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# Summary of the Main Theses of This Book

Throughout this book, we have considered three questions:

(1) Does quantum mechanics put an “observer” (human or not) at the center of its description of the world?
(2) Does quantum mechanics imply the “death of determinism”?
(3) Does quantum mechanics mean that there exist instantaneous actions at a distance?

We first explained in Chap. 2, using the double-slit experiment, why there appears to be support for these three ideas: whether one slit or both slits are open influences the behavior of the particles, as shown by the interference patterns. And the same thing happens if we check a posteriori through which slit the particle goes. That gives credence to (1): “knowing” through which slit the particle goes seems to affect its behavior. Assertion (2) is supported by the fact that one cannot control or predict where the particle will land on the second screen and assertion (3) by the fact that the two slits can be far apart, although the interference effect does decrease with the distance between the slits, or if the second wall is close to the first one. This leads to paradoxes: in the delayed-choice experiment, it seems that one can determine by the choices we make now, what happened in the past, even billions of years ago.

In Chap. 3, we emphasized that the mere fact that one cannot predict or control certain events does not mean that they do not obey deterministic laws. Indeed those laws might be unknown to us. We also explained that events that do obey deterministic laws, like throwing coins or dice, may appear “random” if one does not describe their behavior in sufficient detail.



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In Chap. 4, we introduced the fundamental concept on which all quantum predictions are based: the wave function. We emphasized that the latter gives a very efficient way to predict the *results of measurements* carried out in the laboratory, but is not supposed to mean anything outside of that framework. Indeed, the rules of quantum mechanics assume that the wave function behaves differently when the quantum object is being measured or observed than when it is not. Outside of measurements, the wave function evolves deterministically, while, during measurements, it collapses in a random fashion.

With the wave function concept, one can predict the observed behavior in the double-slit experiment and the one of many other more complicated situations.

But, of course, this formalism seems to justify assertion (1), since measurements are given a special role in it, and it seems to justify assertion (2), since the formalism assigns probabilities to results of measurements but those probabilities cannot be derived from a deterministic dynamics, at least not in ordinary quantum mechanics.

In Chap. 5, we tried to go further by giving a meaning to the wave function that would go beyond the recipes outlined in Chap. 4. If we want to understand the collapse rule by analyzing the measurement process using the quantum mechanical formalism, we run into the problem of macroscopic superpositions, which are illustrated by Schrödinger's cat.

One can also try to give a statistical interpretation to the wave function, namely consider that it determines the probability of a particle to have certain properties, like a position and a velocity, whether we measure them or not, and then, consider that measurements simply reveal those properties. Introducing those properties means that one introduces what are called hidden variables, namely variables that complete the usual quantum description. But we then have to face the no hidden variables theorems: in particular, it is simply impossible to assign to particles a statistical distribution of positions and velocities, independently of measurements, that would coincide with the quantum mechanical predictions for those measurements.

This sort of results, maybe even more than the usual quantum formalism, lead some people to a form of despair or renunciation: one cannot understand what is going on in the microscopic world and we have to limit ourselves to "predict the results of experiments".

In Chap. 6 we discussed the opposite attitude: that everything is all right after all, since quantum mechanics predicts what one can observe and since everything we know about the world derives from our observations. But that attitude reflects a misunderstanding of the problem: the observations that one is talking about in quantum mechanics are observations made thanks to certain instruments in laboratories and they are treated as a *deus ex machina* by the usual theory. There is nothing remotely similar in any other scientific theory, where observations are explained as resulting from certain interactions between the physical world and our instruments. In physical theories other than quantum mechanics, these interactions are described by the theory and are not given a special status.

In Chap. 7, we turned to issue (3): we did show that there are perfect correlations in the world that cannot be explained by local causal mechanisms, where "local" means that those causal mechanisms propagate at a finite speed. This is certainly the most surprising consequence of quantum mechanics, but it is based on a simple logical argument and on well verified experiments. The argument consists in two steps: one is that the perfect correlations in certain spin experiments require that spin values be pre-determined before their measurements, if we rule out any nonlocal causal effects, or, in the analogical story with Alice and Bob, that both Alice and Bob have pre-determined and coinciding answers to the questions that they are asked when they arrive at X and Y. That part is due to Einstein Podolsky and Rosen and means that one needs "hidden variables", since those spin values are not included in the pure wave function description. The second step is due to Bell and is a no hidden variables theorem: assuming the mere existence of those pre-determined values leads to a contradiction. If one consider only one of those two steps, as is often done, nothing dramatic follows. But if one combine both, a local view of the world becomes untenable.

Chapter 8 is the heart of this book: we discussed there the de Broglie–Bohm theory, which is simply a completion of ordinary quantum mechanics. In that theory, particles have positions at all times, whether they are observed or not, and therefore also trajectories and velocities, and the motion of the particles is guided by their wave function. We showed that this accounts in the simplest possible way for the results of the double-slit experiment: the particle, being always localized somewhere, as particles should be, goes through only one slit. But the wave, being delocalized, as waves should be, goes through both slits and guides the particles in a way that leads to the interference effects.

An obvious objection to the de Broglie–Bohm theory is that, if the no hidden variables theorem of Chap. 5 does not permit an assignment of values to both positions and velocities, how come that in the de Broglie–Bohm theory, particles do possess both of those properties? The answer is simply that the "measured" values of the velocity in that theory do not coincide with the actual values of the velocity of the particles. We considered the simple example of a particle at rest in a box, namely with zero actual velocity, but whose "measurements of velocity" will agree with the quantum predictions that give a well-defined statistical distribution of velocities, which are in general not equal to zero.

This leads us to the deepest lesson of the de Broglie–Bohm theory: measurements other than measurements of positions (which simply record where the particle is) do not, in general measure any intrinsic property of the particles, but are genuine interactions between the latter and the measuring device.

So, not only does the de Broglie–Bohm theory give a clear physical meaning to the wave function, it also explains how measurements work, without making them a *deus ex machina*, as in ordinary quantum mechanics.

This also applies to the measurements of spin, introduced in Chap. 7. But applied to the EPR-Bell situation, it implies that the interactions between the particles and the measuring devices has a nonlocal character. Because of the results of Chap. 7, showing that there are nonlocal effects in Nature, this is a quality and not a defect of the de Broglie–Bohm theory.

Furthermore, one accounts in the de Broglie–Bohm theory for the randomness of the results of quantum experiments by suitable assumptions of the randomness of the initial positions of the particles. This point was not developed in detail, because it would be too technical to do so.

Finally, reconciling the nonlocality of the de Broglie–Bohm theory with relativity is an open question, but it is a problem caused by the nonlocality of the world, shown by EPR-Bell, not by the de Broglie–Bohm theory in particular.

In Chap. 9, we discuss a rather popular "interpretation" of quantum mechanics: the many-worlds one, where the wave function never collapses and the universe constantly splits into zillions of parallel universes in which copies of ourselves live different lives, totally unaware of each other. This interpretation has an obvious science fiction character, which can be appealing or not. But we argued that it cannot be formulated in a way that would make most copies of ourselves observe the quantum predictions.

The main claim of Chap. 10 is that critics of the orthodoxy, Einstein, Schrödinger, de Broglie, Bohm and Bell, far from being refuted, were generally ignored and misunderstood.

Bohr did not understand Einstein's objections, which were based on the implicit nonlocality of quantum mechanics if the latter is supposed to be complete, and not simply on the lack of determinism or on Heisenberg's uncertainty principle. Schrödinger's cat was a *reductio ad absurdum* of the usual quantum formalism but is nowadays often interpreted as showing that the unfortunate cat is both alive and dead before anybody looks at it.

De Broglie is a tragic figure in the sense that he did initiate the de Broglie–Bohm theory, but did not really believe in it (partly because of its nonlocal character) and was not supported in his endeavor by other critics, such as Einstein and Schrödinger.

When Bohm rediscovered and completed de Broglie's theory, in 1952, the times were as bad as they could be for the reception of that theory: first of all, after the war, people were convinced that the pre-war "philosophical" debates about quantum mechanics were either futile (the slogan being "shut up and calculate") or had been won by the "Copenhagen" side. Besides, Bohm was victim of the McCarthyite witch hunts, which forced him to leave the United States; this drastically limited his possibility of having his views given a fair hearing.

Finally, Bell's result is almost universally viewed as a no hidden variables result, which it is, but, since it rules out hidden variables that would be necessary to save locality (as shown by EPR), his result is, in reality, a nonlocality result. This produced a sort of comedy of errors: while Bell has always defended the de Broglie–Bohm theory, he is often supposed to have proven that hidden variables theories, such as the de Broglie–Bohm one, are refuted by experiments!

In Chap. 11 we reviewed various extrapolations and abuses of quantum mechanics in the pseudo-sciences, religions, philosophies, politics and human sciences. We argued that those abuses are illegitimate irrespective of one's views of the foundations of quantum mechanics, but that they have sometimes been encouraged by famous physicists.

In a nutshell, the message of this book is that:

(1) Ordinary quantum mechanics predicts results of all sorts of measurements with remarkable precision, but one cannot understand it as a theory about the world outside the laboratories. That is why the observer or observations play a central role in that theory.
(2) One can use experiments whose results are predicted by quantum mechanics in order to show, indirectly, that there are some nonlocal effects in the world.
(3) There is a way to complete quantum mechanics into a theory about the world, where experiments are accounted for by the theory and do not enjoy a special status. That theory is nonlocal, but deterministic and the quantum randomness comes only from randomness in the initial conditions of the particles.