Quantum Non-Locality and Relativity

second edition

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Metaphysical Intimations of Modern Physics

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QUANTUM NON-LOCALITY AND RELATIVITY

For Vishnya, who always believed in it

Preface to First Edition

I state my case, even though I know it is only part of the truth, and I would state it just the same if I knew it was false, because certain errors are stations on the road to the truth. I am doing all that is possible on a definite job at hand.

Robert Musil

If the introductory chapter of a book is the overture to the ensuing score, a brief, undeveloped melange of themes and leitmotifs destined to appear again and again, the preface serves as program notes. Here may one find some small account of the events which propelled the project; some acknowledgement of the many friends who encouraged and nourished it; and some explanation of idiosyncratic elements which arise from the author's own peculiarities. And as an intriguing introduction may encourage the reader to warm to the subject, so the successful preface may inspire some sympathy and understanding in the reader for the author's plight, for the many compromises, lapses, and errors that attend the writing of a book. So how did this book come about?

In October 1990, John Stewart Bell succumbed quite suddenly and unexpectedly to a hemorrhage of the brain. Anyone who had studied Bell's works mourned the passing of an incisive intellect; those who had had the pleasure of discussing the knotty problems of quantum theory with him felt even more sharply the loss of a figure of inspiring integrity, clarity, and humor. Here at Rutgers, Renée Weber suggested that we honor Dr Bell's memory with a symposium on his work. David Mermin treated us to a non-technical exposition of Bell's Theorem, Shelly Goldstein spoke of the relationship Bell's work and that of David Bohm, and Professor Weber recounted some parts of her recent interview with Bell.

My part was to be a short discussion of the compatibility between Relativity theory and the violation of Bell's inequality.

When I originally agreed to the assignment, I thought that I knew just what I was going to say: Relativity has been interpreted in two quite different ways, as forbidding superluminal effects and as demanding Lorentz invariance, and one must sort out how to construe Relativity before one can address the question of compatibility with quantum theory. But after a few days I realized that another construal of Relativity was available (no superluminal signals), then another (no superluminal energy transmission), then yet another (no superluminal information transmission). Since all of these interpretations of Relativity were provably non-equivalent, this situation posed an straightforward analytical task: how do the various interpretations relate to one another and how does each fare if Bell's inequality is violated? This manuscript is my attempt to work through that analytical problem.

In writing the book I have been constantly surprised by the variety and beauty of the interconnections between these various questions. But I have been even more impressed by Bell's deep and steady understanding of the problematic. Over and over I found some terse passage in Bell's work to contain exactly what needed to be said on a subject, the decisive pronouncement. I have often felt that whatever is of value in this book could be found in Bell's "The Theory of Local Beables" (1987, ch. 7), and have consoled myself that this book will have served a great purpose if it does no more than encourage people to read Bell with the care and attention he deserves.

My foremost goal in composing the book has been to make it comprehensible to the non-specialist. The sparks which fly when quantum theory collides with Relativity ignite conceptual brushfires of particular interest to philosophers, problems about causation, time, and holism, among others. Unfortunately, much of the work done by philosophers presupposes a considerable amount of familiarity with the physics. This is particularly sad since the physics is not, in most cases, very complicated. I fear that many readers may be frightened off from the topic by unnecessary formalization, so I have tried to keep the mathematical complexity of the discussion to a minimum. But on the other hand, I have not wished to drop to the level of vague metaphor which sometime infects popularizations. Every compromise between rigor and simplicity is a bargain with the devil, and I have struck mine as follows. The presentation of Bell's inequality needs no more than some algebra, and is quite rigorous. Understanding Relativity also requires no more than algebraic manipulation, but enough that a purely mathematical account would tax the patience of the average reader. So I have tried to present

Relativity pictorially, so far as possible. The figures in the book present the concepts of Relativity accurately, but demand of the reader some skill in interpretation. Pictures of space-time look misleadingly like pictures of space, and the novice must unlearn some of the conventions of normal pictorial representation to avoid being misled. Newcomers should therefore take great care with the pictures in chapter 2: if those are properly understood, the sequel will be easy.

Quantum theory itself has been another matter. Most of the content before chapter 7 can be understood without much discussion of quantum formalism. That formalism itself also uses no more than linear algebra and vector spaces. Interested neophytes can find enough technical detail in any standard introductory text. A particularly nice and accessible presentation of the requisite mathematics is provided in David Albert's *Quantum Mechanics and Experience* (1992, ch. 2).

Just as professional physics scares off the uninitiated, so does professional philosophy. Philosophers have developed many languages of technical analysis which permit concise communication among the cognoscenti but which make amateurs feel like unwelcome guests. But most clear philosophical ideas can be presented intuitively, shorn of the manifold qualifications, appendices and terminological innovations that grow like weeds in academic soil. I have been very selective in my discussions of the philosophical corpus, usually focussing on a single proposal which illuminates a region of logical space. I do not pretend to comprehensiveness in my review of the philosophical literature, and can only plead for understanding that my decisions reflect a desire for a short, provocative text.

Finally, I feel I should explain the "metaphysical intimations" of my subtitle. Metaphysics has acquired rather a bad reputation in this century, following the insistence of Kant that all metaphysical speculations must be pursued a priori. It was not always so. The fount of metaphysics as a philosophical pursuit is the treatise on First Philosophy by Aristotle which has come down to us as the *Metaphysics*. Aristotle was concerned with analysis of what there is into its most generic categories: substance, quality, quantity, etc. I see no reason to believe that Aristotle thought such an examination could not be informed by experience. At its most fundamental level, physics tells us about what there is, about the categories of being. And modern physics tells us that what there is ain't nothing like what we thought there is.

I have used "intimations" rather than "implications" because we still do not know how this story ends. Quantum theory and Relativity have not yet been reconciled, and so we can now at best only guess what picture of the world will prevail. But we do know enough to make some guesses.

This book would not have come to be without help of all sorts. David Albert, Nick Huggett, Martin Jones, Bert Sweet, Paul Teller, and Robert Weingard all devoted their own time and insight reviewing the manuscript and generously shared their views with me. Abner Shimony pushed me to clarify the models in chapter 6, and thereby saved me from repeating some errors in print. Steve Stich expended considerable effort finding the manuscript a home, and always had a word of encouragement. The National Endowment for the Humanities graciously provided financial support in the form of Summer Stipend FT-36726-92 (money = time). And the atmosphere in which the book was completed was lightened by Clio Maudlin, who also improvised some emendations with her feet.

Preface to Second Edition

Publication of the second edition of this tome affords the opportunity, beside typographical corrections, for two more substantial changes. The first is a new derivation of the Relativistic mass increase formula, to be found on pages 65 to 69. The new derivation is somewhat simpler than that in the first edition, and has the advantage of allowing the exact formula to be obtained by means of a few lines of algebra. There are many methods for deriving the formula, but to my knowledge this one is novel. The second is the addition of an Overview of Quantum Mechanics. The overview contains just the bare mathematical bones of the theory, but that is enough to explain how violations of Bell's inequality are implied by the theory. It is hoped that the overview, while not a complete account of quantum theory, helps make this study more self-sufficient.

Beyond providing the chance for small improvements, the issuing of the second edition invites reflection, at some years' remove, on the plan of the original. Perhaps the most vexing question confronting any study of Bell's inequality is how the role of quantum theory ought to be treated. On the one hand, there is little doubt that Bell's inequality, and the experimental observation of violations of that inequality, would never have been discovered if not for the existence of the quantum formalism. On the other hand, the inequality itself is derived without any mention of quantum theory and the violations are matters of plain experimental fact. So the explication and analysis of the importance of Bell's work can in principle proceed without mentioning quantum mechanics at all. Should an account of Bell's inequality emphasize its historical roots in the great mysteries of quantum mechanics or rather sever those ties in the interest of logical clarity?

In composing this book, I chose the second option, playing down the role of quantum theory in favor of pure experimental results. In retrospect, I stand by that decision: the interpretation of quantum theory is troublesome enough in its own right to overshadow and confuse the relatively straightforward proof of non-locality. But once the main points have been made, the connections between non-locality and the interpretive problems of quantum theory are both intriguing and instructive. In particular, non-locality appears at exactly the point where the "measurement problem" which infects standard quantum theory is resolved. If one resolves the measurement problem by allowing a real physical process of wave collapse, it is the collapse dynamics which manifests the non-locality, and which resists a fully Relativistic formulation. If one resolves the measurement problem by postulating additional variables beside the wave function, it is the dynamics of these variables which manifests the non-locality and which resists a fully Relativistic formulation. The regrettably widespread opinion that there is no real non-locality inherent in the quantum theory is therefore deeply intertwined with the regrettably widespread opinion that the measurement problem can painlessly be solved without postulating either additional variables or any real collapse process.

Having thrown some rocks at the hornet's nest of the interpretation of quantum theory in this preface, I am obliged now to do more than turn heel and walk away. Although this book is not the place to thrash out those issues, I have thrashed them from time to time in other venues. Some discussions may be found in Maudlin (1995), (1996), (1997), and (1998).

Finally, I must note that although there has been some discussion of Bell's theorem and non-locality in the eight years between the two editions of this book, there had been, to my knowledge, no fundamental change in the basic logic of the situation, and no real progress in reconciling quantum theory and Relativity.

Contents

Introduction

In the 1930s, Otto Neurath was one among many philosophers engaged in the project of purifying scientific language of its ambiguities, its vagueness, and its "metaphysical" contents. One might hope to accomplish this task by an act of radical innovation, building anew from elements of perfect clarity and precision. Neurath realized that such hopes are unattainable, that at best we can only successively improve the language we have, always retaining some of its deficiencies. He illustrated our situation with a resonant image:

> No *tabula rasa* exists. We are like sailors who must rebuild their ship on the open sea, never able to dismantle it in dry-dock and reconstruct it there out of the best materials. (Neurath 1959, p. 201)

The physical sciences themselves suffer the same fate. Fundamental conceptual changes occur, but they are always modifications of a previously existing structure. The entire edifice is not reconstituted anew; rather, tactical adjustments are made in order to render the whole consistent. The *ad hoc* nature of this procedure may leave us with lingering doubts as to whether the whole really is consistent.

During the last century our physical picture of the world has undergone two revolutionary modifications. The Theory of Relativity has overthrown classical presumptions about the structure of space and time. The quantum theory has provided us with intimations of a new conception of physical reality. Classical notions of causality, of actuality, and of the role of the observer in the universe have all come under attack. The ultimate outcome of the revolutions is now but dimly seen, at best. The final reconciliation of quantum theory and Relativity is a theoretical problem of the first magnitude. No quantum version of General Relativity exists, and the prospects for one are murky. But even apart from that hurdle, problems about the consistency of our two fundamental physical theories may appear.

The problem that will concern us here is easily stated. It arises from the remarkable results derived by John Stewart Bell in 1964 concerning the behavior of certain pairs of particles that are governed by quantum laws. Bell showed that observable correlations between the particles could not be accounted for by any theory which attributes only locally defined physical states to them. The particles appear to remain "connected" or "in communication" no matter how distantly separated they may become. The outcome of experiments performed on one member of the pair appears to depend not just on that member's own intrinsic physical state but also on the result of experiments carried out on its twin.

Many features of this quantum connection are puzzling. It is, for example, entirely undiminished by distance. This distinguishes it from any connection mediated by a classical force, such as gravity or electromagnetism. But even more amazingly, the connection exists even when the observations carried out occupy positions in space and time which cannot be connected by light rays. The particles communicate faster than light.

It is this last feature which raises questions about the consistency of our fundamental theories. Relativity is commonly taken to prohibit anything from traveling faster than light. But if nothing can go faster than light, how can the particles continue to display the requisite correlations even when greatly separated? The two pillars of modern physics seem to contradict one another.

The predicted correlations have been experimentally confirmed. Indeed, they have been seen even in conditions where the communication between the particles would require superluminal velocities. So we are presented with the problem of determining whether Relativity has been violated, and, if so, whether our present account of space-time structure must be modified or abandoned.

The question of whether the quantum correlations are consistent with Relativity seems precise enough to admit a decisive answer, but on closer examination this appearance of clarity dissolves. Exactly what sort of constraints Relativity imposes on physical processes is a matter of much dispute. Many physicists and philosophers would agree that Relativity prohibits *something* from going faster than light but disagree over just what that something is. Among the candidates we may distinguish:

> Matter or energy cannot be transported faster than light.
> Signals cannot be sent faster than light.

> Causal processes cannot propagate faster than light.
> Information cannot be transmitted faster than light.

Most of these prohibitions are easily seen to be non-equivalent. For example, signals could in principle be sent without any accompanying transmission of matter or energy. Or again, superluminal causal processes could exist which, due to their uncontrollability, could not be used to send signals.

Yet another interpretation holds that Relativity requires only that

> Theories must be Lorentz invariant.

This requirement is compatible with the violation of every one of the prohibitions listed above.

Not surprisingly, the various prohibitions are justified by different considerations. In one case it is claimed that a violation of the prohibition would require an infinite amount of energy, in another than it would engender paradox, in yet another that some relativity principle would be abrogated. We are therefore left with a rather tangled thicket of problems. We must consider each of the proposed prohibitions and ask whether it is violated by the quantum connection. We must ask how each prohibition is justified and how it connects with the formalism of the Theory of Relativity. We would also like to see how the prohibitions relate to one another. Until this work is done we cannot begin to evaluate the implications of the quantum correlations for our picture of the world.

This problematic directly dictates the structure of our inquiry. Chapter 1 presents Bell's results with a minimum of technical machinery. Chapter 2 is a short intuitive account of Special Relativity. The following four chapters examine the four prohibitions listed above, tracing their connection with Special Relativity on the one hand and their compatibility with quantum non-locality on the other. Chapter 7 delves into the technical requirement of Lorentz invariance and its implications. Chapter 8 touches on the difficulties involved in passing from the space-time of Special Relativity to that of General Relativity.

Any book which attempts to deal with quantum theory, Special Relativity and General Relativity courts various forms of disaster. Technical and mathematical detail can easily push the discussion beyond the ready grasp of the general reader, and the philosophical interpretation of the mathematical formulae can be even more daunting. In this last respect an asymmetry regarding our two fundamental theories should be noted. Relativity is quite well understood. Although it employs ideas that depart radically from those of classical physics, the concepts are themselves unproblematic and become quite transparent with use. Quantum theory, in contrast, still presents deep and basic interpretational problems, the discussion of which could fill several volumes. Fortunately, our concerns will not draw us much into these controversies. Bell's theorem can be proven without so much as a mention of quantum theory, and although one uses quantum theory to predict the violation of Bell's inequalities, the violation itself is confirmed by straightforward laboratory technique. The observed facts, not merely some interpretation of the theory, stand against locality, so the thorny problems surrounding the interpretation of quantum formalism can be almost entirely avoided.[1] For aficionados, more detailed remarks concerning the interpretation of quantum theory will be provided in appendices or in notes such as the one above.

Technical details of physics are not the only casualties of our approach. The philosophical literature on this subject is large and growing, and we will be forced to pass over much of it with little examination. I hope that the philosophical views discussed will be accepted by my colleagues as simplifications rather than caricatures.

For those interested in the fundamental structure of the physical world, the experimental verification of violations of Bell's inequality constitutes the most significant event of the last half-century. In some way our basic picture of space, time, and physical reality must change. These results, and the mysteries they engender, should be the common property of all who contemplate with wonder the universe we inhabit. So in telling this tale I have tried to leave behind the arcane technicalia of the academy. In doing so, I have sacrificed no small degree of precision, and perhaps also some important subtleties. But I hope at least to have provided a framework sturdy enough and correct enough to serve both professional and amateur naval architects who propose to redesign the craft which carries us on our journey.

NOTE

1 To be precise, the only assumption we will be making is that when one does, for example, a polarization experiment and gets some result (photon passed or absorbed), there is, after the experiment is finished, something in the physical state of the universe which picks out that result over the other possible results. Our assumption is held in common by all wave-collapse theories, whether collapse is caused by interaction with macroscopic devices, by conscious experience, or by random "hits" as in the theory of Ghirardi, Rimini, and Weber (1986). It is also held by no-collapse theories such as Bohm's which use additional variables to describe the world. Indeed, I know of only two interpretations which deny the assumption: the many-worlds

interpretation of Everett and Wheeler (De Witt and Graham 1973) and the Many Minds interpretation of David Albert and Barry Loewer (1988, 1989; Albert 1993). The many-worlds theory is incoherent for reasons which have been often pointed out: since there are no frequencies in the theory there is nothing for the numerical predictions of quantum theory to mean. This fact is often disguised by the choice of fortuitous examples. A typical Schrödinger-cat apparatus is designed to yield a 50 percent probability for each of two results, so the "splitting" of the universe in two seems to correspond to the probabilities. But the device could equally be designed to yield a 99 percent probability of one result and 1 percent probability of the other. Again the world "splits" in two; wherein lies the difference between this case and the last?

Defenders of the theory sometimes try to alleviate this difficulty by demonstrating that in the long run (in the limit as one repeats experiments an infinite number of times) the quantum probability assigned to branches in which the observed frequencies match the quantum predictions approaches unity. But this is a manifest *petitio principii*. If the connection between frequency and quantum "probability" has not already been made, the fact that the assigned "probability" approaches unity cannot be interpreted as approach to certainty of an outcome. All of the branches in which the observed frequency diverges from the quantum predictions still exist, indeed they are certain to exist. It is not highly likely that I will experience one of the frequencies rather than another, it is rather certain that for each possible frequency some descendants of me (descendants through world-splitting) will see it. And in no sense will "more" of my descendants see the right frequency rather than the wrong one: just the opposite is true. So approach of some number to unity cannot help unless the number already has the right interpretation. It is also hard to see how such limiting cases help us: we never get to one since we always live in the short run. If the short-run case can be solved, the theorems about limits are unnecessary; if they can't be then the theorems are irrelevant.

The Many Minds theory does not have this problem, and may be the only existing interpretation of quantum theory which requires no non-local effects. We will discuss the Many Minds theory in chapter 7.