

Foreword

“Love at first sight!” was how Nicolas Gisin described his emotion when he learned about Bell’s theorem. When I heard this, I relived an autumn day of 1974 when I was immersed in study of John Bell’s paper, little known at the time, and understood that it was possible to render an experimental verdict on the debate between Bohr and Einstein on the interpretation of quantum mechanics. Even though a few physicists knew of the problem raised by Einstein, Podolsky, and Rosen (EPR), not many had heard of Bell’s inequalities, and few were those who considered questions relating to the fundamental concepts of quantum mechanics worthy of serious attention. The EPR paper, published in 1935 in *Physical Review*, was readily available in university libraries, but the same could not be said for the paper by Bell, published in an obscure new journal that was destined to disappear after only four issues. In those pre-internet days, papers not published in the major journals had to rely on photocopies for their dissemination. I had got my own copy from a file put together by Christian Imbert, a young professor at the *Institut d’Optique*, on the occasion of a visit by Abner Shimony, invited to Orsay by Bernard d’Espagnat. But once under the spell of Bell’s ideas, I decided that my doctoral thesis would deal with experimental tests of Bell’s inequalities, and Imbert accepted to take me under his wing.

In Bell’s (impressively clear) paper, I was able to identify the crucial challenge for experimentalists: altering the orientations of the polarization detectors while entangled particles were still propagating from their source into the measurement regions. The point was to preclude influence of the polarizer orientations either on the emission mechanism or on the measurement, by application of the principle of relativistic causality, which forbids physical effects from propagating faster than the speed of light. Such an experiment would be able to scrutinise the essence of the conflict between quantum mechanics on the one hand and the world view held by Einstein on the other. Einstein defended local realism, which combines two principles. First, that there exists a *physical reality* of a system. Second, that a system cannot be influenced (the *locality assumption*) by anything that happens to another system separated from the first by a spacelike interval of spacetime, since those two systems would have

to communicate with influences propagating faster than light. Eventually, our experiments confirmed the predictions of quantum mechanics, forcing physicists to give up local realism, the view of the world defended so convincingly by Einstein. But should we give up realism or give up locality?

The idea that one should give up the notion of physical reality is not one I find convincing, because it seems to me that the role of a physicist is precisely to describe the reality of the world, and not just to be able to predict the results that show up on our measurement devices. But then, if quantum mechanics is confirmed on this count—as indeed seems unavoidable today—does that mean we must accept the existence of nonlocal interactions, in apparent violation of Einstein’s principle of relativistic causality? And is there any hope of exploiting this quantum nonlocality to transmit a usable signal, e.g., to switch on a lamp or place an order at the stock exchange, that would travel faster than light? But this is where another characteristic feature of quantum mechanics comes into play, namely the existence of *fundamental quantum indeterminism*. This amounts to the absolute impossibility of influencing the actual result of any specific experiment whenever quantum mechanics predicts that several results are possible. It is true that quantum mechanics can be used to make very accurate calculations of the probabilities of the various possible results, but these probabilities have only a statistical meaning when the same experiment is repeated many times, and they tell us nothing about the result of any specific experiment. It is this *fundamental quantum randomness* which forbids the possibility of faster-than-light communication.

Among the many popular accounts of recent progress in quantum physics, the present book by Nicolas Gisin takes a definite line here, stressing the key role played by this fundamental quantum randomness, without which we might dream one day of designing a superluminal telegraph system. If it ever became a reality, this mythical invention of science fiction would require a radical revision of physics as we know it today. Naturally, the aim here is not to suggest that there might be untouchable and immutable physical laws, beyond any form of revision—quite the contrary, I am personally convinced that every physical theory will one day be superseded by one of wider scope. But some of our theories are so fundamental that their revision would involve a truly far-reaching conceptual revolution. And although we all know of a few examples of such revolutions through human history, they are nevertheless so exceptional that they should not be envisaged lightly. In this context, the explanation as to why quantum nonlocality, no matter how extraordinary it may be, cannot overthrow the principle of relativistic causality which forbids superluminal communication seems to me a particularly important feature of Nicolas Gisin’s book.

The fact that this book adopts a particular stance on this issue, in contrast to other popular accounts, should come as no surprise, since Nicolas Gisin has been one of the key players in the new quantum revolution that took place in the last quarter of the twentieth century. The first quantum revolution, at the beginning of the twentieth century, was based on the discovery of wave-particle duality. It provided a way of describing with great accuracy the statistical behaviour of atoms that make up matter, of the clouds of electrons that conduct the electric current in a metal or semiconductor, and of the billions and billions of photons in a beam of light. It has also provided tools to understand the mechanical properties of solids, whereas classical physics was unable to explain why matter, made up of positive and negative charges that attract one another, does not simply collapse. Quantum mechanics has given a precise quantitative description of the electrical and optical properties of materials, and offers the conceptual framework needed to describe phenomena as surprising as superconductivity and the strange properties of certain elementary particles. It was in the context of this first quantum revolution that physicists invented new devices like the transistor, the laser, and integrated circuits, which have brought us today into the age of the information society. But then towards the 1960s, physicists began to ask new questions that had been pushed aside during the first quantum revolution:

- How can we apply quantum physics with its purely statistical predictions to single microscopic objects?
- Do the astonishing properties of *entangled pairs of quantum objects*, as described in the 1935 EPR paper but never actually observed, really correspond to the way nature behaves, or have we reached the limits of quantum mechanics with this issue?

It was the answers to these questions, first given by experimentalists, then further refined by theoreticians, that launched the second and ongoing quantum revolution.¹

The behaviour of individual quantum objects has been the subject of lively debate between physicists. For a long time, the majority of the physics community thought that the question itself made little sense, and that it was in any case of no importance since it seemed inconceivable that one could ever

¹ See, for example, A. Aspect: John Bell and the second quantum revolution, foreword of J. Bell: *Speakable and Unsayable in Quantum Mechanics: Collected Papers on Quantum Philosophy*, Cambridge University Press (2004); J. Dowling and G. Milburn: *Quantum technology: the second quantum revolution*, *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* **361**, 1809, pp. 1655–1674 (2003).

observe a single quantum object, let alone control and manipulate it. In the words of Erwin Schrödinger:²

It is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo.

But since the 1970s, experimentalists have developed ways to observe, manipulate, and control single microscopic objects such as electrons, atoms, and ions. I still recall the enthusiasm at the international conference on atomic physics in Boston in 1980 when Peter Toschek presented the first image of a single trapped ion, observed directly by the fluorescence photons it emitted under laser illumination. Experimental progress has since led to direct observation of quantum jumps, thus ending decades of controversy. It has also demonstrated that the quantum formalism is perfectly capable of describing the behaviour of single quantum objects, provided that one interprets the probabilistic results of the calculations in the right way. As for the second question, concerning the properties of entanglement, the quantum predictions were first tested on pairs of photons, in a series of experiments that is gradually converging upon the ideal conditions dreamt of by theoreticians like John Bell. And these experiments have consistently validated the quantum predictions, however surprising they may seem.

Having put together an applied physics group working on optical fibres in the 1980s, and having always had a personal and theoretical interest in the foundations of quantum mechanics (although secretly, or at least discreetly with regard to his employer, since in those days raising questions of this kind was not necessarily considered a worthwhile occupation), it was quite natural that Nicolas Gisin should have been among the first to test quantum entanglement on photon pairs injected into optical fibres. With his detailed knowledge of optical fibre technology, he was able to use the commercial telecommunications network around Geneva to demonstrate that entanglement is maintained even at separations of several tens of kilometers, to the surprise of the experimenters themselves! He used several conceptually simple tests to bring out the absolutely astounding features of entanglement between remote events, and to implement a quantum teleportation³ protocol. Combining his skills as a theoretician on quantum foundations and expert in optical fibre applications, he was among the first to develop applications of entanglement such as quantum cryptography or the production of truly random numbers.

² E. Schrödinger: Are there quantum jumps? *British Journal for the Philosophy of Sciences*, Vol. III, p. 240.

This combination of talents is evident throughout this fascinating book, which succeeds in presenting the subtle issues of quantum physics in a language that remains accessible to the general non-scientific public, and without recourse to mathematical formalism. He explains entanglement, quantum nonlocality, and quantum randomness, and describes a number of their applications. But this is more than just a popular account, and quantum specialists will find deep discussions of these phenomena, the true nature and consequences of which still remain largely beyond our grasp, as the author points out. Concerning the question as to whether the experimental refutation of local realism compels us to abandon the notion of physical reality or the idea of locality,³ I take the same line as Nicolas Gisin: even if the concept of local realism may have been consistent and intellectually satisfying, cutting it into two pieces and keeping only one of them is distinctly less so. How should one define the autonomous physical reality of a system that is localised in space-time if this system is affected by what happens to another system separated from it by a spacelike interval? This book suggests a less brutal solution by showing that, if one takes into account the existence of fundamental quantum randomness, a nonlocal physical reality can be allowed to coexist in a more peaceable way with the relativistic causality so dear to Einstein. In this manner, even those physicists who know of these issues will find matter for reflection in Nicolas Gisin's book. And as regards the non-specialist reader, discovering here the mysteries of entanglement and quantum nonlocality, she or he will be carried straight to the heart of the problem and learn of all its subtleties, explained with enlightening clarity by one of the world's leading experts.⁴

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³ We may forget the desperate solution that consists in rejecting the notion of free will, a step that would make human beings into mere puppets under the direction of goodness knows what kind of Laplacian determinism.

⁴ In 2009, Nicolas Gisin was the first winner of the prestigious John Stewart Bell prize, attributed for research on foundational problems of quantum mechanics and their applications.

Preface

Had you lived at the time of the Newtonian revolution, would you have wished to understand what was going on? Today, quantum physics gives us the opportunity to live through a conceptual revolution of similar importance. This book aims to help you understand what is happening, without mathematics, but also without trying to conceal the conceptual difficulties. Indeed, while physics needs mathematics to explore the consequences of its hypotheses and to precisely calculate some of its predictions, mathematics is not needed to tell the great story of physics. For what is interesting in physics is not the mathematics but the concepts. So my purpose here is not to manipulate equations, but to *understand*.

Certain parts of the book will demand a genuine intellectual effort on the part of the reader. Everyone will understand something and no one will understand everything! In this field, the very notion of understanding is blurred. But I claim nevertheless that everyone can understand at least a part of the conceptual revolution that is under way, and take pleasure from that understanding. To achieve this, one must simply accept that not everything is going to be transparent, and certainly not start out with the opinion all too often voiced that understanding physics is a hopeless task.

If part of the discussion seems too difficult, just read on. What comes next may throw light on the matter. Or sometimes you will realise that it was just some subtle point slipped in for my physicist colleagues, for they too may take pleasure in reading this book. And if necessary, go back later and reread those passages that caused you problems. The important thing is not to understand everything, but to acquire an overview. At the end of the day, you will find that one really can understand quite a lot of quantum physics without the need for mathematics!

Quantum physics has often been the subject of verbose interpretations and fuzzy philosophical dissertations. In order to avoid such pitfalls, we shall only have recourse to common sense here. When physicists carry out an experiment, they are questioning an external reality. The physicist decides what question to ask and when to ask it. And when the answer comes back, for example, in the form of a little red light that comes on, they do not ask themselves whether

that light is really red or whether it is just an illusion of some kind. The answer is red' and that's the end of it.

The reader will see that certain anecdotes turn up in several chapters of the book. My experience as a teacher has taught me that it is often extremely useful to repeat certain important points in different contexts. Finally, the book makes no claims to historical accuracy. Any notes on my illustrious predecessors reflect only my own impressions, picked up over the 30 years of my life as a professional physicist.

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Quantum Chance

Nonlocality, Teleportation and Other Quantum Marvels

Gisin, N.

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