Review of *Quantum Chance* by Nicolas Gisin

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Nicolas Gisin has written an accessible account of many of the physical and philosophical issues raised by quantum theory. Accessible, that is, to anyone with a certain amount of determination. In a short book, he brings out precisely what is truly revolutionary about quantum theory: I refer not to the still unproven claim that nature is somehow intrinsically indeterministic, but the fact, almost proven, that events in one place can sometimes instantaneously have effects somewhere else, and in a way that does not diminish with their distance. This is quantum nonlocality.

Gisin himself is one of the select group who has demonstrated this by astute combinations of crystals, optical fibres, and electronics, a startling read in itself, which will give the layperson some insight into what science can do these days. And at the same time, although an experimentalist, he remains equally concerned about understanding the deeper issues, as he stresses in the preface. The book reflects this through its clarity and commitment to the reader.

Everything is explained and illustrated, starting with the core subject of the book: local and nonlocal correlations. His aim is to derive and explain the significance of some inequalities discovered by the late CERN physicist John Bell, whose work has inspired a whole generation of other physicists. These inequalities must hold when correlations are local, but it turns out that there are some correlations between the results of experiments on so-called entangled particles which clearly violate them.

That was predicted soon after quantum theory came into being, but has only been demonstrated (almost) fairly recently, by Gisin among others. He describes several of his experiments in outline, focusing on the significance of the results and avoiding all unnecessary technicalities. He even discusses the remaining loopholes in these experiments, which necessitate the 'almost' in brackets above. And along the way, he introduces the notions of quantum cloning and entanglement, and he goes on to present applications, including one that he himself has already commercialised, viz., random number generators, not to mention quantum cryptography and quantum teleportation.

All this in only a hundred or so pages. One might think it must be superficial, but this is not the case. Brevity is achieved by another of Gisin's great talents, which is to focus on the essential and always attempt to expose it clearly, no matter how subtle it may be. Indeed, there is more here than just a popular account for the curious bystander. The book should also interest actors in the field, be they physicists or philosophers, for Gisin does not hesitate to bring up the major issues that arise from these discoveries: the question, still undecided, of whether the world is deterministic or indeterministic, and the consequences this may or may not have for our notion of free will.

Interestingly, his book instantiates one aspect of a schism that has sprung up among the many partisans of the work of John Bell. On the one hand, it is clear that the discovery of Bell's inequality, which must hold in any locally causal world and yet which contradicts some of the correlations predicted by quantum theory, has inspired tremendous experimental advances, beginning with the work of Alain Aspect in the 1980s, in the attempt to put quantum theory to the test on this issue. (And quantum theory has been more or less vindicated.) On the other hand, Bell was more than sympathetic to the work of David Bohm, who developed what is often known today as Bohmian mechanics, a fully deterministic account of non-relativistic quantum physics.

Bell's motivations were deeply philosophical: Bohmian mechanics exemplifies a feature he considered essential in any theory that has something to say about what happens in the world around us, described in the arena we know as spacetime, namely, it contains local beables in its ontology, i.e., entities that do things in space as time goes by. For one of the key difficulties with quantum theory as it is usually expounded, with an ontology which at best contains only wave functions, is that wave functions don't 'live' in spacetime at all, but in configuration space. This leaves us with a major problem in deducing anything about the world we actually observe, an issue that has become known as the measurement problem. In Bohmian mechanics then, there is no measurement problem.

It seems clear that, in his support for Bohmian mechanics, both from a philosophical point of view and as an essential part of any course on modern physics, Bell was not motivated by the idea of 'saving' determinism. On the other hand, the idea that quantum theory proves the world to be inherently indeterministic has become a dogma today, which often clouds people's view of what we know, or rather, gives a false impression of what options actually remain. For in the higher spheres of physics and philosophy, there is still a serious debate, and Gisin makes his allegiance clear. Along with most of the experimentalists and others achieving such technologically astonishing results in the quantum optics community, he is a staunch supporter of indeterminism. For him, there is no option but to accept the existence of 'le vrai hasard', that is, true randomness or the possibility of intrinsically chance-like events that are not caused by anything that came before (or at least, are not fully caused by such).

And Gisin works hard to lay the ghost of determinism, throughout the book. His argument begins in Box 5 (p. 22), with what he takes to be a principle of good old common sense: there can be no communication without the transmission, point to point through space, of something physical. Then in Box 7 (p. 31), he argues that determinism would imply precisely this kind of communication without transmission. However, there is a very telling loophole in the argument of Box 7. According to the hypothesis of determinism, there would be some relation that determines the result produced by each box in his version of 'Bell's game' as a consequence of the direction in which the joystick is pushed. His idea then is that any deterministic relation between the direction of one joystick and its result would allow the other player to read off what choices were made for that first joystick from a distance and thus achieve communication without transmission.

At first glance, the argument is very convincing, for we have a simple equation between four variables (two joystick positions and two results). When two of the variables are related in a *known* way, viz., one of the joystick positions and its result, the equation becomes a relation between three variables, two of which are known by the other player. The trouble is that the latter must *know* the relation between the first player's joystick position and its result. The author claims that nothing could stop the second player from knowing this relation, but here is the problem.

This is the annoying thing about the *mere existence* of a theory like Bohmian mechanics, for those that don't like it, whether it be a true theory (in the sense of corresponding to what happens out there) or not. For it is fully deterministic and makes the same predictions as quantum mechanics. So how can that square with the conclusion we have just reached? In fact, Bohmian mechanics manages to preserve a deterministic world despite these arguments because the actual particle configuration of the world which it postulates cannot be known by anyone. Put another way, the argument in Box 7 in conjunction with the existence of Bohmian mechanics might prove that, in Bohmian mechanics, one cannot ever establish the actual particle configuration of the world. But Bohmian mechanics knows this already, even provides an explanation for it, because it shows why measurement experiments do not establish pre-existing particle configurations, but create new ones.

It thus becomes crucial to dispose of Bohmian mechanics in some other way for Gisin's argument to work. By the end of Chap. 3, true randomness and nonlocality have become indissociable, apart from this remaining issue. In the author's view, only the hypothesis of irreducible randomness can prevent the second player from knowing the relation between the first player's choice and her result, because if this were not true intrinsic inescapable randomness, the second player would end up finding the relation, and so would the world of physics. But if Bohmian mechanics is right, the world of physics would not find that relation, and it tells us why.

Since I have made it clear how much I admire Gisin's book, let me play devil's advocate for a moment. Deeper down, one suspects that the author has an ulterior motive: to rescue the notion of free will from what he feels would be the dire prospect of a deterministic world. He concludes Chap. 3 with the claim that winning this version of Bell's game without communication necessarily implies that the two players' boxes produce results in a truly chance-like way, and that the randomness is fundamental and cannot be reduced to a complex deterministic mechanism. In the author's own words, this means that nature is capable of 'pure acts of creation'. And, of course, human beings, too.

On the other hand, the kind of creation *we* engage in, when we make any kind of choice, is not really intended to be intrinsically random! The implication of the kind of reasoning in the last paragraph, which looks so appealing on the face of things, doesn't really bear scrutiny. In fact, we would very much like our choices and decisions to have causes in the reasoning that lay behind them, and that reasoning in the further reasoning prior to that, and all this will have neural correlates, which puts things firmly back into the realm of a deterministic world view, although not yet necessarily one based on fundamental physics, in an absolutely reductionist way.

Free will is an issue in this book. There is a short section in Chap. 9 in which the author makes his position clear, in the discussion of what has become known as superdeterminism, which is really just the same thing as determinism, except that it explicitly extends to our own 'acts'. A desperate hypothesis, in the author's view. Certainly, trying to explain quantum correlations as resulting from a situation in which the experimenters' choices are themselves somehow dependent on what the entangled pair is doing *is* a desperate hypothesis, of little theoretical interest. Particles don't care about us. We can safely detach the issue of our own free will, whatever it may be, from the problems of quantum physics. Unless nature cares enough about us to be particularly mischievous, the choices being made by a brain can easily be sufficiently independent of the agitations of an entangled pair of particles to make entangled pair experiments worth doing. Bell himself put it this way.

Furthermore, it is not at all clear that, in a superdeterministic world, we could win Bell's game with certainty, i.e., more often than would be allowed by quantum physics, as Gisin suggests (p. 90). That assumes precisely what Bohmian mechanics would prove to be impossible, if one accepted Bohmian mechanics, namely that one can determine exactly what all the Bohmian particles are doing at any given time. As a consequence, this theory, even the very existence of this theory, be it true or false, remains a serious thorn in the side of anyone who would like to 'save' free will in this way.

So what does Gisin have to say explicitly about Bohmian mechanics? There are several remarks aimed in its direction. Here is one, where the author introduces this theory in the following way (p. 87):

> One might also consider an influence able to travel at infinite speed, still as defined relative to some privileged frame. This is indeed possible mathematically, as was shown by David Bohm in 1952 [...]. However, this hypothesis implies that influences can instantaneously connect arbitrary regions of space. But how would we understand space if influences could instantaneously connect arbitrarily remote regions? In a sense, accepting such influences as an explanation for nonlocal correlations means that one accepts that these influences do not in fact propagate in our space, but follow some short cut of zero length outside our space. The explanatory power of such a hypothesis thus seems weak to me. Few physicists are interested in this alternative, even though it must be said that it is viewed sympathetically by quite a few philosophers.

This is to be contrasted with Gisin's own solution to this conundrum in terms of the notion of true randomness, which I think can be captured best by the following quote (p. 105):

> [...] as soon as we have taken on board the idea that these events are irreducibly chance-like and not just something pre-existing that was hidden from us, we understand that nothing can prevent this randomness from cropping up in several places at once without that implying any communication between those places.

But the remark that physicists are not interested in Bohmian mechanics is striking! Few physicists were interested in Bell's inequalities in 1980! Fortunately, we do not chase truth by democratic election.

Here is a further remark (pp. 90–91):

> Some physical theories are deterministic, as exemplified by Newtonian mechanics or certain interpretations of quantum theory. Raising these theories to the status of ultimate truths in a dogmatic, almost religious way amounts to a straight error of logic, since they are contradicted by our experience of free will.

This is a heartfelt comment about those who still uphold Bohmian mechanics as a possible theory, and in particular about the way they uphold it. But more importantly, the conclusion depends heavily on there being a contradiction between living in a deterministic world and being able to do experiments. He puts it this way:

> If we did not have free will, we could never decide to test a scientific theory.

The point I wish to make above is that, provided our decisions can remain sufficiently independent of what is happening within the subject of our experiment, e.g., an entangled particle pair, then there would be no problem deciding to test a theory, even in a deterministic world. This is effectively Bell's own argument for the irrelevance of superdeterminism.

But that still leaves the problem of whether we could have free will in such a world. Gisin puts it like this:

> I have no proof that you have free will, but I certainly enjoy free will, and you will never be able to show otherwise.

In a way, he is saying: "I know it, so it must be true." Fortunately, he never uses this form of argument to deal with issues of physics! But we get the point. We do feel that our decisions are our own, and how could that be if everything were predetermined in the early stages of the universe? These are big questions. Maybe in this instance we need to turn to philosophers like Daniel Dennett.

A final remark aimed at Bohmian mechanics appears in footnote 27 on p. 94, concerning the possibility of denying the existence of true randomness:

> Of course, one can cheat here. One can always adjoin nonlocal hidden variables to the quantum theory which determine the whole future. These parameters could simply *be* the future! They are necessarily nonlocal and hidden from our present day view. Quite frankly, that does not look very interesting to me. Once again, it's more a play on words than anything else.

Of course, Bohmian mechanics postulates particles, Bell's local beables, and given their positions at any time and given the wave function, one does know the whole future, because the theory is entirely deterministic. But the existence of these particles and the kind of dynamics they engage in is not postulated in anything remotely like the arbitrary way suggested here by Gisin's proposal for simulating the future, which is purely ad hoc.

In any case, the crunch comes for all our arguments when we try to square up quantum nonlocality and relativity theory. Once again, Gisin's readers will find a to-the-point discussion of the problem and several remarkable experiments he himself has run to eliminate some of the suggestions that have been put forward here. But once again, it is striking that Bohmian mechanics is the theory that brings out most starkly what the problems are going to be, just as it shows most clearly the significance of quantum nonlocality: the wave function is a function on configuration space, not on space, and the very notion of a configuration space depends on a choice of spacelike hyperplane. In this connection, Gisin has recently published a short and crisp disposal of any covariant deterministic nonlocal hidden variable extensions of quantum theory. The only way out, mentioned at the end of that paper, is to assume the existence of a preferred universal reference frame which determines unequivocally one and only one time ordering for all events. But the Bohmians have long since established this explicitly for the case of theories postulating particles with continuous worldlines. The debate is far from through!

So finally, returning to the schism among Bell's supporters mentioned above, we may wonder how it might have come about? Why are these two communities, the Bohmians and the quantum opticians, so much at loggerheads? At the end of the day, the answer may be purely sociological, a consequence of the fact that both have been marginalised by the greater scientific community (see Gisin's remarks about the difficulty in publishing anything about Bell's inequality on p. 92), although the opticians have been getting their revenge since Aspect's experiment. Both groups have had to fight to be heard, and the Bohmians are still in this position to some extent, despite a huge amount of progress on this front. But since Bell himself promoted both, with such sound arguments all round, perhaps the time has come for greater mutual understanding.