number. There are various possibilities to explain why this happens. One way might be to assume that the pair of dice are loaded so that they have some internal property that determines what number will appear when they are thrown. This explanation can be easily excluded by throwing the same pair of dice more than once. We might find that each one independently shows a random sequence of numbers, but that the number is always the same for both dice on the first throw.

Another possibility would be to assume that the two pairs of dice somehow manage to "talk" to each other when they are thrown. In other words, perhaps there is transfer of information from A to B, whereby the behavior of one die is influenced by the behavior of the other. Any information transfer from one die to the other can be ruled out as an explanation because the two dice instantly "know" to show the same face on the first throw.

The idea that each die has its own internal properties, and that B can only be influenced by the state of A if there is a transfer of information from A to B maximally at the speed of light, is called local realism. It is a very interesting consequence of twentieth-century physics that we now know that such a worldview is not tenable. It has been shown by John Bell that predictions of local realism contradict the predictions of quantum mechanics for certain experiments on entangled particles. Increasing experimental evidence clearly confirms the predictions of quantum mechanics and thus disproves local realism.

It is now important to address what this means from a conceptual viewpoint. A simple consequence is that we cannot assume that entangled particles possess their individual properties before they are measured. When one particle is measured, it assumes a given property in a random manner. In the case of the dice, the die randomly decides "which number to show," and the same holds for the second particle; it also randomly decides "which number to show." Both dice, however, show the same result, which begs the question, "How can two random events give the same result without there being any connection between them?" This mystery is the reason why Erwin Schrödinger called entanglement *the* essential feature of quantum mechanics, the issue that forces us to abandon all our cherished views about how the world works.

From a more in-depth perspective, we notice something remarkable here. While the properties of the individual system (for example, the number that a die will show) are completely undefined, and the observed result is random in an absolute way, the relation between the two sides is fully defined. They both have to show the same result. *Therefore, it is impossible to build an ontology of the individuals, but it is possible to build an ontology of relations.* The relation between two objects is well defined and can be predicted with certainty. That is, we can predict with certainty that the two dice will show the same number, even though the properties of the individuals are completely undefined. We therefore conclude that one consequence of entanglement is that relations are more important than individuals.

In quantum teleportation, very deep philosophical issues have been raised concerning what constitutes the identity of a system. In such experiments the quantum state, which is the representation of all information carried by a system, is transferred completely from one system to another. This is not copying, however, because the original loses its individual characteristics. The question arises: Is the new system the original or not? Let us briefly analyze again what has happened. The original has lost all its properties, and a new original has come into existence that has exactly the same properties as the first.

In teleportation, matter is not transferred; it is only the features, the information carried by a system, that are. The original system becomes a system without properties (something never encountered in everyday life or in classical physics) and the new system becomes identical to the original. It turns out that the question of identity cannot be answered from an ontological point of view without making additional assumptions, which might be unwarranted in a quantum context. If one adopts an operational approach, however, then the answer has to be a positive one because no possible operation can distinguish the new original from the old. Such an approach seems to suggest that a criterion of operational decidability is important for the concept of identity.

Most interestingly, in some experiments one can have individual quantum events (registrations of individual particles), which can be brought about at some earlier time but whose meaning is disclosed later — not only is this disclosed at a later time, but the experimenter also has the choice to define later their meaning. For example, a later measurement can decide whether the data on the system already observed can be understood as implying entanglement with another system or not. Again, these experiments tell us that there is no meaning attached to individuals. The result from the individual measurement previously obtained has no meaning in itself; it cannot be understood on its own. The only way to understand it is in *relation* to other events that will happen in the *future.* We note that actually there might be a long chain from past to future where meaning may slowly be built up.

This means that we are faced with a very interesting situation. While the events themselves exist with no need of interpretation, the connections between them and the meaning that we give them are not absolute but depend on the acts of the observer. Furthermore, the individual events in quantum physics are random in an irreducible way. This objective randomness is probably the strongest indication there is a world existing independently to us.

The quantum state gives us probabilities of future events. In my view, however, it would be going too far to assume that it describes reality directly. Rather, it is the representation of our knowledge of the situation that allows us to make predictions about the probability of future events. To assume that the quantum state describes anything like reality between these events is not necessary, and appealing to Ockham's razor is one way to suggest its redundancy.

It immediately follows that if one assumes that the quantum state is simply a device to yield probabilities of future events, then all the well-known puzzles and paradoxes of quantum physics disappear. The photon does not go through both slits at the same time in a double-slit experiment; it is just the objective observer's independent lack of information regarding which slit the photon passes through that makes the interference pattern possible. Schrödinger's cat is not both alive and dead at the same time.

Such a position should not be confused with the assumption that reality does not exist unless it is observed. It suffices to say that quantum physics does not make any statements about an unobserved reality. It simply tells us what we can know should we decide to perform a certain experiment.

It should also be noted that the experimenter plays a very important role in quantum physics that goes beyond that of classical physics. This new role is related to the notion of quantum complementarity; that two (or more) concepts may be mutually exclusive. For position and momentum this is expressed quantitatively in the Heisenberg uncertainty relations. The important point here is that the experimenter has a choice of which quantity to measure, position or momentum. Once the choice is made, for example a measurement of position, that quantity will be what emerges as a result of conducting the experiment. The other quantity, momentum, is not only unknown, but the quantum system does not possess a definite value for that quantity. It is the choice of experimental setup, therefore, that determines which physical quality becomes reality. This means that the nature of existing reality is not independent of human action, yet the answer Nature gives us as the result of the individual measurement is random. The result is beyond our control, which indicates an independent physical reality.

In conclusion, it is argued that one should adopt a middle ground that is neither purely ontological nor purely epistemological. Instead, quantum physics may suggest to us that a separation between reality and information, between existing and being known, and in other words between ontology and epistemology, should be abandoned. What are the practical implications of this view? It is important to bear in mind that, when considering what existence might mean, we are simply reflecting on the information we have gathered so far about what exists. Our knowledge that we have acquired of the experimental results is what we are really talking about. Being, therefore, without also being known, makes no sense at all.

In a similar manner to Berkeley's "esse est percipi," information itself is a concept that has no meaning unless it refers to something else. Information always refers to existence and, therefore, always has a referent. In physics we have learned to abandon distinctions that cannot be operationally verified. For example, a huge progression within the discipline occurred when Newton realized that the distinction between the motion of heavenly bodies and the motion of objects on Earth had to be abandoned. He proposed that the same law of gravity governs the motion of planets around the sun, as it governs the motion of an apple falling from a tree. The history of physics is full of such unifications. What we are discussing here is something very similar. We propose that the distinction between reality and information should be abandoned, and that the two concepts should be considered as two sides of the same coin. From that point of view, it does not make sense to make an ontological statement without at the same time admitting that one speaks only about information. Information in this sense stands in relation to the observer — the person who takes note of the information and has the potential to take action as a consequence of it.

If the position outlined above is correct, then ultimately what can be said about the world must define or at least restrict what can exist. Thus, one might gain some understanding of the physics used in making a careful analysis, and in doing so realize what it means to make statements about the world. If we accept such a position, we immediately realize that there are certain inherent structures that follow. For example, we can make one, two, or three statements about the world, but not 1.3 statements. Making statements, therefore, is a quantized procedure by its nature. Furthermore, it has been suggested that the principle of quantization in physics follows from the fact that information itself is quantized.

The ideas outlined in this chapter also have practical implications, and they have been actualized in an interesting research program. In the group for which I work, it has been possible to generate a new understanding of entanglement in this manner, to give a reason for the randomness of individual events using this principle, and also to understand quantum complementarity in a more fundamental way. In summary, quantum physics, from the point of view outlined within this paper, is both a science of information and also a science of what can exist, because of the impossibility of separating epistemology and ontology.

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