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New Interpretations of Quantum Mechanics and the Theory of Knowledge

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Abstract

After recalling some features of two well-known theories of knowledge (by Wittgenstein and Bohr), one describes briefly a new interpretation of quantum mechanics, by so-called consistent histories, which has been developed by Gell-Mann, Griffiths, Hartle, Zurek and the author. Although it agrees in most practical cases with Bohr's predictions, it leads to significantly different epistemic consequences. This is shown in two steps. The first one is by now firmly established and it consists in a new theory of knowledge, the main features of which are described. The second step is more speculative, depending upon the answer to be given to the so-called "objectification" problem. It suggests a limit to Husserl's "Cartesian programme" and the consideration of new forms of realism.

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About theories of knowledge

The debate about foundations we are trying to pursue together has two levels, as far as I understand it. The basic one is a theory of knowledge specifying how the "world" we are investigating is defined. Then comes a philosophy of knowledge investigating and exploiting this definition. Both of them can be considered as applying to a specific domain of knowledge, as for instance physics, mathematics or philosophy, though philosophy offers two different aspects when it is either taken as a specific subject by itself or as a synthesis of various special fields, which may be a metaconstruction over physics, mathematics and whatever else. I wish to discuss here briefly three different theories of knowledge. They refer primarily to physics, though one should not forget that they may imply wider extensions to philosophy. Two of these theories are well known and they have been proposed respectively by Ludwig Wittgenstein and Niels Bohr. The third one follows from some recent developments in the interpretation of quantum mechanics and it will be our main topic.

Wittgenstein

According to Wittgenstein, the world is made of *Tatsachen*. This has been first translated in English by "atomic facts", a particularly unlucky choice since real physical atoms turned out to be incompatible with them. A later translation by "states of affairs", though not very clear, has later been adopted. Each of these building elements can be expressed by an elementary proposition. These propositions may be either true or false, which means that they describe potentialities and not only actual facts (this remark will turn out to be important later on). The vast logical construction starting from there in the *Tractatus* makes it also plain that there is fundamentally a unique logical framework embodying all the *Tatsachen*. This important point will become clearer by comparison with other theories of knowledge, but one can notice how Wittgenstein develops it in the *Philosophical Investigations*, when dealing with the theory of language. One remembers how the master has to say a name for his apprentice and then to point a finger at the real thing: "that". One might say that this means that the essence of physical reality is to be unique (otherwise "that" would be pointless).

Bohr

Wittgenstein was aware however that the atomic nature of matter could raise serious difficulties for his construction and one remembers his famous elliptic and somewhat conjuring sentence according to which "this table is not made of electrons". One thus comes to the second important theory of knowledge, by Niels Bohr. It was not primarily motivated by philosophical qualms, but by necessity and because of many difficulties arising from quantum mechanics.

One of these difficulties was an apparently irreducible opposition between two "worlds", one of experiments and one of atoms. Determinism is a basic feature of our experimental, actual world. One needs determinism to make sure that an apparatus (a voltmeter, a car) is going to work according to the user's notice. This is determinism as a prediction, from now to the future. One also needs to make records of experimental data and they must be reliable witnesses of some facts having occurred in the past. This is determinism in the other direction of time, from now to the past. The atomic world has none of these deterministic features and, on the contrary, it is absolutely random, probabilistic. Another opposition between the two worlds is in the representation and the language one must use for them. The experimental world uses ordinary language and common sense, as needed since an experiment is an action. We have a clear intuition (a visual representation) of it. On the contrary, the atomic world can only be fully expressed by abstract mathematical

concepts. Common sense is badly hurt by the negation, total or partial, of locality, causality, distinguishability and so on. Gifted people have still some intuition, but a partial one, glimpses of connections, never a full and clear-cut vision.

Comparing Wittgenstein and Bohr

What is common between Wittgenstein's and Bohr's approaches, and what separates them? Disregarding their different vocabularies, one can recognise Wittgenstein's "states of affairs" in Bohr's classical phenomena. They are described by elementary propositions, with essentially the same logic and the same notion of truth. Bohr adds however that they only apply to macroscopic objects, far above the scale of elementary particles, and to the properties directly accessible to a human observer. The main point of departure with Wittgenstein is however that these states of affairs or classical phenomena are not the only ones to occur in physical reality or, if one prefers, the world is *not* made of them, it only contains them. The properties of the atomic world cannot any more be expressed by elementary propositions that are either true or false because, for instance, if a proposition about the position of a particle were true, it would preclude any proposition about momentum to be either true or false. There is not a unique *Denkbereich* (universe of discourse) for these propositions, but many different ones, a multitude of languages, whose multiplicity is expressed by Bohr's famous complementarity principle. The theory of knowledge was accordingly dramatically truncated by Bohr : he considered that classical statements are the only ones to be significant and useful for logic (allowing for a notion of truth). The atomic world was rejected into the "unspeakable".

Formal science

Later advances in physics have strongly confirmed quantum mechanics, up to now, and the lack of a sufficiently wide theory of knowledge has been badly felt since then by philosophers. Maybe, since we are dealing here with the "Foundational Debate", I might mention that this is, in my opinion, an aspect of a more general crisis arising from the present abstract status of science. The point is that our science has lost most much of its intuition, both in physics and mathematics. These sciences have been deprived of their original visual representation to become formal. Some mathematicians, like Brouwer, have tried to react against this. Perhaps physicists are even more worried and Feynman said aloud what everybody thinks privately, namely that, finally, *nobody understands quantum mechanics*.

The difficulties of physics and mathematics with too much abstraction are not by the way completely unrelated. A physicist hesitates when talking of even a trivial macroscopic object, a pencil for instance. He sees it double: as an apparently simple thing from the standpoint of classical physics, and an utterly complicated one when considering it to be made of atoms. As a matter of fact, one begins only now to have some understanding of what is a pencil as an object, from the standpoint of the principles in quantum mechanics. In the same way, to speak of a set of pencils looks simple in a classical language, but it is dreadfully complicated from the standpoint of the principles of physics. The idea that simple finite sets, as mathematicians like to introduce them as an early stage in their constructions, are simple enough to build mathematics upon them without question is certainly naive, when one comes to a philosophical synthesis. It is well known furthermore that particles cannot be used as substitutes for classical objects: they are indistinguishable and there is no axiom of choice, even for a finite number of them!

Interpretation in terms of consistent histories

One might define the interpretation of quantum mechanics as a theory of knowledge for that specific field of physics. It seems that a breakthrough has occurred recently in this

domain. It did not happen as a consequence of the fundamental or philosophical worries of many people about quantum physics, but from almost purely technical advances, directly issued from already known basic principles that are not supposed to be questioned, at least to begin with. There are essentially two such principles: (i) one stating the mathematical framework and language of the theory, including the idea that a physical observable is associated with a definite operator in a Hilbert space; (ii) another one stating that dynamics is governed by the Schrödinger equation. No assumption was made concerning quantum measurements, states or probabilities, which were found later on to be almost automatic consequences of the first principles. This final result perhaps provides the best summary of the new interpretation, namely that it shows interpretation (and a theory of knowledge) to be a direct and necessary consequence of the basic principles alone.

Decoherence

The first significant advance to be found was the so-called *decoherence effect*. It was discovered independently several times, by Feynman and Vernon, Hepp and Lieb, Zurek, Joos and Zeh and Caldeira and Leggett. The contribution by Wojciech Zurek, in 1982, certainly played a decisive role in its recognition. The effect has to do with macroscopic systems, explicitly described in terms of quantum mechanics without referring to classical physics. Among the many observables pertaining to the system, one only considers the so-called collective observables, which are essentially the ones one would use in classical physics (the position and momentum of a pendulum, for instance). The decoherence effect, which is a consequence of Schrödinger's dynamics, states that no quantum interference effect can be observed by looking at these observables, at least after an extremely short "decoherence time". A simple way of saying this would be to say that Schrödinger's cat must be either dead or alive according to naive probability calculus, and there are no observable interference effects showing the cat in a superposed state. The origin of the effect is strongly linked with the large number of degrees of freedom in the system, in a quantitative way. It was also observed that another aspect of the effect is to direct the evolution of the system (the motion of the pendulum, for instance) along a motion obeying classical physics.

Histories

Another essential contribution was the idea of *consistent quantum histories*, by Robert Griffiths, in 1984. I shall try to describe it more explicitly, because it has much to do with foundations. Von Neumann had already noticed that one can try to describe what occurs at a definite time in the atomic world by so-called elementary predicates, which I shall rather designate as properties. A property states that the value of some given observable A lies in some definite range Δ . Although it can be stated in words, it fits nicely the formal principles of the theory in so far as there is a one-to-one correspondence between properties and projection operators in Hilbert space. One "speaks", though through mathematics.

A history is a sequence of properties occurring at various successive times. It can be compared with a unique property in a way analogous to a motion picture when compared with a snapshot photograph. As a matter of fact, most physicists are always describing a physical system by some sort of history, in spite of Bohr's interdiction to speak of the atomic world as such. One may say for instance that, at some time, a neutron has gone out a reactor (this is a property concerning position); some time later, after crossing a velocity selector, the neutron momentum is in some definite range (a momentum property); later, it has entered a hydrogen target (position property); still later, a reaction $n+p \rightarrow d+\gamma$ has occurred (this is a property because it corresponds to the projection operator on the $d+\gamma$ sub-Hilbert space). Finally, the photon is found to be in the space region inside a detector where it can be registered. This is a typical history, and there can be an infinity of them, describing some experiment or another.

In spite of their obvious simplicity, the use of histories is far from trivial (otherwise, after all, one would not have waited since 1984 before using them systematically). The reason why is easy to show: if one had been discussing an interference experiment, why not introducing the properties specifying through which arm of an interferometer a photon has gone. But nobody has ever been able to give a meaning to such a statement. It seems therefore that some histories can make sense and others do not. Griffiths' breakthrough was to find what distinguishes among the two categories: there are histories to which one can attribute a well-defined and correct (i.e. positive, normalised and additive) probability. They are the ones making sense. It turns also that they are the ones for which amplitude probabilities agree with additive probabilities. Other ones have no such probabilities. This is the case for the interference experiment: the sum of the formal probabilities for crossing one interferometer arm or the other do not add up to the probability for crossing the two of them. One can thus characterise the meaningful histories, as compared with the meaningless ones, by explicit mathematical criteria, the so-called Griffiths consistency conditions, and the microscopic world becomes in some way "speaking".

Logic

One might wonder however if there is any deeper reason for attributing a meaning to the consistent histories. This is where enters another contribution by the present author in 1988. One can notice that a "good" history belongs to a family of alternative histories. For the nuclear reaction already considered, the neutron could have missed the hydrogen target, or enter in it and not provoke a nuclear reaction, or the photon could have ended elsewhere, and so on. This looks very much like a family of allowed atomic "states of affairs" and one can wonder whether or not they are subject to a logical treatment. The various possible properties generate a field of propositions and it is easy to define the basic logical operations "not, and, or" as acting on them. The logical implication between two propositions, "if a , then b ", can also be defined by a simple mathematical equation for the conditional probability : $p(b | a) = 1$. It turns out that the ordinary elementary axioms of logic are perfectly satisfied with these conventions, which is why, after all, one could say that consistent histories make sense whereas non-consistent ones (not satisfying Griffiths consistency conditions) do not make sense.

A further investigation of these logical opportunities reveals a few remarkable features. One can use for instance very simple logical conditions on the probabilities to be expected for histories and discover unexpected consequences. For instance, there must exist a density operator, though one does not yet know how to derive it from a preparing process (this result going back to Gleason. It can be mentioned by the way as a nice example where physics can make use of an abstract existence proof, by far much easier than the constructive one). It can also be shown that the probability of a history is defined in a unique way. Accordingly, probabilities enter physics by a "logical gate" without yet any obvious connection with physical randomness. Probabilities only provide the tests of logical inferences.

Another result is to understand what complementarity means. It was always somewhat mysterious but it now becomes quite simple: It consists in the fact that different families of consistent histories, though dealing with the same physical system, are not mutually consistent, i. e. there is no larger consistent family including both of them. For instance, some position properties asserting that a particle has a straight-line trajectory are inconsistent with similar properties asserting that the particle momentum was constant and directed along this line. There is not therefore, as with Wittgenstein, an overall unique *Denkbereich* describing the atomic world, but many different (complementary) ones. The best analogy one can give is with mathematics, where one gets different universes of discourse when stating or rejecting Cantor's continuity hypothesis.

Such a multiplicity of logical frameworks looks very dangerous at first sight: Is there no risk of paradoxes (apories), where one could have a logical inference $a \Rightarrow b$ in one framework and the opposite conclusion where a does not imply b in another framework. Fortunately, it can be proved that this is impossible, with the remarkable conclusion that *paradoxes are impossible in quantum mechanics*.

All these remarks can be summarised into a new (logical) axiom for quantum mechanics, according to which any description of a physical system must be expressed in the framework of a consistent family of histories. When reasoning on the basis of this description, one must make sure that the logical inferences to be used are mathematically valid. One thus gets a well-defined proposition calculus for quantum mechanics.

An example can be given with the previous experiment in nuclear physics from which the following line of reasoning can be drawn: the photon has been observed, therefore the nuclear reaction occurred, therefore ... the initial neutron velocity is known. This justifies the phenomenology and kinematics reconstruction that was used by experimentalists all along, when they superbly ignored Bohr's interdiction of speaking about the atomic world.

Classical physics

It was already mentioned that decoherence can give an explanation for the classical behaviour of most macroscopic systems. A perhaps deeper approach consists in fully exploiting the previous logical axiom together with the peculiarities of macroscopic systems, as seen from the standpoint of quantum mechanics. Decoherence is one of them, though not the only one, and I shall only indicate the main results. They say, in a nutshell, that classical physics (including its common sense logic) is a consequence and a special case of quantum mechanics (and its own logical framework). This means that a possibility is now offered of getting rid of Bohr's insistence on the primary character of classical physics and to consider that there is only one kind of physics.

A classical property refers to the position and momentum, together, of some macroscopic part of an object. For instance, they are given at some time with error bounds large enough as compared with the uncertainty relations. A mathematical theorem by Hörmander shows that this property can be associated with a family of equivalent projection operators in Hilbert space. This means that, though using the language of classical physics, we can stay within the framework of the quantum logical axiom and its language.

A more remarkable result has to do with classical determinism. It is not universal, as it is shown by chaotic systems. When it holds, it is basically a logical equivalence between two classical properties occurring at two different times, from which prevision and memory can be understood. Here again, by a theorem (reciprocal of Egorov's theorem in microlocal analysis), one can prove this logical equivalence from the standpoint of quantum logic. Classical determinism thus appears like a consequence of quantum mechanics, despite, or rather because of the probabilistic logic of the quantum world. There is of course a price to pay, which is that there is always a tiny probability for determinism to be violated. This is attributed to quantum fluctuations.

One can go further and prove that physical common sense, which is a form of ordinary logic dealing with the classical properties of macroscopic objects, is a special case and a consequence of the basic quantum axioms, including the logical one. This is the basis of the new theory of knowledge we shall discuss in a moment.

Measurement theory

Measurement theory is only marginally interesting for our present purpose, so that one can be very brief. It becomes deductive and all the familiar axioms that were put forward by Bohr become so many theorems. One should perhaps mention however that the randomness of a series of measurements events is a necessary consequence of the theory : only at this stage do probabilities acquire their statistical meaning, while there were only logical tools up to then. As for wave packet reduction, when it deals with a statistical series of double measurements where an observable A is measured before another B, it is also a straightforward theorem, following essentially from the occurrence of decoherence in the measuring devices. Finally, it should be mentioned that the synthesis of the various partial discoveries into a consistent interpretation was performed independently by Gell-Mann and Hartle and by the present author.

A new theory of knowledge

The results that were just mentioned yield very naturally a new kind of theory of knowledge. It does not coincide with the one Bohr sustained, because the status of classical facts, which we had identified previously with *Tatsachen* , is very different in the two approaches.

One cannot say, like Wittgenstein, what exactly the world is made of, because physics is not at an end. The world certainly contains particles, at least if one agrees not to distinguish particles and quantized fields. It also involves space, although we do not understand it completely. Much more important is the fact that we know some general principles of physics, those of quantum mechanics, particle theory and the relativistic theory of gravitation. *These principles are going to replace older principles of philosophy.* They have been obtained by science, thanks to the effort of many generations and, in some way, the approach that is proposed here is similar to what Francis Bacon had predicted long ago : "Now my plan is to proceed regularly and gradually from one axiom to another, so that the most general are not reached till the last; but then when you do come to them you find them to be not empty notions but well defined, and such as nature would really recognise as her first principles, and such as lie at the heart and marrow of things." One must be aware that these principles may change with an increase of knowledge, but this has no essential consequence on the theory of knowledge, presuming of course that the present principles will reappear as approximations or practical rules that one can derive from any future form of the basic principles.

Classical physics, i.e. the existence of macroscopic objects with properties that can be visualised, obeying their own simple logical rules, is in good agreement with the basic principles we stated first. As a matter of fact, macroscopic physics follows from these principles from the standpoint of theory. These classical phenomena, or restricted *Tatsachen* , constitute our environment. If one accepts the familiar point of view according to which our observation of this environment is responsible for our developing a visual representation, language and common sense, one can see that these essential psychological features are finally the remote consequences of the basic principles of nature. The point of view we just mentioned is, as well known, initially due to Locke and Hume and it permeates our contemporary cognition sciences. It is also in fair agreement with Wittgenstein's theory of language. Of course, it should be completed by evolutionary considerations about the development of species and brains at the contact of outside order, as well as sociological considerations as to the constraints and opportunities of society, but this is another story. The main point is that there is a rather direct way from the basic principles of physics to the rules of common sense.

This is clearly a reversal of tendencies, at least in epistemology and perhaps in philosophy; One does not any more rely upon common sense as a foundation, upon which all the so-called philosophical principles were, after all, derived by some abstraction. The right and unique way for a philosophical critique of science does not consist consequently in an analysis of scientific concepts from the standpoint of some philosophical principles. This has been done many times for quantum mechanics, which was weighted on the balance of causality, locality, separability, and so on. As a matter of fact, causality, locality, separability, are properties of a macroscopic system one can prove together with their margin of error, which becomes unbearable when an object is too small. These are not principles, but gross features, illusions of a large size. Now, on the contrary, common sense is considered to be a secondary effect. Its validity can even be proved, together with the limits of its domain.

Of course, when recognising the approximate character of the classical *Tatsachen*, we must accept that philosophy cannot be entirely founded on them and we lose the foundation that was postulated by Wittgenstein. Our starting point is already much more elaborate, since the basic principles of physics we started with require the availability of higher mathematics. The essence of these mathematics cannot furthermore originate from set theory, as was already mentioned, and it might look as if there is no unique foundation after all. But the story is not finished, as we shall now see.

Objectification. Problems and hints

The problem

The theory we are using remains ordinary quantum mechanics and, certainly, not all its problems have been solved once and for all. One problem at least remains. It is the question of "objectification" or "actuality", namely why and how a unique factual datum occurs at the end of a quantum measurement. The purely probabilistic character of the theory forbids the existence, within this theory, of any reason or mechanism for this manifestation of uniqueness. Gell-Mann and Hartle, because of this, tend to consider that the problem does not exist. Other people go so far as wanting to change or to complete quantum mechanics for its sake, either by introducing hidden variables or specific reduction effects. This is indeed related to the question of wave function reduction because, in the old interpretation, wave function reduction had two aspects: One aspect is concerned with the statistics of a second measurement on a subsample of events where a first measurement has given a specific datum. This is what the new interpretation can derive from other principles. Another aspect is precisely objectification after a specific unique measurement, which is the problem we are now considering.

It may be noticed that the new interpretation has been able to explain all the other features of observed physics by using only the first principles, except for one feature, which is this uniqueness of a result. The theory cannot do it because of its probabilistic character, which is even deeper now than it was before. On the other hand, remembering what was said at the beginning about Wittgenstein, one sees that reality is confronting theory with its most essential character: the uniqueness of "that". The ultimate opposition one finds between theory and reality is therefore a conflict between their respective essences, something of the utmost importance.

Everett's answer

Everybody has heard something of Everett's proposal, which is in some sense the answer of theory extremism: Since theory leads us to envision all possibilities on the same footing, it assumes that reality must comply to theory and it is not unique. Each time some tiny phenomenon equivalent to a quantum measurement occurs somewhere in the universe,

the wave function of the universe splits into several branches representing different "realities". In spite of its radicalism, this interpretation cannot be shown to be inconsistent. The recent advances in our understanding of the decoherence effect show on the contrary that no experiment performed within one "branch of reality" will ever allow us to ascertain or disprove the existence of other branches. It might be therefore that an answer to the problem of objectification is not within the range of "falsification" in Popper's sense. It might not belong to the domain of science. It should be clear that this remains a possibility and not a necessity. I personally believe that all the possibilities, either within physics or philosophy, should be explored with equal seriousness. Now however, we shall try to say more about the philosophical option.

Bohr's answer revisited

Another way out of the objectification problem was essentially proposed by Bohr, although it was then intermingled with the obscurities of wave function reduction. It becomes clearer now and it brings us back to an old debate about foundations, which stands at the beginning of physics. The question is: why and up to what point is it possible to describe correctly physical reality by a mathematical theory? To answer that this is always possible and for all aspects of reality is what Husserl had called the "Cartesian programme", which was strongly criticised and rejected by Heidegger. It should certainly be at the heart of our discussions in this meeting.

The suggestion is very daring and it amounts to propose that science has reached at least a frontier in the Cartesian programme. The existence of objectification, at least if one adopts a philosophical attitude towards it, would simply indicate that not all the features of reality are explained nor explainable by a mathematical theory. This would mean that the persistence of the grand problem of objectification does not indicate a failure of quantum mechanics, as so many people say, but a matchless mark of achievement. In favour of this position, I would like to add an argument by considering what an extreme Cartesian realism would imply: Would it not be outrageous to believe that Schrödinger's equation, or any other equation, can replace the history of the universe? Everything would then be contained in the initial conditions, so that time would be an unnecessary and illusory artefact, whereas ever-changing Reality would be reduced to a timeless and frozen mathematical image. Many scientists do not realise how they have been brainwashed by the Cartesian programme, to the point of not even mentioning it as an assumption among their philosophical foundations.

If one were to give some credit to the present proposal, it would have clearly direct consequences for the status of realism, which would have to be seriously reconsidered. One may wonder for instance if it might be linked with the so-called realistic or platonic philosophy of mathematics, according to which our human mathematics would be exploring a specific kind of reality, a second kind of reality, different from the physical one: a *Logos*. But this would be the subject of a different lecture for another debate, in some other year maybe..

REFERENCES

Full references to the authors and matters that were taken up in the present communication would be much lengthy. The following article and books by the present author contain full references as well as more systematic developments. About the necessary background in physics, one may consult:

Consistent Interpretations of Quantum Mechanics, Rev. Mod. Phys. **64**, 339, 1992.

The Interpretation of Quantum Mechanics, Princeton University Press, 1994.

The philosophical developments, which were the actual subject of the present communication, are given more completely in

Philosophie de la science contemporaine , Gallimard, Paris, 1994.