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Chapter 17

QUANTUM INTERPRETATIONS

"*God does not play dice with the universe.*"

Einstein

There is no question that quantum mechanics is a theory that works. It has been enormously successful in explaining phenomena at the atomic and subatomic level. Semiconductors, transistors, microchips, lasers and nuclear power are among its fruitful applications. What the theory really means, however, has been, and still is, a mystery. Its concepts are difficult to understand as well as to believe. Often, they are in conflict with common-sense notions derived from what we observe in the everyday world.

Some forty years after the birth of quantum mechanics, Richard Feynman, American Nobel-Prize physicist and renowned teacher (1918-1988), remarked during a lecture:

"I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you really have to understand in terms of some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. ... Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get … into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that." [1]

A number of different interpretations have been proposed for quantum mechanics. Although mutually exclusive, they all meet the requirements of an acceptable theory. All accurately account for known experiments; all correctly predict the outcome of new experiments.

The “orthodox” view of quantum mechanics has been the "Copenhagen Interpretation", so called because its main proponent, Bohr, worked in that city. It has been taught in colleges to future physicists.

The Copenhagen Interpretation ruled for more than 50 years until well into the 1980s. The great majority of physicists have given at least lip service to this interpretation. What has mattered all along to most physicists is that quantum mechanics does indeed work as a practical tool. In more recent years, however, increasing efforts have been made to find alternative interpretations. These efforts, however, have in no way diminished the mysteries of the quantum world.

THE COPENHAGEN INTERPRETATION

Bohr first presented the basic concepts of this interpretation in September of 1927. The whole theoretical package, which incorporated the views of Bohr, Born, Heisenberg and others, was essentially completed in the early 1930s.

According to Bohr, a fundamental quantum entity, such as an electron or a photon, is neither a particle nor a wave, but both wave and particle pictures are necessary to explain the quantum world. They are *complementary* aspects of the electron's complex nature. Depending on the nature of the experiment under consideration, an electron (or photon, or proton) can be observed to behave in some cases as a particle, in others as a wave, but *never as both*. This is Bohr's "principle of complementarity".

As we saw, Born interpreted Schrodinger's "wave function" as the basis for a probability wave. According to Bohr, an electron (or any other quantum entity) does not really exist in the form of a particle, when nobody is looking at it. It exists merely as a superposition of states. The probability wave, we might say, gives us the shape and density of a swarm of ghostly electrons distributed somehow in space. When an observation is made, only one of these ghostly electrons materializes. Suddenly and mysteriously, the probability wave "collapses" and the electron appears, as a whole particle, at one particular point.

The objective existence of an electron at some point in space, independent of actual observation, has no meaning. The electron seems to spring into existence as a real object only when we observe it.

Heisenberg's uncertainty principle tells us that it is not possible to measure at the same time the momentum and the position of a particle with whatever precision we might wish. The Copenhagen interpretation goes further. What is questioned is whether, prior to some observation, there is a particle that exists on its own and has a precise momentum and a precise position.

According to classical physics, the entire universe consists of nothing but ordinary objects, where by "ordinary object" we mean an entity that possesses attributes of its own, whether they are observed or not. Quantum mechanics, instead, denies the common-sense notion that ordinary objects are themselves made of ordinary objects. In Heisenberg's words, "Atoms are not things".

There are "static" attributes, such as mass or charge, which do intrinsically belong to an electron, and distinguish it from other kinds of particles. On the other hand, according to the Copenhagen Interpretation, there are "dynamic" attributes such as position or momentum, which seem to depend on how they are measured. A dynamic attribute seems to belong jointly to the electron and the measuring device. There is no hidden value of position that the electron "really" has when it is not being measured.

In classical physics, a system of interacting particles can be compared to some elaborate clock mechanism, which functions on its own, whether or not it is being observed. In quantum physics, the observer is viewed as interfering with the system under observation to such an extent that the system cannot be thought of as having an independent existence of its own. In the microworld, the very act of observing something changes it: the observer is very much part of the experiment.

The reality that is observed cannot be divorced from the observer and what he chooses to observe. In Bohr's view, there are no atoms, only measurements. The atom is a creation of the human mind to bring some order into the chaotic pattern of observations. Only what we observe can be considered real.

About any quantum experiment, according to Bohr, all that can be said is that, if physicists set up an experiment in a certain way and make certain measurements, they will get certain results. What are regarded as physical attributes of an electron are actually relationships between electrons and measuring devices. These properties "belong" to the whole experimental setup, not to the electrons.

To account for atomic phenomena, one must abandon the notion that the movement of a particle can be represented by a continuous succession of positions in space along a particular path. A subatomic particle does not appear to follow a well-defined trajectory at all. A particle seems to be able to go from one place to another without traversing the space in between!

The Copenhagen interpretation does not attempt to explain what might *really* be happening "behind the scenes" in the quantum world. It claims that *no* theory can explain subatomic phenomena in any more detail. It is not necessary to know how light can manifest itself both as particles and waves. It is enough to know that it does. Developing overall views about the nature of reality does not matter much. Pragmatically, what matters in physics is the development of mathematical equations that enable the physicists to predict and control the behavior of particles. In Bohr's words: "It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can *say* about nature." [2]

The Bohr-Einstein Debate

In October of 1927, some thirty eminent physicists met to discuss the meaning of the new quantum theory. Einstein, Planck, de Broglie and Schrodinger were among those who were disturbed by the direction the new theory was taking in the emerging Copenhagen interpretation.

To focus the issues, Einstein proposed a simple thought experiment in which we are asked to imagine a single electron passing through a very small hole. The probability wave associated with the electron is diffracted by the hole, and starts spreading in a hemispherical pattern toward a concentric hemispherical screen. There are two different viewpoints as to what actually happens.

In Einstein's view, the electron is a real particle with an existence of its own. Its associated probability wave must be supplemented by some still undiscovered process that will explain why the electron lands where it does. Otherwise, we would have to imagine some mysterious action-at-a-distance that would suddenly cause the wave to collapse. Instantly, the probability of the electron landing somewhere on the screen would become zero everywhere except at the point where the electron is detected. This instantaneous action-at-a-distance would violate the Special Theory of Relativity. Quantum mechanics, therefore, must be considered an incomplete theory.

In Bohr's view, instead, the quantum theory is complete. There is no additional process still to be discovered. We can talk only about what we can observe. There is no particle out there on its own; it materializes only when we look for it. There is no reality until that reality is perceived. Reality depends on what and how we choose to observe.

This was the beginning of an intense, but friendly, debate on the nature of reality between Bohr and Einstein, a debate that would continue for almost 30 years until Einstein's death in 1955. Over the years, Einstein proposed one thought experiment after another trying to undermine Bohr's interpretation. Again and again, Bohr was able to win the argument by showing how the thought experiment actually could not be carried as proposed by Einstein.

Ultimately, Einstein lost the debate. Reluctantly, he had to concede that Bohr's views were at least consistent. He refused to concede, however, that they were the last word. Someday, he was convinced, a new discovery would restore order to the world of particles.

At the heart of the debate was a fundamental concept of quantum mechanics: randomness. Quantum mechanics predicts only the probability of some result. Consider, for instance, the radioactive decay of a large number of identical atoms. The theory says that the decay is a completely random process. It can tell us precisely what percentage of the atoms will decay, but it cannot predict which particular atoms will.

Classical physics too acknowledged the randomness of many processes. For instance, it was accepted that, when a roulette wheel is spun, the ball will drop at random in one of the numbered compartments. In principle, however, it was believed that the winning number could be predicted if one knew exactly the location of the wheel at the instant the ball was dropped, the speed of the wheel at the time, and various other physical variables. The randomness of the game of roulette was seen as the result of our ignorance of certain "hidden variables".

The Copenhagen Interpretation, instead, asserts that there is something absolutely fundamental about randomness. Although one atomic nucleus decays and another does not, both were previously in identical states. There are no hidden variables that might explain why one nucleus decays and the other does not; just pure randomness. To Einstein and others, this violated a fundamental principle of science, the principle of causality, whereby every effect must have a cause. Einstein summarized his refusal to accept this with his famous remark "God does not play dice with the universe".

The idea of hidden variables was dealt a serious blow by John von Neumann (1903-1957), a Hungarian mathematician who moved to the United States in 1930. In 1932, he presented a mathematical proof, which stated that no theory based on hidden variables could ever properly describe the behavior of quantum entities. Von Neumann concluded that electrons cannot be ordinary objects, nor can they be made of ordinary objects that are presently unobservable. The existence of an ordinary reality underlying the quantum facts, he claimed, is mathematically incompatible with quantum theory. He was one of the greatest mathematicians of his day, and his conclusion went undisputed for more than 30 years

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The EPR Paradox

In 1935 in Princeton, Einstein and two other physicists, Boris Podolsky and Nathan Rosen, proposed a new thought experiment, known as the EPR experiment from the initials of the three men. Their intent was to show that, following impeccable reasoning strictly in accordance with the rules of quantum mechanics, they were led to a conclusion so absurd that the theory had to be viewed as incomplete.

A simplified version of the EPR experiment was later proposed by the American physicist David Bohm. It starts with generating somehow a pair of protons that are in close proximity and "correlated" with one another in such a way that they have equal and opposite "spins". If one spin is "up", the other must be "down". The actual spins, however, remain indeterminate until some measurement is made.

Suppose now that the two protons move in opposite directions until they are far apart. When we decide to investigate one of them, we find that its spin is "up". Quantum mechanics requires that the other proton orient itself to acquire an equal and opposite "spin down", as if it knew instantly the spin status of its twin.

Here is the key point of this thought experiment. Even though the two protons may be now millions of miles apart, quantum mechanics tells us that the second particle must be affected by something we have decided to do far away to the first particle. Einstein and his collaborators believed that "no reasonable definition of reality could be expected to permit this".

What appeared to be violated was the common-sense principle of "local causes", or "locality" principle. What happens in some area cannot be affected by what an experimenter may decide to do in some other distant area, if the two areas are so far apart that there is not enough time for a light signal to connect the two events.

In Einstein's view, the proton that had moved far away was independently real and had all along some particular spin. He could not accept that this spin could be affected instantly by what was done far away to the other proton.

In Bohr's view, one could talk only about the spin that was measured when it was measured. Until a measurement is actually performed, the two protons must be regarded as a single totality, however far apart they may be.

The EPR experiment had brought out an unexpected implication of quantum mechanics, "non-locality". It became known as the EPR paradox, and was never resolved in Einstein's lifetime.

Bell's Inequality

In 1966, the Irish physicist John Stewart Bell (1928-1990) showed that von Neumann's proof, which denied the possibility of hidden-variable theories, was based on a false assumption. Bell proved that hidden-variable theories could be made to work, provided we accept non-locality.

A "local reality" - the kind of common-sense reality envisioned by Einstein - is defined as one that is "local" (no influence can propagate faster than the speed of light) ***and*** "real" (whether we observe them or not, real particles exist "out there" with well defined properties of their own).

This definition of "local reality" plays a key role in a thought experiment proposed by Bell. In principle, it could be carried out on many "correlated" pairs of photons emitted simultaneously from an atom in two different directions. Bell showed that, if we live in a "local reality", then some particular pattern A of measurements must occur more often than some other pattern B. This is the famous "Bell's inequality" (A occurs more often than B).

On the other hand, if this inequality is violated, then ours is not a "local reality", which means that influences can propagate faster than the speed of light and/or particles do not exist independently of our observations.

Bell's criterion to test for local reality was quite specific; the trick was to carry out the very difficult experiment called for. At the time, not even Bell thought his experiment was a practical possibility.

Over the next 20 years, however, a number of ingenious experiments were actually carried out along these lines. The most comprehensive and conclusive of these experiments were those done by the physicist Alain Aspect and his colleagues in Paris in the early 1980's. The results of the Aspect experiments (and others) show that the Universe is not both "local" and "real".

These experiments "tell us that particles that were once together in an interaction remain in some sense parts of a single system, which respond together to further interactions. Virtually everything we see and touch and feel is made up of collections of particles that have been involved in interactions with other particles right back through time, to the Big Bang, in which the universe as we know it came into being. ... The particles that make up my body once jostled in close proximity and interacted with the particles that now make up your body."[3]

FEYNMAN'S CENTRAL MYSTERY

One of Feynman's key contributions to quantum theory was the idea that, when going from place A to place B, a particle takes account of every possible route, however complicated it might be.

Feynman's version of quantum mechanics says that we must calculate the effects of all the possible paths from A to B and add them together. It is called the "sum-over-histories" approach. The resulting wave function is the same as the one derived from Schrodinger's equation.

In his famous lectures on physics, to illustrate the strangeness of the quantum world, Feynman chose the 2-slit experiment, the one Young had used in the 1800's to "prove" the wave nature of light.

Feynman described the 2-slit experiment as "a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by explaining how it works. We will just tell you how it works. In telling you how it works, we will have told you about the basic peculiarities of quantum mechanics." [4]

For both water waves and light waves, we previously saw how, after going through two suitably narrow slits (or small holes) in some barrier, a wave gives rise to two diffraction waves, which spread out as two patterns of semicircular ripples and interfere with one another. In the case of light waves, a pattern of alternating dark and light fringes can be generated on a screen or photographic film placed at some distance on the other side of the barrier.

Following Feynman, let us consider now another version of the experiment, using a barrier with 2 holes. Imagine, he said, a somewhat wobbly machine gun shooting a stream of bullets at some armor plate with two holes A and B, each somewhat larger than a bullet. As it fires, the machine gun sprays the bullets randomly in a cone-like pattern aimed at the two holes in the armor plate. On the other side, at some distance from the plate, there is a backstop, perhaps a thick wall of wood, on which are mounted, close together, many little boxes or bins that can collect the bullets that go through the holes.

Suppose now that, after covering hole A, we shoot bullets for, say, 30 minutes, and then count the bullets accumulated in each little box. We will find the bullets distributed in a certain pattern. The box directly opposite hole B, which is open, will contain the largest number of bullets; nearby boxes will contain fewer bullets, and boxes further out will contain even fewer.

We repeat now the experiment with only hole B covered. Again, we shoot bullets for 30 minutes, and then count bullets in the various boxes. We will find the same distribution pattern, except that it is centered now in front of hole A, which is open.

We repeat the experiment one more time with *both holes uncovered*, and then count what we find in the various boxes. As we would expect, the number of bullets in each box is the sum of what we found there in the two previous experiments with one or the other hole uncovered.

In his lectures, back in the early 1960s, Feynman described next what happens when electrons are used in a two-hole experiment. The electrons are emitted one by one, go through the two holes of a barrier, and land on a screen where they can be detected. At the time, this was only a thought experiment, and Feynman described how the electrons were expected to behave according to quantum mechanics. (Actual experiments later confirmed these expectations.)

If we perform the experiment with *either hole covered*, we get a situation similar to what we saw for bullets. This is what we would expect since we are inclined to think of electrons as very tiny bullets. Like the bullets, the electrons arrive as identical individual lumps, one by one, each landing at some spot that will be generally different from one instant to another. Their distribution pattern will be similar to that of the bullets.

The situation, however, is strikingly different when the experiment is performed with *both holes uncovered*. The electrons still arrive, one by one, as identical individual lumps, but their distribution pattern is not the sum of the patterns observed when either hole is covered - as it was for bullets. The pattern appears to be random. Slowly but surely, however, it keeps building up to a pattern of several dark and light fringes that is characteristic of interfering waves. There are spots on the screen that receive many electrons when only one hole is open, and yet receive very few when both holes are open!

With both holes uncovered, the distribution of electrons detected on the screen is not the sum of the distributions when only one hole is open. What we get, instead, is an interference of probability waves from the two holes.

We can easily understand that a wave, which is spread out, can pass through both holes, creating diffraction waves that interfere with one another. An electron, however, still seems to be a particle, even if it has also wave-like properties. It would seem natural to expect that an individual electron must go through either one hole or the other. And yet, as reflected by the interference pattern of dark and light fringes that gradually develops on the screen, an electron supposedly going through one hole behaves quite differently depending on whether the other hole is covered or not.

The "central mystery" of quantum mechanics is that the electron behaves as if it "knows" what the situation at the other hole is.

More surprises are in store, as we consider a variant of the original thought experiment. Suppose we leave both holes open, but we place a detector by each hole so that we can monitor whether an electron does go through that hole. With this arrangement, we always detect an electron going through one hole or the other, never both at the same time. But now the interference pattern disappears!

The act of observing the electron wave with a detector makes it collapse and behave like a particle when it is going through the hole. Actually we don't need two detectors. Even if we monitor only one of the holes, the interference pattern disappears. The electrons going through the second hole "know" that we are looking at the first hole and behave like particles.

The electrons not only "know" whether both holes are open, they also know whether we are "watching" them, and they behave accordingly! If we set up the experiment expecting to see particles that go through one hole or the other, the electrons behave like particles, very tiny bullets, and no interference occurs. If, on the other hand, we don't attempt to see which hole they go through, they behave like waves, and interference occurs. Quantum mechanics seems to show that the observer's consciousness affects the nature of the physical reality that is observed.

In the mid-1980s, a team working in Paris was able to generate single photons going through an actual 2-hole experiment, one at a time. On the other side of the holes, some distance away, a photographic plate records the arrival of each photon as a white dot. The pattern of white dots appears random at first. But, as more and more photons keep landing, one by one, the white dots start merging to form the typical pattern of wave interference: white stripes with dark stripes in between, just as predicted by quantum theory. Each photon seems to "know" where to land on the film to make its own contribution to the overall interference pattern!

In 1987, a Japanese team carried out an actual two-hole experiment using electrons. The results were exactly the same as for the experiment with photons. Similar results were obtained in the early 1990s by a German team using atoms of helium.

Delayed-Choice Experiments

In the late 1970s, the eminent American physicist John Wheeler proposed, as a thought experiment, a variation of the two-hole experiment using photons. Detectors that can monitor the passage of the photons are placed somewhere between the two holes of a barrier and the screen where they are detected. We can then see whether the photons are behaving like particles or like waves *after* they have gone through the holes, but before they land on the screen.

If we choose not to look at the photons as they pass and switch the detectors off, the photons will create an interference pattern on the screen. On the other hand, if we choose to "look" and switch the detectors on, quantum mechanics says that no interference pattern will be formed. Paradoxically, whether the photons behave as particles or as waves as they go through the two holes is determined *after* they have gone through! Furthermore, we can wait until after the photons have gone through the two holes, before we even decide whether to switch the detectors on or off. If we look, we don't get an interference pattern; if we don't look, we do.

An actual "delayed-choice" experiment along these lines was carried out in the mid-1980s by two teams independently, one American, the other German. It confirmed the predictions of quantum mechanics. "The behavior of the photons is affected by how we are going to look at them, even when we have not yet decided how we are going to look at them!" [5]

In the early 1980s, Wheeler proposed a cosmic variant of his thought experiment extending over a huge span of time. The experiment involves photons that would have a choice of two different routes to reach Earth from a distant star. They could go either way, or they could mysteriously split up and travel both ways at once. Which route they follow - starting out, say, a billion years ago - would depend on whether or not an astronomer on Earth presently decides to switch on a detector attached to his telescope.

According to Wheeler, our misconception about this thought experiment is the assumption that, in his words, "a photon had some physical form before the astronomer observed it. Either it was a wave or a particle. Either it went both ways ... or only one way. Actually quantum phenomena are neither waves nor particles but are intrinsically undefined until the moment they are measured. In a sense, the British philosopher Bishop Berkeley was right when he asserted two centuries ago 'To be is to be perceived'." [6]

Wheeler has gone so far as to suggest that the entire universe exists only because someone is watching it.

OTHER INTERPRETATIONS OF QUANTUM MECHANICS

In the mid-1980's, eight top quantum physicists were interviewed in a British broadcast program. They all had different views of quantum mechanics, each firmly convinced that his interpretation was correct and the others were impossible.

Only two additional interpretations, which differ substantially from the Copenhagen interpretation, will be mentioned. Both have lately begun to gain wider recognition.

Wholeness and the Implicate Order

At the end of the 1940s, David Bohm (American, 1917-1992) refused to comply, when asked to testify before the Un-American Activities Committee of the House of Representatives about the political views of some of his colleagues in the Manhattan Project. Two years later, he was tried for contempt of Congress. Although acquitted, he found it impossible to get a job in the United States. He settled at Birkbeck College in London, England, where he developed his quantum interpretation over the next four decades.

Bohm was not deterred by von Neumann's "proof", which denied the possibility of "hidden variables" theories. As de Broglie had attempted back in 1925, Bohm pursued a quantum theory based on hidden variables and real particles that have at all times an intrinsic position and velocity. Any attempt to measure these properties, however, will destroy information about them by altering a "pilot wave" associated with the particles. This pilot wave is aware of conditions existing everywhere in the Universe, and guides its particles accordingly.

Through the pilot wave, everything in Bohm's reality is connected to everything else, and is instantly affected by whatever happens to everything else. Bohm writes about a universe of "undivided wholeness" and distinguishes between an "explicate order" (the one the laws of physics refer to) and an underlying "implicate order".

"Many-Worlds" Interpretation

A different interpretation was developed by Hugh Everett in 1957, when he was a student working under the supervision of John Wheeler. His basic idea is that, whenever the universe is faced with a quantum choice, the entire universe splits into as many copies of itself as there are possible options. For instance, in the two-hole experiment, when an electron is faced with the choice of two holes, the Universe splits into two copies: in one universe, the electron goes one way, while in the other universe, the electron goes the other way.

This theory "requires an infinite number of universes, each splitting into infinitely more versions of reality every split second, as all the atoms and particles in the universe(s) are faced with quantum choices, and follow every possible route into the future at once." [7]

The many-worlds interpretation makes exactly the same predictions as the Copenhagen interpretation. It has, for some, the advantage of avoiding the most vexing questions of the Copenhagen interpretation: When does the collapse of the wave function occur? Is consciousness an essential factor in the collapse of wave functions? The collapse of the wave function makes only one option real. In the many-worlds interpretation, instead, each option becomes real but in a different universe.

Wheeler initially endorsed the idea. A few years later, he changed his mind because he felt it carried too much "metaphysical baggage". After some 30 years of obscurity, the theory has met new interest on the part of some cosmologists.

Strictly speaking, the Copenhagen interpretation requires the existence of an observer *outside* the whole Universe to collapse all the wave functions and make reality real. To avoid this, some cosmologists prefer to believe that there really are countless universes.

The variety of conflicting interpretations of quantum mechanics is a vivid illustration of how subjective even the judgments of scientists can be. All the theories we have discussed are bizarre, whether we talk of particles that are not real until they are observed (Bohr), or of particles each traveling by all possible routes at once (Feynman), or of pilot waves that can sniff everywhere in the universe (Bohm), or of ever splitting universes (Everett). What is "metaphysical baggage" to one physicist is valid theory to another.