AGAINST THE COPENHAGEN ORTHODOXY

The “Montevideo interpretation” of quantum mechanics

By Aníbal Corti (translated from Spanish by Jorge Pullin)

Given its predictive successes, quantum mechanics is one of the best tested theories in the history of science. The problem is that even today, almost 90 years after its birth, there is not a general agreement about the world view it provides.

It is not that traditional physics did not encounter problems of this kind. Not at all. For instance, the meaning of Newton’s second law (the well known equation that states that the vector sum of all forces that act on a body is equal to its mass times its acceleration) is something that was under debate for a long time, since there was no agreement on the physical nature of forces, although in fact no physicist denied its mathematical formulation.

We should take into account that the forces are not seen nor measured directly: only their effects are measured directly, that is the changes in the velocities, that is, the accelerations. Starting in Newton’s time it became quite a debated question if classical mechanics describes a world in which forces really exist or if the latter are mere fictions that are useful at the time of carrying out computations and formulating predictions.

Now, the mathematics involved in classical Newtonian mechanics has physical interpretations that are fairly obvious and intuitive. In fact, most of the math existed first as description of physical phenomena, before it was “purified” from the empirical interpretations that are more or less evident from its concepts and converted to “pure” math. With quantum physics on has the opposite situation: the mathematical tools that are used to model the quantum world existed first as purely abstract concepts, devoid of any physical significance, until they were used as instruments to model sets of empirical data.

We have direct and everyday intuitions, for instance, about what is a geometric space of three dimensions, but instead we lack similar intuitions with respect to a Hilbert space. One has to have studied a lot of higher math to understand what it is and a lot of physics to understand how it can useful to model empirical phenomena. By comparison, traditional physics used mathematical concepts with much more intuitive empirical applications.

The classical world

The intuitions provided by common sense are historically dynamical: they are influenced by the results of science. In spite of this, it is very natural that the physics with which contemporary human beings are mostly familiar is precisely that which describes everyday objects. That physics is the classical mechanics of Galileo and Newton.

The world described by classical mechanics, to use an eloquent analogy of Gambini, is a world of material particles that move in space and time as the actors of a play on a fixed stage*. Everything that exists in the universe results from the different distributions and motions of those particles. The space and time provide the fixed and immutable stage in which that representation takes place. That is how Galileo and Newton described the world in the 17th century.

At the end of the 19th century, the work of Faraday and Maxwell forced the recognition of a new actor on the stage: the electromagnetic field. This character proved unruly, and it was impossible to accommodate it in the stage conceived for the material particles: that required to radically rethink the ideas of space and time. After the radical transformation that such ideas underwent in the early 20th century, it was no more possible to think of physical reality as reduced to particles moving in a fixed and immutable stage, but it require to assume that the field but also the space and time themselves are physical phenomena subject to relations, interactions and transformations.

Space and time therefore stopped being considered as the fixed stage where physical phenomena take place and started to be considered as other actors in the play, continuing with the suggestive analogy of Gambini.

Since over a century ago, space and time are considered physical phenomena that interact with the rest of the physical phenomena and transform themselves in the course of such interactions.

This is the vision of reality provided by the general theory of relativity towards 1920, and is the vision of the macroscopic world (that ranges from very massive objects like stars and black holes, to objects that we interact with in everyday life and even smaller ones) that remains until today. Nevertheless, such theory does not describe the microscopic world (that ranges from atoms and molecules up to elementary particles). A few years after the birth of the general theory of relativity, quantum mechanics would start to take shape: the theory that offered a vision of the microscopic world that was required to complete the picture of the physical world.

In contrast with the old physics of Galileo and Newton, that at some point aspired to be complete, that is, to describe all fundamental physical phenomena, the general theory of relativity and quantum mechanics do not cover entirely the set of physical phenomena.

An all encompassing theory still does not exist, but it is needed, for instance, to account what happened to the universe in the first few instants after the Big Bang, when it was small enough that its behavior was ruled by the laws that apply to microscopic phenomena, but so massive that, on the other hand, gravitational effects were also relevant and those are only explained by the general theory of relativity.

Even to describe adequately what happens today, some 15 billion years after the Big Bang, the "division of labor" existent in contemporary physics appears as unsatisfactory, since the phenomena described by the general theory of relativity are also quantum in nature, whereas atoms and molecules also produce gravitational effects, without having a satisfactory description from contemporary physics.

The quantum world

Quantum physics has two salient characteristics. The first is that it describes a discrete world, that is, a world that "jumps". Like the pawns of a game that move from a square of a checkerboard to the next, microscopic objects go from a state to a neighboring one without making sense what is in between. The second characteristic is that it describes a world of potentialities, that is, of possible events, that remain mere probabilities until the system is forced to make a decision, choosing one of them. Quantum mechanics does not explain, in principle, how the microscopic physical systems go from mere potentialities to observed facts. A well known experiment can be used to illustrate this point.

Consider a source of light that emits with very low intensity. The particles of light (photons), pass individually, in regular intervals, through a screen with two slits and they are finally detected by a photographic plate (see figure).

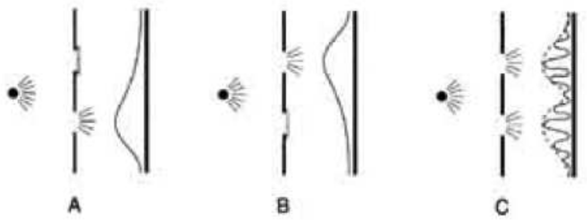

Imagen tomada (con modificaciones) de David Z Albert, Quantum Mechanics and Experience (1992).

Every time a particle reaches the photographic plate, it leaves a well defined imprint in a region of it. After a long enough time so there are enough particles that hit the photographic plate, you will see on the plate a pattern of darkening of the plate proportional to the density of impacts in that region. If the slits are opened alternately, after waiting for a long enough time, one will observe a pattern of darkening that is more intense in front of the plate that remained open (figures A and B).

But if both slits are opened simultaneously, after waiting for a long enough time, one does not observe the expected result: the darkening pattern is not more intense in front of the slits (figure c, dotted line), but one observes the typical interference pattern with alternating bands of dark and clear characteristic of wave phenomena (figure C, continuous line). Such behavior only makes sense if each photon that goes through the membrane with the slits interferes with itself, that is, it behaves like a wave and makes it through simultaneously through both slits. The experiment can be carried out with other elementary particles and one obtains the same result.

As long as only one of the slits was open, the photon behaved like a particle, but, when both were opened, it behaved like a wave, at least insofar as its motion is concerned, since when it hit the photographic plate it behaved as a particle impacting in a definite point, as a particle would do. In some sense the photon exhibits a dual behavior: a wave during its propagation and a particle when it hits the photographic plate. The specific point where it will impact cannot be predicted theoretically: it is only possible to know the probability that it will show up in a given place. The curve of probabilities that is predicted by the theory agrees with the interference pattern observed experimentally: that confirms the predictions of the theory.

The interpretation that suggests that the photon has a dual behavior is reinforced by the following experimental observation: if one attempts to determine the position of the photon in a previous point of its displacement, for instance, when passing through the membrane with the slits, the wave behavior disappears and the pattern that appears in the photographic plate is the one seen in figure A or B.

Physicists call such process “measurement”, but it is important to point out that it does not necessarily involve the participation of a human observer. The measurement only requires that the microscopic system that is to be “measured” interact with another system whose behavior is classical. Obviously, not every system, no matter how classical its behavior, would allow the measurement of any quantity.

In the previous example, the photographic plate is an instrument of measurement, since the interaction of the photon with the plated can determine which is the position where the photon impacted. The membrane with the slits can also be considered a measurement instrument, but, in its interaction with the photon, it is unable to reduce all possible trajectories to one. For that reason the photon goes through both slits, although we know it does not make it through the wall of membrane: in that sense a certain measurement of its position has taken place.

If one has a finer localization mechanism to determine exactly the place where the photon goes through, the possibilities reduce to one or another in an exclusive sense and the wave behavior is completely destroyed. It is not important that a human experimenter observe the process, but it matters that the interaction with the macroscopic object be sensitive to the magnitude that one wishes to measure.

The previous example precisely illustrates the main characteristic of microscopic systems we were referring to before: their states express potentialities of the system, that are realized when they become in contact with macroscopic systems. When a microscopic system interacts with a macroscopic one (a system that has classical behavior) it happens that of the many potential states only one of them becomes real.

In the case of the photon in the experiment, it can be said that potentially it has a spatial localization similar to that of a particle, but it only has it when the interaction with a macroscopic body forces it to occupy a defined position in space.

This phenomenon in which only one of the potential states of the system becomes real is known in the technical jargon as the “collapse of the wavefunction”, or “collapse of the state vector”, “reduction of the wavepacket” or “reduction of the quantum states”. Irrespectively of the names, what is relevant is that of the many possible states of the system only one become real. The problem of answering how and why such a thing happens is known as the “measurement problem” and has been one of the most debated topics in the frontier of physics and philosophy in the last 80 years.

The phenomenon is no doubt strange, but considerably less than the sensationalist literature that has been inclined to the “quantum mysticism” for decades. It is shameful that some very renowned physicists have contributed to the dissemination of such nonsense, although that is not the topic of this article.

Irrespective of what is stated in the sensationalist literature, there is a genuine physical problem in all this. If the objects of the microscopic world exhibit this particular and disconcerting behavior, whereas the objects of everyday life (which are ultimately composed by microscopic objects) definitely do not, the obvious problem arises of explaining why the world we interact with every day does not exhibit quantum phenomena when all the elements that constitute it do.

Copenhagen

The traditional interpretation of quantum mechanics goes back to the years when it was being developed in the late 1920’s. Its formulation is attributed to the renowned Danish physicist Niels Bohr and takes its name from the port city of Copenhagen, capital of Denmark. It is worth pointing out from the outset that what is known as the “Copenhagen interpretation” is not a homogeneous point of view, but it is a set of points of view more or less related among themselves. Due to this, one can find in the literature formulations of the “Copenhagen interpretation” that are not only different, but contradictory.

In any case, what appears distinctive of this interpretation is postulating a duality between the classical and quantum realms: a dividing line between the microscopic and macroscopic world. According to Copenhagen, the universe is not homogeneous but two essentially different physical realities coexist in it, but are not completely insulated one from the other. In the course of the interaction of those two worlds, when the microscopic systems interact with classical objects, the quantum world collapses to the classical one. In some way, in this interpretation, the quantum world is an unstable one.

A well known quote of Werner Heisenberg, perhaps the most famous of Bohr’s students, summarizes well the spirit of the Copenhagen interpretation “The trajectory [of the particle] exists only because we have observed it”.

“To observe” does not mean here, as we pointed out before, that there is the participation of a human observer, a consciousness or a mind. Some have claimed such things, including prominent physicists. But it is not something that has to do with physics but with mysticism. The “observation” in the Copenhagen sense does not assume the existence of an observer but merely that of a measurement device: a macroscopic (classical) object that interacts with the microscopic (quantum) system forcing it to collapses on the classical world.

Physical magnitudes, from this point of view, are associated with the properties that are manifested in given measurement processes. In the two slit experiment, the photon simply does not have a spatial localization until a photographic plate or other measurement device is installed that forces it to adopt on. Before that, its spatial localization is a mere potentiality, subject to the probabilistic laws of the theory. It therefore can be said that the position of the photon only exists after it has been measured: after the world of quantum potentialities has been forced to collapse to the familiar world of classical properties.

Heisenberg's lemma can be summarized as follows: the trajectory of the particle exists only because it (the particle) has interacted with a macroscopic device that has forced it to have a classical behavior.

The Copenhagen interpretation therefore requires a dividing line, a limit that separates neatly the universe in two parts: a world of mere potentialities and another that interferes with it from outside forcing the actualization of those potentialities.

The issue that most disturbs physicists and philosophers in the way the Copenhagen interpretation views the physical world is precisely that it divides physical reality: the concept that a dichotomy must exist in the world in two orders of reality for the problem of measurement to have a solution since the quantum theory itself cannot solve it. To put another way: what has disturbed physicists and philosophers the most about Copenhagen is that it renounces explicitly and cavalierly to offer a solution to the measurement problem internal to the quantum theory itself.

In the Copenhagen interpretation the measurement problem is solve by an external fiat: measurement devices impose physical reality (starting from a world of potentialities) and physical reality is built (according to certain probabilistic laws). Many physicists and philosophers have countered that it should be a phenomenon internal to the quantum theory itself (and not an external phenomenon like the collapse induced by the interaction with macroscopic objects) what should ultimately explain the emergence of the classical world, with its familiar properties, from the disconcerting quantum world. In that sense, several alternative interpretations to Copenhagen have tried to solve the measurement problem without postulating the existence of a radically exterior world that forces the collapse of the quantum world. The most novel of such interpretations arose recently in a small port city that is not Copenhagen.

Montevideo

Gambini and his Argentine collaborator Jorge Pullin, that works in Louisiana, are internationally known physicists, since many years ago, in the field of quantum gravity in one of its specific versions: loop quantum gravity. In several recent papers Gambini and Pullin have presented an original interpretation of the mathematical formalism of quantum mechanics that, for brevity, they call “the Montevideo interpretation”.

The Montevideo interpretation is in line with the critique of the standard interpretation we presented above. What Gambini and Pullin argue is that quantum mechanics must account for all physical reality and not only part of it. In other words, what they assume is that the equations of quantum mechanics are universally valid, that is, they describe adequately not only the microscopic world but also the ordinary world. The macroscopic world is, from this point of view, as quantum as the microscopic one, since both respond to the same laws of physics. If we want to understand in detail the properties that characterize macroscopic objects, one needs to do it through the equations of quantum mechanics.

Let us take for example the case of spatial localization. From this point of view, this property of everyday objects should be well explained by the equations of quantum mechanics that describe the behavior of objects that lack precisely spatial localization. This approach to the problem is, as is evident, opposite to the point of view of the Copenhagen interpretation. From the latter point of view, properties like spatial localization are considered inherent to the classical world. When macroscopic objects with those inherent properties become in contact with the unstable quantum world, they destroy with their distortive intrusion the characteristics of the latter.

Now, if the familiar world of common sense ought to be explained, ultimately, in terms of the equations of quantum mechanics, we need to clarify how is it that the classical properties emerge in a world of potentialities without recurring to an external fiat: one must provide an answer to the measurement problem that is physically and philosophically more satisfactory than the answer of Copenhagen.

The key, in the framework of the Montevideo interpretation to explain the absence of the properties typical of the quantum world in the everyday world is given by time.

In quantum mechanics time is a classical parameter, external to the theory. It is not measured with real clocks, but it is absolute, abstract and mathematical: it flows without depending on anything else, like Newtonian time used to flow. The main methodological innovation of Gambini and Pullin is to propose that the time that appears in the equations of quantum mechanics will have to be measured with real clocks, that is, the time that appears in them is to be interpreted as a real time. The second important idea proposed by the Montevideo interpretation, together with the previous one, is that, if things are done this way, then it is impossible that the real time (measured with real clocks) will coincide with the ideal time (the absolute, abstract and mathematical). In other terms: under very reasonable assumptions one can show that there exists physical limits to how much a real clock can behave like an ideal clock, so the difference between the time measured with real clocks and the ideal time of quantum mechanics cannot be made as small as desired.

When the time that appears in the equations of quantum mechanics is interpreted as the time measured by real clocks (with the physical limits they face in approximating the ideal time), it is possible to show that the superpositions that are characteristic of quantum states are destroyed naturally (under certain conditions) in a way predicted by the quantum theory itself, that is, without involving an exterior fiat to force the reduction.

The key to the Montevideo interpretation therefore is to take seriously one of the lessons of the general theory of relativity and field theory (by the way an area in which Gambini is a specialist): that is, the fact that space and time are not to be considered external parameters of the physical theories but are part of the physical reality that the theories describe, that is, they are phenomena that are part of the same reality that one is attempting to describe and, like any other real phenomena, are affected by the very laws of the theories that describe the behavior of the world.

The author would like to thank Rodolfo Gambini and his colleague Nicolás Wschebor for help during the preparation of this article.