



Nicolas Gisin

Quantum Chance

Nonlocality,
Teleportation and Other
Quantum Marvels

Foreword by Alain Aspect

 Springer

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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 Unspeakable 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 teleportation' 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

Palaiseau, May 2012

Alain Aspect

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.

Introduction

In our most tender age, we learn that, to interact with an object that lies beyond our reach, only two possibilities are open to us. Either we move ourselves over to it, crawling toward it as babies do, or else we procure some long object like a stick which allows us to extend our reach. Later on we discover that more sophisticated mechanisms can also be put into effect, like dropping a letter into the mail box. The letter will be collected by a postman, sorted by hand or by machine, carried by lorry, train, or plane, and finally delivered to the door of the person whose name features on the envelope. Internet, television, and many other everyday examples teach us that, at the end of the day, any interaction and any communication between two spatially separated objects must propagate continuously from one point to the next by some mechanism which may be complex, but which always follows a continuous trajectory that can be identified in space and in time, at least in principle.

Nevertheless, quantum physics, which explores a world beyond the one we can perceive directly, asserts that objects spatially remote from one another can sometimes form a single unit. Indeed, for these systems, no matter how far apart their components, if we should prod one or the other of them, both will quiver! But how could we believe such a thing? Can such an assertion be put to the test? How should we understand it? And could we use this strange effect of quantum physics to communicate at a distance by exploiting these remote objects forming a single whole? These are the main questions we shall try to answer in this book.

I will attempt to share with you this fascinating discovery of a world that cannot be described by interactions propagating continuously from one point to the next, a world in which so-called nonlocal correlations become a fact of life. Along the way, we shall encounter the notions of irreducible chance, correlations, information, and even free will. We shall also see how physicists produce nonlocal correlations, how they exploit them to create absolutely secure keys in cryptography, and how these wonderful correlations can be used for quantum teleportation. Another aim of this book will be to illustrate the scientific method. How can one convince oneself that something totally counter-intuitive is actually true? What proof is required for such a change of

paradigm, and to accept a conceptual revolution of this kind? Stepping back for a moment, we shall see that the story of quantum nonlocality is actually rather simple and very human. And we shall also see that nature produces chance events (irreducibly chance-like!) which can occur at widely removed spatial locations without anything propagating from point to point along any path joining those locations. But we shall find that the chance-like character of these effects prevents any possibility of using this form of nonlocality to communicate, thereby saving from contradiction one of the fundamental principles of relativity theory according to which no communication can travel faster than the speed of light.

We are living in an extraordinary age. Physics has just discovered that one of our deepest intuitions, namely that objects cannot ‘interact’ at a distance, is not correct. The scare quotes on the word ‘interact’ remind us that we must clearly specify what we mean by that. Physicists explore the world of quantum physics, a world populated by atoms, photons, and other objects that seem quite mysterious to us. Missing out on this revolution without giving it further attention would be as much a shame as remaining ignorant of the Newtonian revolution or the Darwinian revolution, had we been their contemporaries. For the conceptual revolution taking place today is of no lesser importance. It completely overturns our previous pictures of nature and will doubtless give rise to a range of new technologies that will simply look like magic.

In Chap. 2, we present the notion of correlation which lies at the heart of the matter by discussing a game that we shall refer to as Bell’s game. We show there that certain correlations cannot be produced if we are only allowed interactions propagating from point to point through space. This chapter will be crucial for the following, even though there will be no mention of quantum physics. It is very likely the most difficult chapter to understand, but the rest of the book will be there to help you.

We then ask how we should react if someone should ever win Bell’s game, something that is apparently impossible even though it is an assertion of quantum physics, before confronting the idea of true chance in Chap. 3 and the impossibility of cloning quantum systems in Chap. 4. The following two chapters introduce this strange theory of quantum physics, first considering the theoretical concept of entanglement, then describing the relevant experiments and drawing the inevitable conclusion that *nature is nonlocal*.

But before accepting this conclusion, we shall ask whether it really is unavoidable. In Chap. 9, we shall survey many imaginative attempts by physicists to save a local description of nature. This story is still hot news and very much a topic of current affairs in the world of physics. Furthermore, it illustrates the natural cunning of the physicist! We continue our story in Chap. 10 by describing some of the fascinating research that is still ongoing. This will get us right up to date in the world of scientific research.

What Use is it?

This is the question I am most often asked. It is almost as though one should never do anything that has no immediate application. I could answer: “What’s the point of going to the cinema?” True, I am paid to do this research I love so dearly, while I have to pay to go to the cinema, so I try to come up with a more politically correct reply. But quite frankly, the best answer is simply that it is so fascinating! Although I direct an applied physics group, I don’t leap out of bed in the morning hoping to invent some new gadget. I am simply fascinated by physics! Just to understand nature, and in particular to understand how it can produce nonlocal correlations, is sufficient motivation. But then, why do I work in an applied physics group? Is it simple opportunism? In fact, there is a very good reason for being concerned with applications even when, and perhaps especially when, our deepest motivation is to understand the concepts. For a new concept of this relevance is sure to have consequences. For one thing, it will necessarily open up new prospects on the practical level. And the more revolutionary the concept, the more futuristic the applications. The great advantage of working on potential applications is precisely that it provides a tool for testing the underlying concepts. In addition, once an application has been identified, no one can deny the relevance of the concept! For how could one deny the relevance of a concept that underpins a working application in the real world?

The story of quantum nonlocality provides a first-rate illustration of this. Up until the first application, entanglement and nonlocality were largely ignored, even maligned as purely philosophical issues by the vast majority of physicists. Courage and even a certain audacity⁵ was required by anyone who wished to consider these things before 1991. Almost no academic positions were attributed to this line of investigation, while today absolutely everyone is following the results of this research. Naturally, the governments that finance these research centers are more concerned with the quantum technologies than the concepts that underlie them, but the important thing is that students in these centers should be learning about this new physics.

Chapter 7 presents two applications that have already been commercialised: quantum cryptography and quantum random number generators. Finally, quantum teleportation, the most surprising of all the applications, will be described in Chap. 8.

⁵ When Alain Aspect was beginning his research career, he went to see John Bell and suggested carrying out Bell’s experiment. To this Bell replied: “Do you have a permanent post?” With all his experience, Bell knew that it was risky for any young physicist to work on a subject that was held in such contempt by the scientific establishment.

Acknowledgement

Having written this book, I think of all my students and other collaborators who have provided such stimulating interactions. I would also like to thank all those who read and criticised the first versions, and in particular the editor of the French edition, Nicolas Witkowski, and also to Stephen Lyle for the English translation. This book owes much to their patience and skills. Thanks also to the *Fonds national suisse de la recherche scientifique* and to Europe for generous funding of my research lab, and to the University of Geneva for being such a pleasant place to work. Finally, I thank providence for allowing me to live in such an exciting age for physics, and to contribute to it in my modest way.

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1

Appetiser

Before presenting the main theme of this book, I would like to begin with two short stories that will help to set the scene. One is a true story about something that happened in the past, while the other is pure fiction, but might actually come about in the near future.

Newton: So Great an Absurdity

Everyone has heard of Newton's universal theory of gravity, according to which all objects attract one another in a way that depends on their masses and the distance between them (or more precisely, the inverse square of that distance, but that will not be important here). For example, the Sun and the Earth are bound together by an attractive force that balances the centrifugal force and holds the Earth on an approximately circular orbit around the Sun. The same goes for the other planets, for the Earth–Moon system, and even for the whole of our galaxy, which revolves around the center of a cluster of galaxies.

But let us focus on the Earth–Moon system. How does the Moon know that it must be attracted by the Earth in a way that depends on the mass of the Earth and the separation between the two? For that matter, how does the Moon know the mass of the Earth and its distance away from us? Does it use some kind of measuring stick, like the baby mentioned earlier? Or does it throw little balls of some kind? Indeed, does it communicate in some special way? This apparently childish question is actually deadly serious. In fact, it greatly intrigued Newton, for whom the hypothesis of universal gravitation, although he discovered it himself and it had brought him such fame, was so absurd that no healthy mind could take it seriously (see box below).

But for the moment, suffice it to say that Newton's intuition was correct, even though it took several centuries and the genius of Einstein to fill the conceptual gap and provide a satisfactory answer. Today, physicists know that the action at a distance which occurs in gravitation, or indeed in the interaction between two electric charges, is not altogether instantaneous. Rather, it results from the exchange of messengers, whence the 'little balls' conjecture mentioned

above turns out to be the right one. These messengers are tiny particles to which physicists attribute names. The messengers for gravity are called gravitons, while those for electric forces are called photons.

Box 1. Newton. That Gravity should be innate, inherent and essential to Matter, so that one Body may act upon another at a Distance through a Vacuum without the mediation of any thing else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity, that I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it.¹

In this way, since Einstein, physics has described nature as a set of localised entities which can only interact with one another contiguously from point to point through space. This idea certainly fits with our intuition of the world, as it would with Newton's. But today, physics is also based on a second theoretical foundation, namely quantum physics, which describes the world of atoms and photons. Einstein was also involved in this discovery. In 1905, he interpreted the photoelectric effect as being due to bombardment by particles of light, or photons, which eject electrons from the surface of a metal by interacting mechanically with them, by direct contact, like billiard balls. But as soon as the full blown quantum theory was developed and formulated, Einstein quickly adopted a more critical stance, for he realised that this strange new theory would reintroduce a new form of action at a distance.² Like Newton three centuries before him, Einstein rejected this hypothesis which he took to be absurd, and which he described as a spooky action at a distance.

Today, quantum mechanics is well established at the very heart of modern physics. And it does indeed contain a form of nonlocality that would probably not have pleased Einstein, even though it is very different from the nonlocality that so bothered Newton. Moreover, this form of quantum nonlocality is well supported by experiment. There are even promising applications for it in cryptography and it makes possible the quite astonishing phenomenon of quantum teleportation.

A Peculiar Nonlocal Telephone

Here is a little piece of science fiction, although not nearly so futuristic as it may seem. In fact, technology will soon make it a reality. Imagine a 'telephone' connection between two speakers to whom we shall refer, according to the tradition, by the names of Alice and Bob, which correspond to the first

¹ Cohen, B., Schofield, R.E. (Eds): *Isaac Newton Papers and Letters on Natural Philosophy and Related Documents*, Harvard University Press (1958).

² Gilder, L.: *The Age of Entanglement. When Quantum Physics Was Reborn*, Alfred A. Knopf (2008).

two letters of the alphabet. As sometimes happens, the connection is rather poor, impaired by noise. In fact, the connection is so bad that Alice can hear nothing of what Bob is trying to tell her. All she can make out is a continuous noise—chzuskryprrrskrzypczykrt. . . . Likewise, Bob hears only the same chzuskryprrrskrzypczykrt. . . . In vain they shout into the receiver, fiddle with it, move around the room. But there is no improvement. How annoying! It is quite impossible to communicate with such a device, and it is abundantly clear that it does not deserve to be called a telephone.

But Alice and Bob are of course physicists. They each record 1 min of the noise produced by their device. In this way, Alice can prove to Bob that she has done her honest best, and conversely. But to their surprise, the noise recorded by the two friends turns out to be strictly identical. As the two recorders are digital, Alice and Bob can check that each bit of information on each recording is exactly the same. Incredible! The source of the noise must therefore be at the operator, or somewhere along the telephone line. As the noise is perfectly synchronised, they deduce that the source must be exactly midway along the line, in such a way that it arrives at the same time with both Alice and Bob.

They decide to test their hypothesis, namely that the cause of the noise is a defect, probably of electrical origin, exactly midway along the telephone line joining them. Alice thus extends her line by adding a long cable. The noise she receives should then be slightly delayed with respect to the noise received by Bob. But, no! Nothing changes. Not only is the noise still there and still identical at each end of the line, but it is still perfectly synchronised. Bob then cuts the phone line. But the noise just goes on!

How can we explain such a phenomenon? Is the wire on the receiver just a way to keep track of it in the flat? Is it just a mobile phone that happens to be attached to the wall out of pure convenience? Or is the noise produced by the receivers themselves rather than by some source situated between them? Could it be the explosion of some distant galaxy that produced the same noise in the two receivers? And how could one test these hypotheses? Bob, who knows something about electromagnetic waves, encloses himself within a Faraday cage, that is, a metal mesh structure that keeps out all radio waves. But the noise persists. Alice suggests that they move very far apart from one another. Then whatever mechanism is allowing the two receivers to communicate, the quality of the connection should decrease and finally disappear. But even then, moving apart has no effect on the amplitude of the noise.

Alice and Bob conclude that their receivers have recorded some very long sequence of noise which they then proceed to reproduce each time they are taken off the hook, delivering a sequence that is chosen very precisely as a function of the exact time. Then there should be no surprise to find that the two receivers always produce exactly the same noise.

Delighted with the success of their evidently scientific approach to the problem, Alice and Bob take the news of their discovery to their physics teacher, who duly commends them. But their teacher makes the following observation: “The assumption that the telephone receivers themselves make the same noise by virtue of some common cause, in fact the same noise previously recorded in the two receivers, is a hypothesis that can itself be tested. This is called a Bell test.” Bell tests or Bell games will be presented in the next chapter. For the moment, let us just say that Alice and Bob rush back to their respective homes to carry out this Bell test on their receivers, and that the test fails. They repeat it several times, but always with the same result. The assumption of a common cause recorded in each of the two receivers is thus refuted.

Alice and Bob are left to wonder what mechanism could possibly allow their two receivers to produce this same noise, while widely separated, without communication, and without the noise being prerecorded in each receiver. But for all their efforts, they are unable to come up with any mechanism that could explain this phenomenon, so back they go to consult their teacher: “It’s not surprising that you couldn’t find a mechanism, because there simply isn’t one. This is not a mechanical problem, but belongs to quantum physics. The noise is produced randomly, but it is a ‘true’ randomness. Each bit of the noise does not exist until the receivers produce it by a pure act of creation. Not only that, but this quantum randomness can manifest itself in several places at the same time, in your two receivers for example.”

“But”, exclaims Alice, “that’s impossible. The signal must decrease with the separation between the two receivers, otherwise that would mean that one could communicate over arbitrary distances.”

“Not only that”, adds Bob, “but the perfect synchronisation would imply an arbitrarily high speed of communication, even faster than the speed of light, which is impossible.”

But their teacher is unmoved: “You told me that the noise remains the same even when you shout into the receiver, even if you move around, spin round, or shake the device. So you see that the very fact that the same noise is produced randomly on both sides means you cannot use it to communicate. The other person learns absolutely nothing about what you are doing.” And he concludes: “There is therefore no conflict with Einstein’s relativity theory. You have shown once again that no communication goes faster than light.”

Alice and Bob are speechless. Since their peculiar ‘telephones’ cannot be used to communicate, they are not really telephones, even though they might look like them. But how do they coordinate so as always to produce the same result without any communication, nor any prior agreement between them? And what about this suggestion of ‘true’ randomness which can manifest itself simultaneously in several different places? After a moment’s silence, Bob finally

comes to his senses: “But if this is really what is happening, it should be possible to use this phenomenon. In which case, I will be able to build something, then play around with it until I understand how it works. After all, that’s how I learnt how electricity works, how the trajectory of a ball will change when the ball is spinning, in fact, everything I’ve ever understood.”

And their teacher agrees. This effect can be exploited to produce random numbers, and to secure confidential communications, which is known as quantum cryptography, and it can even be used for quantum teleportation. But first we must understand the central concept of this book, namely, nonlocality, which we shall do by discussing the idea of correlation and describing Bell’s game.

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