QUANTUM IMPLICATIONS

Essays in Honour of David Bohm

Edited by B.J. Hiley and F. David Peat

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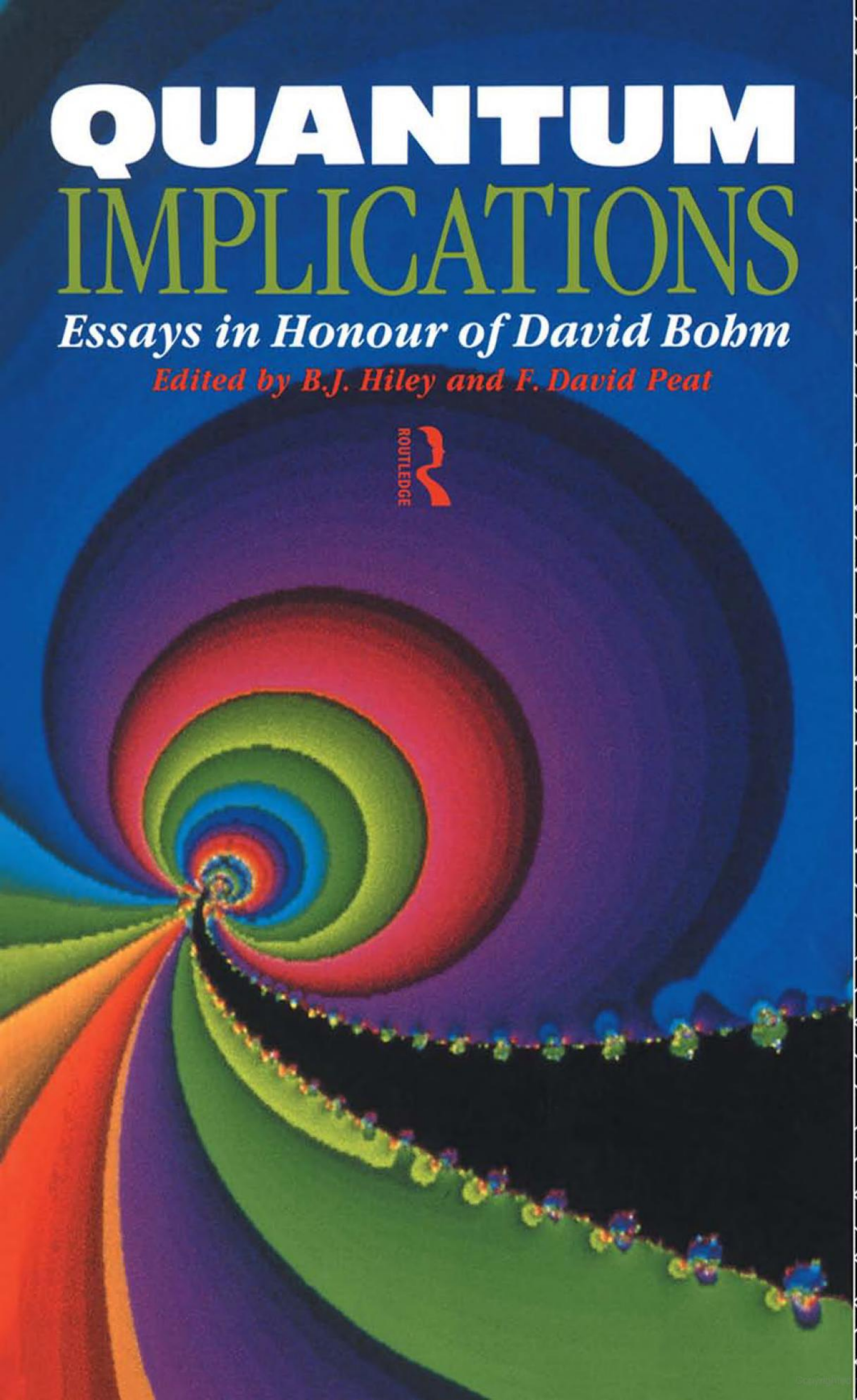

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General introduction: the development of David Bohm's ideas from the plasma to the implicate order

B. J. Hiley and **F. David Peat**

David Bohm was born in Wilkes-Barre, Pennsylvania, in 1917. His father ran a successful furniture business, making his way to the USA from what was then Austria-Hungary. There appears to be no physics whatsoever in the family background. Bohm, himself, became interested in science at an early age, being urged on by a fascination of finding out how things worked. By the age of eight he had already been introduced to science fiction. This fired his imagination and generated in him a deep interest in real science. But it was the nature of the real world that fascinated him most. He recalls the profound effect that a book on astronomy had on him in those formative years. He was struck by the vast order and regularity of the universe. This impressed him so much that he began to devote a great deal of time to science.

Needless to say, his father became somewhat concerned about the boy's future. Being a successful businessman, he could not imagine how anyone could make a living out of 'scientism' as he insisted on calling it. Young David took this as a challenge and using his earlier interest in redesigning mechanical devices he decided to try to make money out of inventing. He was rather proud of one invention in particular: namely, a 'dropless pitcher'. (This ingenious item had nothing at all to do with that great American sporting pastime, baseball. It was a jug or teapot that did not drip!) His principal concern now became how to make this design pay. After almost giving up in despair, he came across an advertisement in a popular science magazine offering, for the sum of $5, advice on how to exploit financially a good invention. Off went the $5 and back came some advice on how to obtain a patent. But that, of course, would cost a few hundred dollars! Would it be worth it? The answer (apparently, included in the $5!) was to do a door-to-door survey to test market demand! It was at this point in his life that he determined that he would become a theoretical physicist.

As he began to study physics seriously, he was repeatedly struck by the interconnectedness of what, at a superficial glance, seemed to be totally unrelated phenomena. As he delved deeper into the substructure of matter and its movement, this characteristic of a rich and highly interconnected substructure became more and more apparent. Furthermore, as Bohm saw it, these deeper structures seemed to possess properties which did not reflect the way physicists were talking about the behaviour of matter. In quantum mechanics, for example, it seemed that this interconnectedness was vital, yet the usual presentation of the subject seemed to minimise this aspect of the phenomena.

In Bohm's original perception, this notion of interconnectedness was rather vague and ill-defined but with its continual reappearance in different forms, the notion slowly took shape, ultimately leading to a very radical and novel way of looking at reality. This view eventually crystallised into what he now terms the implicate order. But much was to happen before that idea eventually became clear.

The first formal indication of Bohm's departure from orthodoxy can be traced to his reformulation of quantum mechanics published in *Physical Review* in 1952.[1] But the ideas that lay behind that formulation seem to many to be totally against the spirit of his later work on the implicate order, so much so that they find it hard to see any connection at all. It is true that those papers were more intent on demonstrating that there was another logically coherent interpretation of the quantum mechanical formalism, other than the usual one. But it is the ideas implicit in this reformulation that have connections with the notion of the implicate order. Since there has been some interest in this connection, we have asked David to write a short article outlining what he sees as the essential relationship between the two.[2]

We would like here to present an overall sketch of the relevant background in which Bohm's ideas took shape so that the reader can appreciate the significance of the various developments in a broader context. This will also enable us to relate the various contributions to this book to the same background and so see where they fit in. By doing this we hope the book will become more than a collection of isolated contributions.

Bohm's interest in the fundamental questions of physics started at high school. Even at that early stage he was beginning to ask how the theories of physics enable one to build up an understanding of reality. At college he soon quickly became fascinated with quantum mechanics and relativity as he began to study these subjects in depth for the first time.

After graduating he began his research project under the supervision of Robert Oppenheimer. His dissertation topic involved a theoretical study of neutron–proton scattering. Yet even while working on this technical problem, he kept up his interests in fundamentals, always probing deeper into quantum theory and relativity. He remembers his long discussions with Joseph Weinberg, who had made a study of Bohr's point of view. During that period he admits to becoming a supporter of Bohr's position.

Before receiving his doctorate in 1943 from Berkeley, he moved to the Radiation Laboratory where he worked on problems connected with the later phases of the Manhattan Project. He was involved in a theoretical study of the ionisation of uranium fluoride in an electric arc which formed part of the broader study of the problems involved in the separation of ^{235}U from ^{238}U. Thus began his interest in plasma physics, to which he made some outstanding contributions.

Although much of this work was basically involved in technical problems, Bohm could not help noticing the philosophical implications. The individual particles in the plasma were highly correlated and behaved like an organic whole rather than a mechanistic system. The plasma constantly regenerated itself and surrounded all impurities with a sheath so as to isolate them completely. To understand in more detail how the plasma functioned, it was necessary to study the relation between the individual and the collective modes of behaviour. It was here that he introduced the idea of collective co-ordinates and developed a general way of handling plasmas.

When he took up the post of assistant professor at Princeton University he extended his earlier ideas to study the behaviour of electrons in metals, where quantum mechanics played an essential role. It was his innovative work in this area that established David Bohm's reputation as a theoretical physicist.

Neither of the editors knew Bohm in those days, but fortunately Eugene Gross, who was one of Bohm's first graduate students, has given a personal sketch of Bohm's thinking in the period he spent at Princeton. This is presented in the introduction to his article on 'Collective variables in elementary quantum mechanics' which appears in this volume.[3] We are particularly grateful for his contribution and find that the final paragraph to his introduction captures the feeling that many of us, students and colleagues, felt towards David Bohm: a totally unselfish man who shares his latest thoughts on many topics with his colleagues and students alike. This enthusiasm for the search for order in nature continues unabated today.

The main part of Gross's contribution is an illustration of how collective co-ordinates can provide a useful way of understanding the behaviour of different systems. He takes as examples the atom–molecule transition, the electron interacting with two lattice oscillators and ends with some remarks concerning the polaron problem. The following article is by another of Bohm's graduate students, David Pines.[4] It is a masterful review of some of the basic ideas involved in the development of plasma physics. He also outlines the role played by Bohm in developing the concepts needed to deal with the problems, and touches on the application of the random phase approximation and its use in liquid helium (^{4}He).

While still at Princeton, Bohm was asked to give a course of lectures on quantum mechanics to undergraduates and was faced with the task of presenting a clear account of the subject that had fascinated him for some time. Here was a theory that had emerged after a long struggle by many physicists to account correctly for a wide range of experimental results, which the classical theory could not even begin to explain. But the conceptual structure of this theory was very different from that of the classical theory. It implied a radical change in our outlook on reality. But precisely what were the nature of these changes did not yet seem very clear. The majority view was (and still is) that the precise nature of the conceptual changes are not important. All that was needed was to work with the self-consistent mathematical formalism, which, in some mysterious way, correctly predicts the numerical results of actual experiments.

After lecturing on the subject for three years, Bohm thought that this was not a satisfactory position to adopt so he decided to try to get a better understanding of the subject by writing a definitive textbook in which the physical aspects of the mathematics would be emphasised. Part of the task would involve clarifying Bohr's interpretation of the theory by drawing, to some extent, on Bohr's book *Atomic Theory and the Description of Nature.*[5]

It was while writing his book that he came into conflict with what eventually became known as McCarthyism. A year or so after arriving at Princeton he was called to appear before the Un-American Activities Committee, a committee of the House of Representatives. He was asked to testify against colleagues and associates. After taking legal advice he decided to plead the Fifth Amendment. A year or so later, while he was in the middle of his book, his plea was rejected and he was indicted for contempt of Congress. While awaiting trial, the Supreme Court ruled that no one should be forced to testify if the testimony is self-incriminating, provided no crime had been committed. Since no crime had been committed the indictment against Bohm was dropped.

During this period the University advised Bohm to stay away, one of the few benefits to emerge from this whole sordid affair. During his enforced isolation he was able to complete the book far sooner than he had anticipated. After that, however, with his contract at Princeton expired, he was unable to obtain a job in the USA and was advised by Oppenheimer to leave the country before the full force of McCarthyism took effect. Fortunately he had some friends in Brazil who were able to offer him a professorship in the University in São Paulo. He held this post from 1951 to 1955.

The textbook *Quantum Theory* was first published by Prentice-Hall in 1951 and is still in print today. It is generally regarded as one of the best textbooks of its day. Apart from a clear presentation of the main physical ideas lying behind the formalism, the book has the additional merit of discussing some of the more difficult aspects of the theory usually omitted from modern texts. For example it contains sections on the approach to the classical limit, the measurement problem and the Einstein, Podolsky, Rosen (EPR) paradox. The latter was of particular importance since it reformulated the EPR example in terms of correlated spin one-half systems. This discussion not only clarified the essential issues raised in the debate but also led to the suggestion of using positronium decay and optical cascades in actual experiments designed specifically to explore the consequences of EPR situations. These experiments have been significant in moving the continuing debate from what was generally regarded as a realm of speculative philosophy, or even theology, into hard physics.

All three of the above topics are still the subject of many current research papers. Indeed the contributions of Clark,[6] Leggett[7] and Penrose[8] are directly concerned with these topics. Terry Clark reports the experimental progress that his group at Sussex University have made in demonstrating quantum mechanical behaviour over macroscopic distances using SQUIDS. The aim has been to develop experimental techniques that could lead to a better understanding of macroscopic quantum mechanics and to explore a new approach to the measurement problem.

Tony Leggett presents an excellent review of the measurement problem which he believes to be a 'glaring indication of the inadequacy of quantum mechanics as a total world view'. He maps out an exploration of the likely direction in which it will break down. His discussion centres around the type of experiments discussed by Clark. By a vigorous and critical approach in these directions he hopes to provide a better understanding of how pure states can be converted into mixtures, thus connecting the microworld with our familiar classical macroscopic world. Roger Penrose examines a similar question, arguing that 'an essentially new and non-linear physical input to bring about the collapse' is needed and that this input should come from a general-relativistic gravity. He argues that the non-local nature of the collapse of the wave function could be connected with the fact that in general relativity the energy cannot be defined locally.

These types of difficulties always tend to leave an uneasy feeling that we really have not got to the bottom of quantum theory. As Gell-Mann puts it, 'Quantum Mechanics, that mysterious, confusing discipline which none of us really understands but which we know how to use.'[9] The problem is that we do not know precisely where the difficulty actually lies. It is quite clear that quantum theory is a statistical theory in the sense that the description of the individual particle can only be given in terms of a probability of it being observed at a certain point in space-time. There is no description of the individual process except in terms of its possible observation by some suitable measuring device. There is no way to understand what is happening: there is no actual fact. There is only a sequence of results of measurements, with no possibility of discussing what goes on between measurements.

This feature has led some physicists to question the existence of micro-realism. Bernard d'Espagnat has given a great deal of attention to this question in his books on the *Conceptual Foundations of Quantum Mechanics*[10] and *In Search of Reality.*[11] In the present volume he continues the discussion in a new way that involves a detailed comparison of Wheeler's point of view, which is essentially Bohrian, and that of Bell, who assumes there is a micro-reality.[12]

In classical physics, of course, any description in terms of probability can ultimately be understood in terms of ensemble averages over a well-defined individual behaviour. Here the statistical results would have their origins in a collection of well-defined individual events. Is there an underlying individual behaviour that could account for the statistical results of quantum mechanics? Of course, the individual behaviour would not be classical, but something different. The existence of such processes would not in any way detract from the present statistical theory which would still be valid and very useful in dealing with the more common situation involving many particles, such as for example in electron conduction, etc. However, if an underlying process did exist then an understanding of this process would lead to a better intuitive understanding of the quantum phenomena in general.

If such a process existed then it would require some set of parameters to specify it and traditionally these parameters have been called 'hidden', presumably because one is discussing a new, as yet unknown, process. All attempts in that direction were brought to a halt as a result of a theorem contained in von Neumann's book *The Mathematical Foundations of Quantum Mechanics.* He writes, after presenting the theorem, 'It should be noted that we need not go any further into the mechanism of the hidden parameters since we know that the established results of quantum mechanics can never be rederived with their help.'[13] Because of the high (and justified) mathematical reputation of von Neumann, this statement, together with the various writings of Bohr, Heisenberg, Pauli, etc., gave rise to the dogma that there is no alternative. The wave function had now come to be regarded as the most complete description of the state of the system, a statement which essentially creates many of the 'problems of quantum mechanics'.

A year or two after completing his book, Bohm produced an alternative approach to quantum mechanics which he published as two papers in the *Physical Review.* They were entitled 'A suggested interpretation of the quantum theory in terms of "hidden" variables'.[1] The original purpose of these two papers was simply to show that there is, in fact, an alternative interpretation of quantum mechanics contrary to von Neumann's remarks and the prevailing view of that time. As Bohm points out in his second book, *Causality and Chance in Modern Physics*, this approach was never intended to be an ultimate definitive statement of what lies behind quantum mechanics.[14] Rather it was simply intended to point out that certain assumptions are made in the usual interpretation which turned out to be too restrictive. Indeed this alternative interpretation allows certain things to be done which in the ordinary approach are deemed to be impossible. As Bell puts it, 'In 1952 I saw the impossible done.'[15] (Some of the features of this approach had already been anticipated by de Broglie[16] in the pilot wave theory and by Madelung[17] in his hydrodynamical approach. However, both theories faced serious difficulties with many-body systems. In fact de Broglie conceded defeat by an objection raised by Pauli[18] and gave up his approach until Bohm showed how Pauli's objection could be answered.[1])

Unfortunately the physics community did not take very kindly to the appearance of this alternative view. Certainly the physicists who had contributed most to the evolution of the ordinary interpretation felt there was some fundamental flaw in Bohm's argument. Some of the early technical objections raised were quickly answered as they were based on a misunderstanding of how the approach actually worked. In fact, no sustainable technical objections against the theory have ever been made. In its primitive form, the approach gives the same statistical results as the quantum theory and therefore experiment cannot be the arbitrator. Ultimately the objections have their roots in the assumptions one makes about the nature of reality, i.e. what constitutes a set of reasonable requirements necessary for a physical theory to be acceptable?

Such a question falls outside the normal sphere of discourse of the usual physics journals and it is not surprising to find that nearly all the objections to the theory appear in books, conference reports or Festschrifts of one kind or another. What we have found remarkable is the emotional nature of the responses. For example, in his book *Physics and Philosophy*, Heisenberg tries to sustain the argument that it is logically impossible to develop an alternative point of view and starts with a quotation from Bohr: 'We may hope that it will later turn out that sometimes $2 + 2 = 5$.'[19] But exactly where the logical contradictions lie is never made clear. Again in the Born–Einstein letters, Born writes, 'Pauli has come up with an idea that slays Bohm'.[20] An examination of Pauli's article[21] in *Louis de Broglie, physicien et penseur* reveals a criticism that can only accuse the alternative approach of being 'metaphysical'; a word which nowadays, together with the word 'philosophical', is used as a derogatory euphemism to condemn a theory which doesn't fit into the common consensus. The situation has been summarised very succinctly by Bopp: 'We say that Bohm's theory cannot be refuted, adding, however, that we don't believe it.'[22]

But it is not simply a question of belief. Bohm's original intention was to show that a consistent alternative does actually exist. This, in itself, is important since it opens the possibility of exploring new ideas without being trapped into believing there is no possible alternative. As someone once aptly remarked, 'I do not know whether quantum mechanics is a beautiful building or a prison with very high walls.' With the appearance of an alternative approach at least a ray of light has appeared through those very high walls!

The emotive terms associated with these arguments led to the implicit view that to mention the term 'hidden variables' was in some sense to commit a cardinal heresy. Even today the term often provokes a sceptical, if not irrational and antagonistic, response. Bohm now admits it might have been a mistake to call his theory a 'hidden variable theory'. After all, it only uses positions and momenta, whereas the real drive for the hidden variable approach was to find 'additional' parameters to describe the underlying process.

One can sympathise with the use of the term 'hidden' in the sense that although a particle can have a simultaneous position and momentum, we still cannot measure them simultaneously. It is in this sense they were called 'hidden'. But perhaps it would be more appropriate to call the wave function ψ the 'hidden variable'[23] because, although both x and p can be measured (even though *not* simultaneously), ψ itself only shows up indirectly through the quantum potential, which is reflected only in the behaviour of the ensemble of particles. In the 1952 work the quantum potential plays a crucial role. The essential difference between classical and quantum mechanics is accounted for by this potential. We will bring these features out later.

To answer the more general criticisms of his approach, Bohm presented his own ideas in a broader context in his book *Causality and Chance in Modern Physics.*[14] This book showed that Bohm was not only a master in handling the mathematical tools used in physics but that he could also think deeply about the philosophical background implicit in the physicist's framework. The book begins by analysing the philosophy of mechanism, within which the nineteenth century physics had developed. It then goes on to discuss the usual interpretation of quantum mechanics within this context and to explain, in more general terms, the alternative approach that he outlined in his 1952 papers. Here we already see emerging, for the first time, his dissatisfaction with his 1952 papers. He stressed that his discontent was not with the logical consistency of the approach. Rather he felt that it did not go far enough and thought that it was in some way a coarse-grained view of something yet deeper underlying quantum mechanics.

In his final chapter he raised the possibility of a more general concept of physical laws that went beyond mechanism. He suggested the notion of the qualitative infinity of nature in which all theories have limitations on their domains of validity so that every theory must be qualified by its context, conditions and degrees of approximation to which they are valid. In this way scientific research can be freed from irrelevant restrictions which tend to result from the supposition that a particular set of general properties, qualities and laws must be the correct ones to use in all possible contexts and conditions and to all degrees of approximation. This was a clear signal that David Bohm was not going to be tied down by any consensus that insisted that quantum mechanics was the last word and that all that was left was to obey its rules.

Again this position was not well received in the late 1950s and early 1960s. The physics community in general had made up its mind that the earlier achievements of quantum electrodynamics, with its successful treatment of divergences through renormalisation techniques, had established the paradigm for future work. The central problem thus became one of trying to apply the same method to the weak and strong interactions in particle physics. Anyone attempting to question the conventional approach to quantum mechanics was regarded, to put it mildly, as rather odd. (In actual fact statements made at that time were often much stronger!)

The prevailing atmosphere therefore was such that development of the ideas along the lines of the 1952 paper were not pursued further. By that time Bohm had moved from Brazil via Israel to England, where he held a research fellowship at Bristol University from 1957–61. There he took on a young research student, Yakir Aharonov. Together they published a paper on what has become known as the Aharonov–Bohm (AB) effect.[24] They discovered that if one confines a magnetic field in the geometric shadow between the two slits of an electron interference device, and ensures that the electrons travel only in a field-free region, then the resulting fringe pattern is shifted, the shift being a function of the flux enclosed in the inaccessible region. Actually the effect had been discovered ten years earlier by Ehrenberg and Siday[25] at Birkbeck College, where Bohm was to be appointed in 1961 to a chair in theoretical physics. The Aharonov–Bohm paper is cited as the definitive work on the subject because of its incisiveness. The discussion goes straight to the point at issue in a very clear and simple way, a feature that has always characterised Bohm's work.

The AB effect was quite surprising and initially the work was received with some suspicion. As Weisskopf puts it, 'The first reaction to this work is that it is wrong, the second is that it is obvious.'[26] Indeed it is a direct result of application of the standard rules of quantum mechanics. It is, in fact, the first example of a gauge theory of the type which today, when generalised, seems to offer the best possibility of uniting the weak, electromagnetic and strong interactions and, it is hoped, will eventually include gravity.

In spite of the fact that there are at least four independent sets of experimental techniques verifying the existence of the AB effect, papers still appear arguing that no such effect exists. The problem arises because the vector potential plays a fundamental role in the calculations, whereas in classical physics this potential is regarded merely as a mathematical device. The classical charged particles respond only to the fields and not to the potentials.

It is a great pity that the stigma of hidden variables has stuck with Bohm. We have often been greeted by physicists with the question, 'How is David Bohm getting along with his hidden variables?' This shows a very deep misconception of what Bohm is trying to achieve and ignores completely the radical nature of his ideas. As we have pointed out before, the content of the 1952 papers was intended simply to show that there was an alternative to the accepted view. They were not intended as an end in themselves, but simply to open the way for further progress. To go beyond hidden variables one must first see exactly what novel features quantum mechanics introduces, and to do this one needs to consider Bohr's work a little more closely.

Perhaps Bohr's deepest perception was not wave-particle duality, nor complementarity, but *wholeness*. Bohr writes, 'The essential wholeness of a proper quantum phenomenon finds indeed logical expression in the circumstances that any attempt at its well-defined subdivision would require a change in the experimental arrangement incompatible with the appearance of the phenomenon itself.'[27] Remember of course that for Bohr the word 'phenomenon refers only to observations obtained under circumstances whose description includes an account of the whole experimental arrangement'.[28] This notion of phenomenon used by Bohr is different from its more customary meaning. It is based on the assumption that 'in quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with the recognition that such an analysis is *in principle* excluded'.[29]

The sentiments expressed in these quotations are sometimes summarised in the phrase, 'the inseparability of the observed and the observer'. If these notions are, in fact, correct then quite clearly some very deep questions as to the nature of reality are raised, as is clearly recognised by d'Espagnat.[11] Unfortunately most physicists either do not know what Bohr wrote or, if they do, they do not quite understand what he is getting at. When various quotations of Bohr's work are put to them they tend not to believe them, yet continue to defend the usual (Copenhagen) interpretation! They praise Bohr, but think like Einstein.

As we have remarked already, Bohm's early perception when he began thinking seriously about physics was to notice the interconnectedness of the process. When Bohm found Bohr was advocating an extreme form of interconnectedness, he became very fascinated with this notion and explored it with much more energy. What turned out to be rather surprising was that the quantum potential also contained a notion of wholeness, even though analysis was still possible. Thus the quantum potential approach, rather than refuting Bohr's position, actually supported it on the question of wholeness, a feature that was totally unexpected. As this is a very important feature of Bohm's ideas, we feel that we should try briefly to outline how these aspects emerge from the quantum potential approach.

One of the main difficulties in trying to understand the precise changes implied by quantum mechanics lies in the formalism itself. It is very different from that used in classical physics and consequently a comparison becomes very difficult. In order to bring the formalisms closer together we can do one of two things. (1) Either we can try to reformulate classical physics in terms of operators in Hilbert space and hence see how the intuitive classical ideas translate into the quantum formalism. Such an approach has been adopted by Prigogine and his co-workers. Perhaps the clearest introduction to their work is presented in *Physica*.[30]

(2) Or we can try to reformulate quantum mechanics in a language which is closer to that of classical physics. This is the essential feature of Bohm's approach. It is achieved in a very simple way by writing the wave function in the form:

$$\psi = R \exp(iS/\hbar)$$

By assuming ψ satisfies Schrödinger's equation one can obtain two real equations, one of which is essentially a classical equation of motion supplemented by an additional potential term (called the quantum potential). It is this additional term alone that is responsible for producing the quantum behaviour. To understand this equation you have to assume there is an underlying micro-reality in which particles have both position *and* momentum, although these cannot be measured simultaneously. The solutions of the equation of motion give rise to an ensemble of individual particle trajectories arising from various initial conditions. If the distribution of initial conditions agrees with that calculated from the initial wave function, then this ensemble will give rise to the expected probability distributions found in experiment. This is guaranteed by the second equation derived from Schrödinger's equation, which is a continuity equation corresponding to the conservation of probability.

The details of this approach are presented in the article by Vigier, Dewdney, Holland and Kyprianidis.[31] This article contains illustrations of the calculated trajectories for electrons incident on a two-slit screen (Figure 9.3, page 177). It will be immediately noticed that these trajectories are very different from those expected on purely classical reasoning. The differences arise purely from the presence of the quantum potential. The quantum potential approach therefore is not an attempt to return to classical physics. All the strange features are accounted for by the quantum potential, which is in no way like a classical potential.

Before proceeding to discuss the difference between the classical and quantum potentials we feel it is necessary to point out an essential difference between Bohm's approach and that of Vigier *et al.* which has caused some confusion. To Bohm the quantum potential arises formally from the mathematics and, in order to demonstrate the logical consistency of the whole approach, it is unnecessary to seek a deep explanation of the potential's physical origins. In fact all of the illustrations of how the quantum potential accounts for various quantum phenomena that have been carried through recently by Bohm and one of us (B. J. Hiley)[32,33,34,35] do not require any specific action of the underlying process. In all these cases there are no differences with the results predicted by the usual approach.

The advantage of the approach even in the absence of a specific underlying process is that one can obtain a sharp picture of what is involved. With the trajectories, for example, we can see clearly how the interference pattern arises. In transition processes the time of transition for a particular process is sharp. Aharonov and Albert[36] further illustrate this sharpness by raising the question of retrodiction in quantum mechanics, contrasting von Neumann's collapse postulate with the time-symmetry of the experimental probabilities. These issues are rather unclear in the usual formulation but they show how the quantum potential approach gives a much clearer picture. This feature of clarity in Bohm's approach is quite general and can be regarded as one of its advantages.

Naturally if one were to take the model as a definitive physical theory of quantum phenomena one must seek a physical explanation of its origin. But here there are a wide variety of possibilities and Vigier *et al.* have adopted a particular position in which they argue that the quantum potential has its origins in 'non-locally correlated stochastic fluctuations of an underlying covariant ether'. However, many of the examples cited in their article do not require such an assumption.

Bohm's position with regard to the underlying process is very different and depends on a much more radical approach. Both ideas stem from the recognition that the many-body approach exhibits some form of 'non-locality' and the difference arises from the interpretation of what this non-locality means. For Vigier the explanation must arise from some phase-like process in space-time; it can be regarded as a 'quasi-mechanical' explanation. For Bohm the quantum non-locality has more of an affinity with Bohr's notion of 'wholeness', which ultimately calls into question the very notion of an *a priori* given space-time manifold.

In order to provide a context in which the latter notions take meaning, we will outline some of the key developments in which the notion of quantum non-locality emerged. The first clear account of the nature of this quantum non-locality was presented by Schrödinger[37], using the usual approach of quantum mechanics. He developed the line started by Einstein, Podolsky and Rosen[38] in their well-known paper where they criticised the completeness of quantum mechanics. Schrödinger showed that there was what he called an 'entanglement relation' appearing in the quantum formalism. By this he meant that the states of the subsystems cannot be separated from each other and this implied that, for a certain class of systems, the results of a measurement of a subsystem A, spatially well-separated from its companion B, depends not only on the results obtained at B *but on what one decided to measure at B.* It is this last phrase that contradicts our usual notion of locality. *What* is done to B should not influence the result of a measurement of A, especially when they are spatially separated and are not connected through a classical potential. Thus the usual formulation of quantum mechanics showed, in the hands of Schrödinger, that some notion of non-locality is involved. As Dirac puts it, 'For an assembly of particles we can set up field quantities which do change in a local way, but when we interpret them in terms of probabilities of particles we get again something which is non-local.'[39] However, because the usual approach cannot discuss the individual actual process, the question of locality becomes rather fuzzy and these questions can be conveniently ignored.

The quantum potential approach shows quite clearly that for a certain class of wave function, particles that are separated in space with no classical potential connecting them are not really separated but are connected through the quantum potential.[40] They are, as it were, 'together yet apart'. Furthermore the quantum potential contains an instantaneous connection rather than the expected retarded connection. In some ways this is like a reintroduction of a kind of action-at-a-distance, a feature that goes against the whole historical development of physics. Einstein, of course, could not accept this way out of the paradox, insisting that 'physics should represent a reality in space-time, free from any spooky action at a distance'.[41] In view of his position, it is not surprising that he did not like the quantum potential approach.

John Bell noticed the non-locality but, rather than reject it outright, he raised the question of whether it was a particular defect of the quantum potential approach or whether it was true for any model based on locality.[42,43] By assuming a pair of particles with dichotomic variables and by proposing a simple and reasonable definition of locality, Bell was able to produce an inequality involving correlation functions which must be satisfied by a theory which is to be called 'local'. Under certain conditions quantum mechanics is found to violate this inequality, a fact that has been confirmed by a series of experiments which culminated in the work of Aspect *et al.*[44] Although the debate continues, focusing essentially on two questions:

1 whether Bell's notion of locality is too restrictive;
and
2 whether in fact the experiments actually measure what they intend to measure;

there is a general but somewhat reluctant acceptance of the presence of some form of non-locality in quantum mechanics.

This reluctance is very understandable since the notion that all physical phenomena occur within a local reality is one of those self-evident truths that seem utterly absurd to contradict. Relativity itself, with its maximum signal velocity, has gone a long way to reinforce this notion. Even Dirac who, as we have seen, clearly recognised non-locality in quantum mechanics wrote, 'It (non-locality) is against the spirit of relativity but it is the best we can do.'[39]

No one has yet suggested a way of accounting for the results of quantum mechanics in a theory based on locality. Bohm, himself, with one of us (B. J. Hiley)[45], did propose a tentative local but non-linear theory that could in principle account for quantum non-locality, but the assumptions upon which it was based implicitly required a radical view of nature in which process rather than particles-in-interaction was taken to be fundamental. But even this approach is far from satisfactory. Some authors have noticed that one can escape from violating the Bell inequalities in quantum mechanics by allowing negative probabilities.[46] It has generally been regarded that such a notion is meaningless and amounts to replacing one difficulty by another. But it is well known that negative probabilities arise elsewhere when one tries to obtain quantum mechanical averages using phase-space distributions, so the question of negative probabilities is not restricted to the question of non-locality. Richard Feynman has thought a great deal about these problems and, indeed, has admitted to having difficulty in trying to understand the world view that quantum mechanics represents. He has always tried to narrow the problem down to particular features and explore them in depth to try to learn something new. In this volume he re-examines the notion of negative probabilities and explores its possibilities.[47]

It is thus clear that quantum non-locality is one of the most radical features of quantum phenomena and a careful discussion of its full implications is extremely important. What is its relation to Bohr's notion of wholeness? Can we learn anything more from the quantum potential approach? One important factor in the discussion is that if the quantum potential were simply a classical potential then there would, indeed, be violations of relativity and this would be strong grounds for rejecting the whole approach. But the essential point is that the quantum potential is not like a classical potential. And the pursuit of the quantum potential approach is not a question of 'jumping out of the frying pan into the fire'.[48] On the contrary, what this approach does bring out ultimately is a clearer understanding of what Bohr was referring to when he talked about 'the essential wholeness of a proper quantum phenomenon' or 'a closed indivisible phenomenon'.

It is vital to bring out these points more clearly as they are a key feature of Bohm's thinking. He actually discusses these issues in his own article, but it is our experience that people do not generally fully grasp the significance of this radical feature of the quantum potential. We therefore make no apologies for repeating the arguments here.

Unlike a classical potential, the quantum potential appears to have no point-like source. Moreover, since the field from which one derives the potential satisfies a homogeneous equation, the field is not radiated, as is, for example, the electromagnetic field. But there are two further very important differences.

1. The quantum potential does not produce, in general, a vanishing interaction between two particles as the distance between those particles becomes very large. Thus two distant systems may still be strongly and directly connected. This is, of course, contrary to the implicit requirement of classical physics, where it is always assumed that where two systems are sufficiently far apart, they will behave independently. This is a necessary condition if the notion of analysis of a system into separately and independent existent constituent parts is to be carried out. Thus the quantum potential seriously calls into question the notion that all explanations of complexity must be understood by considering independent systems in interaction with each other.
2. What is even more striking is that the quantum potential cannot be expressed as a universally determined function of all the coordinates of the particles. Rather it depends on the 'quantum state' $\psi(r_1 \ldots r_n)$ of the *system as a whole.* This means that even if at some time the positions and momenta of two sets of particles are the same, but they are in different quantum states, then their subsequent evolution can be very different.

All of this implies that the relationship between two particles depends on something that goes beyond what can be described in terms of these two particles alone. In fact more generally, this relationship may depend on the quantum states of even larger systems, ultimately going on to the universe as a whole. Within this view separation becomes a contingent rather than a necessary feature of nature.

This is very different from the way we perceive the macroscopic world around us, where separation seems basic. However, it is well known that when we go to low enough temperatures, bulk matter behaves very differently. Currents flow without dissipation in superconductivity, superfluids flow without viscosity, etc., but as the temperature rises, the distant correlations necessary for non-dissipation break up and the particles no longer flow without resistance. If we regard these long-range correlations as stemming from quantum non-locality, then they seem to be very fragile and can be broken quite easily, simply by raising the temperature. In fact it is this fragility that makes it impossible to send signals in EPR situations. This is another way of explaining why a conflict with relativity is by no means necessary.

But this fragility is not always the case. The binding of electrons in atoms, covalent molecular bonds, etc., are much stronger. Nevertheless these, too, can be broken, provided enough energy is supplied. This could be either in the form of heat or chemical energy. Thus it is in thermodynamic systems that separability arises. In fact there seems to be a deep connection between irreversibility and the break-up processes, but the details are not clear.

Prigogine and his group have studied the question of irreversibility in physical systems in great depth. Although most of this work has been concerned with classical systems, very wide-reaching results have been obtained, some of which have deep epistemological consequences. In his paper with Elskens, Prigogine argues that in making the transition from dynamics to thermodynamics, the introduction of irreversibility at the microscopic level implies deep changes in the structure of space-time. Here irreversibility leads to a well-defined form of non-locality in which a single point in space-time is replaced by an ensemble of points giving rise to a geometry which contains a unique time order. Their paper outlines the basic concepts that are involved in the new dynamics.[49]

This new dynamics has not yet been used to address the question of how a breakdown of the correlations discussed above can occur. Nevertheless, it seems likely that it could provide a deeper understanding of the process involved, not only in breaking the correlations, but also in establishing non-local correlations in systems that are far from equilibrium. Indeed Fröhlich has recognised such a possibility and has conjectured that in certain dielectric systems longitudinal electric oscillations may extend over macroscopic distances, giving rise to quantum non-local correlations.[50] These effects are of particular interest in biological systems and are themselves maintained in equilibrium through a constant supply of energy, i.e. they are, like all living systems, far from thermal equilibrium. But there are deeper problems for the application of quantum mechanics to biological systems. One such problem is raised by Fröhlich in this volume; namely, can there also be non-locality in time?[51]

Such questions are already implicit when we extend the notion of wholeness to relativistic quantum mechanics. Here relativity puts space and time on an equal footing so that non-locality in space suggests the possibility of non-locality in time. Such questions, in fact, have been discussed in Bohm's group but their work in this area has not been published yet. Any meaningful discussion along these lines cannot take place until the quantum potential approach has been applied to relativistic quantum mechanics. Some work, particularly by Vigier's group in Paris, has explored the Klein-Gordon[52] and Dirac[53] equations with some success. However, the Klein-Gordon equation produces difficulties even before one introduces the quantum potential ideas. Bohm has long felt that the best generalisation is through relativistic field theories. Thus in an appendix to his 1952 paper, Bohm sketches an approach to the electromagnetic field. Here the superwave function leads to a generalised Hamilton-Jacobi equation containing a super-quantum potential in addition to any classical potentials. This equation is a field equation which, when the super-quantum potential is neglected, reduces to the classical d'Alembert equation.[33]

In this approach the quantum field may be non-locally connected, so that instantaneous effects may be carried from one point of the field to another distant point. As with the non-relativistic case, it can be shown that no signal connecting distant events instantaneously is possible, provided the measurements that would detect these signals are limited by the statistical nature of the results of quantum theory.

This whole approach through the super-quantum potential offers a new way to explain the quantum properties of fields. Here the energy may spread out from one source, ultimately to focus on another as a result of the non-local non-linear terms in the super-Hamilton-Jacobi equation. Thus, a quantised field is not basically a collection of individual quanta (i.e. particles); rather, it is a dynamical structure, organised by the super-quantum potential so that it gives rise to discrete results, even though the process itself is not discrete.

The relevance of this way of interpreting the theory can be seen even more clearly in the case of an electromagnetic wave that is formed from interference of weak beams from two independent optical lasers as described by Pfleegor and Mandel.[54] The photon picture raises the unanswerable question: from which laser does the photon come? But in the super-quantum potential interpretation, there is no problem because there are no permanent photons. There is only a total field of activity arising from both lasers, organised non-linearly and non-locally by the super-quantum potential, and it is this feature that gives rise to the excitation of a single quantised transfer of energy to the detector.[35]

All of this deals with boson field systems; nothing has been done with fermion fields. The quantum potential approach itself does not include spin very happily. Bohm worked on this problem together with Tiomno and Schiller[55] during his stay in Brazil. They were able to show that it is possible to obtain a causal description of the Pauli equation. Bohm, himself, has made some comments on the application of the quantum potential approach to the Dirac equation but the details have not been worked out.[56] Cufaro-Petroni and Vigier[57] have explored a possible approach using the Feynman-Gell-Mann equation for spin-half particles but, as yet, there is no method for discussing spin-half *fields*. The first tentative steps in this direction appear in this volume in an article by John Bell.[58] He argues for the exclusion of the notion of 'observable' and the introduction of a beable whose existence does not depend on observation. If we replace the three-space continuum by a dense lattice and define a fermion number operator at each lattice point, we can regard the fermion numbers as local beables. The dynamics is replaced by a stochastic development of the fermion number configuration. Bell goes on to discuss the consequences of this model.

For many years Bohm himself never felt the need for a detailed exploration of these particular aspects of field theory. Rather he felt that the novel nature of quantum wholeness that emerged both from the quantum potential and Bohr's work required a radical restructuring of our view of reality, and this could not be obtained simply by reworking everything in terms of the quantum potential and the super-quantum potential. He has only recently returned to these topics, essentially for two reasons.

1 There have been considerable advances in experimental techniques which have made possible an exploration of the foundations of quantum mechanics using single particles or single-atom emitters. These experiments have raised the old issues again and, with the new generation struggling to make sense of these results in terms of the usual quantum mechanics, Bohm felt that a careful and more detailed explanation of his original ideas sketched in his 1952 papers was needed.
2 Bohm has found, as he explains in his article, that it is now useful to re-examine those aspects of the super-quantum potential which offer a guide as to the limitations that must be imposed on the implicate order if it is to produce results that are not contrary to our experience of quantum phenomena.

None of this should be taken as a return to the old model. On the contrary, it is to be seen as a way of explaining the deep nature of his new view on the nature of reality that has emerged from different explorations that he has made in the last twenty years.

In order to bring these out, it is necessary to sketch how these views developed from the perception of the holistic view that quantum mechanics demanded. Since nearly all our habitual thinking involves analysis into independent entities of one kind or another interacting to form complex systems, we are faced with a very difficult problem. Do we follow Bohr and rule out any possibility of analysis in principle, thus leaving ourselves with an 'algorism' from which we calculate the outcome of given experimental situations? Do we restrict ourselves to the quantum potential approach trying to explain its origin in some deeper underlying process in space-time, as does Vigier and his group? Or can we try something else? If so, what is this something else? Where do we start?

In order to motivate a point of departure let us look at Bohr's position and try to see why he insisted on unanalysability. One strand of the argument involved what he called the 'finite quantum of action'. This notion arises from the uncertainty relation

$$\Delta x \Delta p \geqq h$$

where h has the dimensions of the classical action. Thus the product of the uncertainties cannot be less than this 'finite quantum of action'. Bohr took this to imply that it was not possible to make a sharp distinction between the observer and the observed. It was like a blind man with a rubber stick exploring a room. By feeling the reactions to his prodding stick he cannot obtain as sharp an image of, say, the walls of the room than he could have obtained with a rigid stick. The flexibility in the stick could not be 'calculated' away. There was an indivisible, uncontrollable and unpredictable connection between subject and object which rendered a sharp separation between the two impossible.

The second strand of the argument involved regarding 'the concepts of classical physics as refinements of the concepts of daily life and as an essential part of the language which forms the basis of all natural science'.[59]

Thus, according to Bohr, classical concepts are inherent in all logical thinking. As Bohm writes:

> Such a point of view implies that every understandable and describable aspect of experience could in principle be analysed by regarding the world as made out of various component parts, each having at any moment a definite position and a definite momentum. If we in practice do not do this in everyday life but use other concepts instead, this means only that we are approximating to the ideal of such a complete analysis.[60]

But quantum mechanics is already suggesting that such an analysis is in principle excluded. This, in turn, suggests that our desire to pinpoint precisely, say, the positions of particles is not necessary. In other words, could it not be that our insistence on the use of a Cartesian co-ordinate system to describe physical processes is at fault? After all, when we are describing the location of common objects, we resort to phrases like 'It is *on* the table' or 'It is *on* the shelves *between* two books' etc. We hardly ever use a co-ordinate system but rely very much on topological relations. Could it then be that our insistence on a co-ordinate description as opposed to a topological description is leading us to the conceptual problems in understanding quantum theory?

It was in the late 1960s that the group at Birkbeck began an exploration of topological methods. This involved excursions into the mathematical techniques of homology and cohomology. At that stage few physicists studied these mathematical disciplines, although there were notable exceptions, including John Wheeler, whose lucid explanations of cohomology for physicists were a very great help in clarifying some of the questions involved.[61] It was not difficult to show that many of the main laws of physics, such as the Hamilton-Jacobi theory, Maxwell's equations and even the Dirac equation, could be given a very simple meaning without resorting to the continuous space-time backcloth.

There was one notable exception and that was general relativity, which could not be expressed naturally in this topological language. But clearly a simple mathematical transcription was not sufficient, so Bohm began to investigate the notion of order in a more general way. One of his main investigations was to develop new principles of order that would replace those implied in the concept of continuity.[62]

One such idea was to regard the particle as a break in some background structure. Here one was exploiting the analogy of a dislocation in a crystal. Frank had already shown that an edge dislocation migrating through a crystal could be regarded as a particle having an effective mass, where the mass itself varies in the same way as mass varies in relativity, but now the speed of light is replaced by the speed of sound.[63] The fields themselves could be thought of as the stresses arising from the deformations caused by the presence of the dislocations.

Bohm wanted to abandon the traditional notion of particles and fields-in-interaction in a continuous space-time, replacing it by the notion of structure process. That is to say one analyses all physical processes structurally, using as basic building blocks structures called simplexes (analogues of lines, triangles, tetrahedra, etc.) which could be ordered, boundary to boundary, forming a structure called a simplicial complex. The failure of perfect fitting would then correspond to the presence of matter or fields.[64]

This type of approach through topo-chronology offers the possibility of being able to incorporate some notion of wholeness required by quantum mechanics. A particle could not be separated from the surrounding structure because what is called a particle is simply a break in the background structure. Furthermore, two dislocations could not be separated since they are only breaks in the same structure.

Several attempts were made to use matrix representations to describe these structures but it became very cumbersome. Indeed there have been many papers published in dislocation theory exploiting the analogies with continuum dynamics. In this volume two former research students, Peter Holland and Chris Philippidis, have exploited and generalised these ideas to show how *classical* electrodynamics can be interpreted as a theory of a continuously dislocated covariant space-time ether. One of the important features of this work is to show in detail how the particle and field are seen as structurally inseparable even in the continuum limit.[65]

But in order to get a better understanding of quantum phenomena it was the discrete structure process that offered the better prospects. However, even here the structure seems too primitive to be carried very far. Time did not seem to be naturally part of the structure. The structure changed in time but was not of time. The whole approach seemed to be in the category of what Bergson called a cinematographical outlook, a series of 'stills' with no natural flow.[66]

A vital clue on how to overcome this difficulty was provided by some experimental work on the human eye. Ditchburn had noticed that the eye was in continous vibration and that this vibration was vital in order to see.[67] To show this he fixed a mirror system to the eye so as to 'freeze' out the vibration. The result was that the eye could no longer see anything. Thus to see a line or boundary, for example, the eye must scan backwards and forwards across the line. The difference in the response in the retina as the eye crosses the line enables the brain to reconstruct the line. If the scanning is stopped, no line is seen, even though there is a static image on the retina. Thus, movement is basic to perception. But, equally, if there are no relatively invariant features for the eye to scan, then again nothing will be seen. So 'nothingness' does not mean there is nothing there; it could mean simply that there are no features that remain invariant for a sufficient length of time.

Suppose now we carry through this idea to quantum field theory where the vacuum state plays a basic role. We could argue that the vacuum state is not empty, but is in fact full of undifferentiated activity. This could then account for things like vacuum fluctuations which strongly suggest a vacuum state is far from empty. It could be full of activity that is changing so rapidly that it cannot be perceived above a certain level. Could it therefore be that the structure described by the simplicial complex is merely the relatively invariant features of the basic underlying process or activity or what we call movement? Then in order to accommodate wholeness we regard this unbroken activity as the basic notion and what our physics discusses are the quasi-stable, semi-autonomous features of this underlying holomovement.

One important feature concerning the holomovement is that it is not described in space-time but from it space-time is to be abstracted. Thus we no longer start with an *a priori* space-time manifold in order to discuss physics; rather, we construct space-time from the underlying process. It is not, as Wheeler and Hawking suggests, a progression from the continuum via fluctuations to the space-time foam; rather, it is the simplicial description of the relative invariant features of the holomovement that become the foam from which the continuous space-time is abstracted. Thus locality is no longer a primary concept but is also abstracted so that quantum non-local correlations could be explained as a remnant of the basic underlying complex. Furthermore 'staticness' is no longer a problem. The relatively invariant features can change as the underlying holomovement changes. It is like Heraclitus' candle flame dancing and flickering, giving the appearance of an autonomous entity but, in fact, being constantly renewed.

Ideas along these lines have also been suggested by David Finkelstein and we have been very stimulated by his unique way of looking at things.[68] He acknowledges being influenced by Bohm's exploration of structure process, and in his article 'All is flux'[69] he outlines some of the areas of cross fertilisation that have taken place. He too proposes a simplicial approach to quantum theory, calling his basic structures quantum simplexes. As we will see, the simplexes used to describe the holomovement are in fact algebraic and, in consequence, are quantum in origin. Thus both approaches attempt to abstract classical space-time from an essentially quantum structure.

Given the holomovement, it is now but a small step to the implicate order. We can regard the relative invariant features of the holomovement as the explicate order while that which remains in the background is the implicate order. What is missing is the notion of folding and enfolding, and that has its source in three separate and different developments.

In his book on causality and chance, Bohm had already suggested that the trajectories that emerged from the quantum potential approach were some kind of average property of a deeper process. He writes:

> Thus, we are led to a point of view rather like that suggested in section 2 in connection with the Brownian motion of mist droplets near the critical point, namely that particle-like concentrations are always forming and dissolving. Of course, if a particle in a certain place dissolves, it is very likely to re-form nearby. Thus on the large-scale level, the particle-like manifestation remains in a small region of space following a fairly well-defined track, etc. On the other hand, at a lower level, the particle does not move as a permanently existing entity, but is formed in a random way by suitable concentrations of the field energy.[70]

In view of this statement is is not surprising that the unmixing (glycerine) demonstration Bohm saw on television provided a vital stimulus in arriving at the implicate order (see Chapter 2 in this volume). In this example the folding–unfolding idea emerges very clearly.

Also from this example there appears a further principle; namely, that not everything can be unfolded together. Such an idea is already present in perception, where a set of lines can appear to give one form or another but never both together. But in physics the Cartesian notion that everything can be displayed together simultaneously has dominated, albeit implicitly, even though the appearance of quantum mechanics with its sets of commuting operators calls this into question. There is a continual drive to find models in which all aspects of the process can be 'displayed' simultaneously. In the new view it is necessary to distinguish between that which could be unfolded together (the explicate order) and that which remains enfolded (the implicate order). Surely this is the deeper truth that essentially lay behind Bohr's notion of complementarity, although it tended to become trivialised into wave-particle duality.

Perhaps the most significant stimulus for the folding–unfolding notion came from a mathematical technicality, namely, the Green's function approach to Schrödinger's equation. Feynman first pointed out that in quantum mechanics, one can use the Huygens construction to determine the wave function at a point y from the wave function at $\{x\}$, where $\{x\}$ is the set of points on a surface at a previous time. Thus:

$$\psi(y,t_2) = \int_{\text{surface}} M(x,y,t_1,t_2)\psi(x,t_1)\mathrm{d}x$$

where $M(x,y,t_1,t_2)$ is a Green's function. Pictorially this is represented in Figure 1.1. The wave function at all points of the surface S contributes to the wave function at y. Thus the information on the surface S is enfolded into $\psi(y)$. This $\psi(y)$ determines the quantum potential acting on the particle at y so that the particle reacts to the enfolded information of a set of earlier wave functions. In turn $\psi(y)$ itself gets 'unfolded' into a series of points on a later surface S' (see Figure 1.2). In this way we see that the quantum potential itself is determined by an enfolding–unfolding process.

$\psi($

$\psi(y)$

S

Figure 1.1

$\psi(z)$

$\psi(y)$

S'

Figure 1.2

We can now generalise this in the following way: if E and E' are two successive explicate orders, then for continuity we can argue that the enfolded E is equal to the unfolded E', i.e.:

$$EM_1 = M_2E'$$

where M_1 and M_2 are the enfolding and unfolding elements (essentially Green's functions). Then:

$$E' = M_2^{-1}EM_1$$

If we assume:

$$M_2 = M_1 = e^{-iHt/h}$$

we find Heisenberg's form of the Schrödinger equation follows immediately.[71] It was a generalisation of arguments of this kind that led Bohm to suggest that the basic mathematics required to describe the implicate order will involve the use of matrix algebras. Furthermore, although most physicists use the Hilbert space formalism for quantum mechanics, there is an equivalent formulation in terms of matrices, where the state functions are replaced by appropriate algebraic ideals. Thus there is a common mathematical structure shared by quantum mechanics and the implicate order. All of this, and a lot more, is explained in more detail in Bohm's *Wholeness and the Implicate Order.*[72]

The notion that the space-time continuum should not be taken as basic notion had a number of advocates in the late 1960s. They included Roger Penrose, who was then a member of the mathematics department at Birkbeck College. He would often take part in the seminars run by the physics department and explained to us his idea of a 'spin network'[73] and how he was hoping the twistor would play a part in generating these ideas.[74] At about the same time we were joined by a research student, Fabio Frescura, who carried out a detailed investigation of the algebraic approach and showed that if one took the direct product of a suitable Clifford algebra and a symplectic algebra (essentially the Heisenberg algebra supplemented by the addition of a special element), one could bring about a complete algebraisation of quantum mechanics without any reference to a space-time continuum.[71,75] These algebras are essentially geometric algebras, the Clifford algebras carrying the rotational symmetries and the symplectic algebra carrying the translational symmetries. Thus they have within their structures all the required symmetry properties for abstracting the space-time continuum.

Penrose's approach through the spin network and twistors can be given an algebraic flavour once one recognises that the non-relativistic spinor is simply an ideal in the Paul Clifford algebra (C_2) while the twistor is a similar ideal in the conformal Clifford algebra (C_6). A discussion of the details of how these similarities can be exploited would not be appropriate here and more details can be found in the papers of Bohm and Hiley[76] and Frescura and Hiley.[71] The essential consequence of this approach is that the simplicial complexes used to describe structures in the holomovement are essentially algebraic and hence can be regarded as quantum in origin, as are the simplexes used by Finkelstein that we referred to earlier.

Clive Kilmister has always been very encouraging in our explorations of the algebraisation of the implicate order and his article in this volume investigates the automorphism group of C_4, the Dirac Clifford algebra, providing some simple geometric insights present in this algebra.[77] These results are quite central to the work described above. In the following paper Frescura and Hiley[78] indicate that the algebraic spinor offers a generalization of the usual approach and suggest how this can be exploited in the extension which allows the algebra to carry a structure equivalent to curvature.

We were very happy to learn that Geoffrey Chew's work using an S-matrix approach has found Bohm's implicate order a useful general scheme in which to bring out some of the features of his approach. One of us (B. J. Hiley) still vividly remembers Chew's 1963 Rouse Ball lecture 'The dubious role of the space-time continuum in microscopic physics' which was eventually published in *Science Progress.*[79] There he writes: 'but a growing number of us are reaching the conclusion that to make major progress we must stop thinking and talking about such an unobservable (space-time) continuum'. The main theme of the talk was to point out the advantages of the S-matrix over the more usual quantum field approach. (Perhaps today one could argue that the S-matrix describes various structures in the implicate order.) In the original talk the link between macroscopic space-time and the S-matrix was left as a challenge about which Chew said little except for a rather vague remark concerning the role of photons.

This work has progressed considerably since those early days and Chew explains in a very general way how the soft photons enable the macroscopic space-time to be made explicate.[80] A colleague of Chew's, Henry Stapp, has also done a significant amount of work on questions arising from the S-matrix approach. He has also worked for a long time on the foundations of quantum mechanics and has contributed significantly to the discussions of quantum non-locality.[81] In his article he presents a simple model that incorporates lessons learned from the S-matrix.[82] He shows in detail how the classical concepts emerge from the 'soft' photons which are described by coherent states.

So far we have concentrated mainly on physics but David Bohm's interest and influence extend far beyond physics and embrace biology, psychology, philosophy, religion, art and the future of society. His contributions are not, however, made in the academic sense of someone who makes additions within the accepted, historical framework of a discipline but always in a creative way as one working from a new perspective based on the implicate order. It would be impossible even to summarise his contributions to the discussions over this wide range of topics. Rather we will let the contributors who have been influenced by him speak for themselves.

Brian Goodwin sees Bohm as working in the same tradition as the Renaissance *mage* who sought a unification between mind and nature.[83] His vision of nature as an undivided whole could well be applied to biology, Goodwin argues, where it would counteract an 'atomistic (molecular) fragmentation' in favour of an approach that emphasises the wholeness and relational order of the organism. Goodwin, in his essay, discusses how a revolution in perspective could be achieved and suggests that our current fragmentary view of the organism as divided between phenotype and genotype involved in genetic information processing be replaced by a theory of morphogenetic fields.

Robert Rosen also discusses biological systems and raises the question of the relationship of physics to biology.[84] Does biology simply require an application of the general laws of physics to complex systems or will new ideas not already present in physics be required? He argues for the latter, claiming that physics in its present form is too narrow. This is in no sense a plea to introduce ideas of 'vitalism'; rather new concepts of order will be required, a theme that has a close relationship with Bohm's own thinking. With Bohm, new orders are required within physics. These new orders incorporate 'wholeness' and here a more organic view of nature is required. Rosen suggests that the study of the behaviour of macromolecules may provide a clue as to the nature of these orders. He uses the van der Waals gas to illustrate what he has in mind and shows how this can be reanalysed in the old Aristotelian categories of causation. This leads him to suggest a novel idea that each category of causation is reflected in a logically independent aspect of system description, thus implying that it is no longer possible to think of a description purely in terms of states plus dynamical laws.

Maurice Wilkins, working at the macromolecular level in biological systems, found that the complementary aspects of symmetry and asymmetry seemed to be playing a crucial role. Again, at a different level, in DNA there seems to be a similar relationship of opposites between the precise replication of genes and the extensive rearrangement that now seems to be necessary for evolution to take place. His article[85] explores from a very general point of view how complementarity arises in a number of disciplines ranging from physics, through biology, to the visual arts. Here complementarity is taken to imply a specific interaction between the parts that gives rise to wholeness or perfection. He also asks whether any of the lessons learned can help with the problem of human conflict, a problem that concerns Maurice very deeply in this nuclear age.

In his *The Special Theory of Relativity*[86] Bohm gave considerable attention to the way in which we gain knowledge about the world. But this analysis was not carried out in a simple positivistic sense of building scientific theories out of sense data but rather in an attempt to understand how our concepts of reality grow out of the dynamic activity of perception. During the 1960s, while working with one of his students, D. Schumacher, Bohm began to give emphasis to the role of language and communication in this process; indeed he has more recently chosen to describe it in united, and hyphenated, form as perception-communication. Following Bohr, Bohm discussed the role of informal languages in scientific theories of nature and investigated what he felt to be a failure in communication between Einstein and Bohr himself.

Bohm's interest in language led to the development of what he called the rheomode, a language of communication more suited to his notions of enfolded order.[72] Alan Ford, stimulated by Bohm's writings on physics and language, has attempted to forge a connection between linguistics and category theory, the latter topic being, in Bohm's view, the first step to creating any form of order.[87] As we have already seen, Bohm's researches came to fruition in the form of the implicate or enfolded order and, more recently, generative orders. The essence of the implicate order is a form of enfoldment such that any aspect of the system enfolds and is interior to the whole. Clearly this idea of order is a far reaching one, with implications that extend far beyond current physics. Karl Pribram,[88] for his part, explains how Bohm's insights enabled him to construct a holographic theory of the brain that helped to resolve problems of non-local storage and the way in which spatial frequencies are resolved during vision. Gordon Globus acknowledges the significance of Pribram's model in changing our perspective on the brain, but attempts to go further with what he calls holonomy.[89] While the holographic approach assumes an essential *tabula rasa* into which the external environment is folded, Globus assumes that the brain contains a plenum of *possibilia*. Such an approach, Globus feels, makes relevant the traditions of mysticism with its Godhead as well as Western research on 'altered states of consciousness'.

Bohm's work has always held a particular fascination for the artist for, while the physics may be inaccessible, Bohm's essential approach to nature is sympathetic to their nature. John Briggs[90] explores the relationships between Bohm's theories on the ultimate structure of matter and his own views on the structure of a work of art. Briggs draws attention to a particular aspect of the metaphor, which he calls a reflectaphor, in which each side reflects the other and meaning lies in a continuing reflexive movement. Through an analysis of poetry, the short story and painting, Briggs concludes that in its deepest structure a work of art is built not on explicit forms but out of numerous metaphors that are woven together in such a way that each one reflects all others. Just as each part of nature represents an enfoldment of the entire universe, so each part of a work of art reflects the whole. Clearly Briggs' approach gives insight into Bohm's contention that a unity can exist between the artistic, scientific and religious mind.

For Montague Ullman, Bohm's notions of enfolded order and the non-local nature of reality have a significant connection to dreams.[91] In his paper he analyses the creative way in which images and events are woven together in the dream and discusses its essential healing nature. Ullman also believes that dreams have a social nature and, indeed, that they have a survival value for the human race. Again there is evidence from amongst so-called primitive peoples that dreams fulfil just such a function. Here Ullman touches on one of Bohm's current interests, for it is the latter's belief that a form of true co-operation and harmonious society once existed amongst the early hunter-gatherers and such 'leadership from behind' may even be possible amongst urban society today. To what extent dreams play a role in the creative cohesion of such groups is a matter for further investigation.

This interest in dialogue and the co-operative activity of small groups is also explored by David Shainberg. Shainberg draws attention to the way in which human consciousness erects fixed barriers to the dynamic process of enfolding and unfolding that is characteristic of the implicate order. Shainberg's discussion[92] of the way in which thought seeks security by fixing the moment in endless repetitions of itself brings us close to the heart of Bohm's dialogues with the late Indian philosopher J. Krishnamurti. Bohm met Krishnamurti in the early 1960s and since that time has held a number of dialogues in which the two thinkers have explored many issues together including the nature of reality and the urgent need for a change in human consciousness.

Shainberg traces the origins of these blocks in consciousness and discusses the various approaches that individuals have adopted when made aware of such a trap. In particular he explores the nature of private meditation and a form of group dialogue in which no position is fixed but each participant is sensitive to the constant movement of thought and its tendency to seek security in fixed positions. Within such a dialogue it becomes possible for new insights to develop as relationships are constantly created anew.

The final contribution in this collection of essays takes the form of a dialogue between Renée Weber and David Bohm.[93] Renée Weber felt that the best way that she could contribute to this Festschrift was to try to get David Bohm to explain some of the philosophical ideas that arise in the implicate order. Recently Bohm has come to realise the importance of information and meaning, not only in the context of the human world, but also in the inanimate world. For Bohm meaning *is* being and meaning *is* the essence of reality. These ideas are very different from our normal way of thinking and seem to be essential in the context of wholeness. What Renée Weber does in the dialogue is to bring out the thinking that lies beyond these ideas.

David Bohm has argued that the essence of the scientific mind is the ability to see the fact no matter what it says. This fearlessness and passion of the intelligence characterises all of David Bohm's work and explains its far-reaching attraction for so many of the contributors gathered here. For reasons of space they represent only a small selection of researchers, thinkers, writers and artists who could have contributed to this volume. Clearly David Bohm's ideas have influenced a wide audience and stimulated much discussion which has helped to create new insights and lead to an essentially unified vision of nature in which artist, scientist and religious thinker are no longer divided. Even more significant, perhaps, is the hope that individuals may come together in a spirit of creative co-operation to build a world in which undivided wholeness and creative order are an essential ground.

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2

Hidden variables and the implicate order[1]

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I have been asked to explain how my ideas of hidden variables tie up with those on the implicate order, and to bring out in some detail how both these two notions are related. In doing this, it would perhaps be best to begin with an account of how I came to these ideas in the first place.

The whole development started in Princeton around 1950, when I had just finished my book *Quantum Theory*.[2] I had in fact written it from what I regarded as Niels Bohr's point of view, based on the principle of complementarity.[3] Indeed, I had taught a course on the quantum theory for three years and written the book primarily in order to try to obtain a better understanding of the whole subject, and especially of Bohr's very deep and subtle treatment of it. However, after the work was finished, I looked back over what I had done and still felt somewhat dissatisfied.

What I felt to be especially unsatisfactory was the fact that the quantum theory had no place in it for an adequate notion of an independent actuality – i.e. of an actual movement or activity by which one physical state could pass over into another. My main difficulty was not that the wave function was interpreted only in terms of probabilities, so that the theory was not deterministic; rather, it was that it could only be discussed in terms of the results of an experiment or an observation, which has to be treated as a set of *phenomena* that are ultimately not further analysable or explainable in any terms at all. So, the theory could not go beyond the phenomena or appearances. And, basically, these phenomena were very limited in nature, consisting, for example, of events by which the state of a particle could be ascertained. From a knowledge of this state we could go to a wave function that predicted the probability of the next set of phenomena, and so on.

On thinking about what all this meant, it began to occur to me that the quantum theory might actually be giving a fragmentary view of reality. A wave function seemed to capture only certain aspects of what happens in a statistical ensemble of similar measurements, each of which is in essence only a single element in a greater context of the overall process. Though von Neumann[4] had given what purported to be a proof that to go any further would not be compatible with the quantum theory (which was already very well confirmed indeed), I still realized that mathematical proofs are based on axioms and presuppositions whose meanings are often obscure and always in principle open to question. Moreover, the theory of relativity, which was also regarded as fundamental, demanded a space-time process (e.g. one that could be understood in terms of fields) which constituted an independent actuality, with a continuous and determinate connection between all its parts. Such a process could not be treated solely as a set of fragmentary phenomena that are related only statistically.

This requirement becomes especially urgent when relativity is extended to include cosmology. It seems impossible even to contemplate the universe as a whole through a view which can discuss only in terms of discrete or distinct sets of phenomena, for in a cosmological view the observing instruments, and indeed the physicists who construct and operate them, have to be regarded at least in principle as parts of the totality. There does not seem to be much sense in saying that all these are nothing more than organized sets of appearances. To whom or to what would they appear, and of what would they be the appearances?

I felt particularly dissatisfied with the self-contradictory attitude of accepting the independent existence of the cosmos while one was doing relativity and, at the same time, denying it while one was doing the quantum theory, even though both theories were regarded as fundamental. I did not see how an adequate way to deal with this could be developed on the basis of Niels Bohr's point of view. So I began to ask myself whether another approach might not be possible.

In my first attempt to do this I considered a quantum mechanical wave function representing, for example, an electron, and supposed that this was scattered by an atom. By solving Schrödinger's equation for the wave function, one shows that the scattered wave will spread out more or less spherically. Nevertheless, a detector will detect an electron in some small region of space, while the extended spherical wave gives only the probability that it will be found in any such region. The idea then occurred to me that perhaps there is a second wave coming in toward the place where the electron is found, and that the mathematical calculus of the quantum theory gives a statistical relationship between outgoing and incoming waves.

However, to think this way requires that we have to enrich our concepts to include an incoming wave as well as an outgoing wave. Indeed, since further measurements can be made on the electron, it follows that, as the second wave spreads out, it may give way to a third, and so on. In this way, it becomes possible to have an ongoing process in which the electron is understood as an independent actuality (which will, of course, give rise to phenomena through which it may be detected). One is thus implying that the current quantum theory deals only with a fragmentary aspect of this whole process – i.e. that aspect which is associated with a single observational event.

It seems clear that at this stage I was anticipating what later became the implicate order. Indeed, one could say that ingoing and outgoing waves are enfolding and unfolding movements. However, I did not pursue this idea further at the time. What happened was that I had meanwhile sent copies of my book to Einstein, to Bohr, to Pauli and to a few other physicists. I received no reply from Bohr, but got an enthusiastic response from Pauli. Then I received a telephone call from Einstein, saying that he wanted to discuss the book with me. When we met, he said that I had explained Bohr's point of view as well as could probably be done, but that he was still not convinced. What came out was that he felt that the theory was incomplete, not in the sense that it failed to be the final truth about the universe as a whole, but rather in the sense that a watch is incomplete if an essential part is missing. This was, of course, close to my more intuitive sense that the theory was dealing only with statistical arrays of sub-processes associated with similar observational events. Einstein felt that the statistical predictions of the quantum theory were correct, but that by supplying the missing elements we could in principle get beyond statistics to an at least in principle determinate theory.

This encounter with Einstein had a strong effect on the direction of my research, because I then became seriously interested in whether a deterministic extension of the quantum theory could be found. In this connection I soon thought of the classical Hamilton-Jacobi theory, which relates waves to particles in a fundamental way. Indeed, it had long been known that when one makes a certain approximation (Wentzel-Kramers-Brillouin), Schrödinger's equation becomes equivalent to the classical Hamilton-Jacobi equation. At a certain point I asked myself: What would happen, in the demonstration of this equivalence, if we did not make this approximation? I saw immediately that there would be an additional potential, representing a new kind of force, that would be acting on the particle. I called this the quantum potential, which was designated by Q.

This gave rise directly to what I called a causal interpretation of the quantum theory.[5,6] The basic assumption was that the electron *is* a particle, acted on not only by the classical potential, V, but also by the quantum potential, Q. This latter is determined by a new kind of wave that satisfies Schrödinger's equation. This wave was assumed, like the particle, to be an independent actuality that existed on its own, rather than being merely a function from which the statistical properties of phenomena could be derived. However, I showed on the basis of further physically reasonable assumptions that the intensity of this wave is proportional to the probability that a particle *actually is* in the corresponding region of space (and is not merely the probability of our observing the phenomena involved in *finding* a particle there). So the wave function had a double interpretation – first as a function from which the quantum potential could be derived and, secondly, as a function from which probabilities could be derived.

From these assumptions I was able to show that all the usual results of the quantum theory could be obtained on the basis of a model incorporating the independent actuality of all its basic elements (field and particle), as well as an in principle complete causal determination of the behaviour of these elements in terms of all the relevant equations (at least in a one-particle system, which is as far as I had got at the time).

I sent pre-publication copies of this work to various physicists. De Broglie quickly sent me a reply indicating that he had proposed a similar idea at the Solvay Congress in 1927, but that Pauli had severely criticized it and that this had led him to give it up. Soon after this I received a letter from Pauli, stating his objections in detail. These had mainly to do with the many-particle system, which I had not yet considered seriously. However, as a result of these objections, I looked at the problem again and came out with a treatment of the many-particle system which consistently answered Pauli's criticisms. In doing this, I also developed a theory of the process of measurement which gave an objective account of this process, without the need for the arbitrary and unexplained 'collapse' of the wave function that was implied in the usual interpretation of the theory.[7]

A more detailed consideration of this extended theory led me to look more carefully into the meaning of the quantum potential. This had a number of interesting new features. Indeed, even in the one-particle system these features showed up to some extent, for the quantum potential did not depend on the intensity of the wave associated with this electron; it depended only on the *form* of the wave. And thus, its effect could be large even when the wave had spread out by propagation across large distances. For example, when the wave passes through a pair of slits, the resulting interference pattern produces a complicated quantum potential that could affect the particles far from the slits in such a way as to 'bunch' them into a set of fringes equivalent to those predicted in the usual interpenetration of the quantum theory.[8] Thus, by admitting that, even in an 'empty' space in which there is no classical potential, the particle can be acted on by a quantum potential that does not fall off with the distance, one is now able to explain the well-known wave particle duality of the properties of matter. And by noting that this quantum potential can generally have a major effect on the particle, an effect that indeed reflects the whole environment, one can obtain a further insight into the crucially significant new feature of wholeness of the electron and its relevant experimental context, which Bohr had shown to be implicit in the quantum theory.

When one looked at the many-particle system, this new kind of wholeness became much more evident, for the quantum potential was now a function of the positions of all the particles which (as in the one-particle case) did not necessarily fall off with the distance. Thus, one could at least in principle have a strong and direct (non-local) connection between particles that are quite distant from each other. This sort of non-locality would, for example, give a simple and direct explanation of the paradox of Einstein, Podolsky and Rosen, because in measuring some property of one of a pair of particles with correlated wave functions, one will alter the 'non-local' quantum potential so that the other particle responds in a corresponding way.

Because the above response is instantaneous, however, it would seem at first sight to contradict the theory of relativity, which requires that no signals be transmitted faster than the speed of light. At the time of proposing these notions I regarded this as a serious difficulty, but I hoped that the problem would ultimately be resolved with the aid of further new orders. This indeed did happen later in connection with the application of the causal interpretation to the quantum mechanical field theory, but as this question is not relevant to the subject of the present paper, I shall not discuss it further here.[9] Meanwhile, however, I felt that the causal interpretation was affording valuable insight into a key difference between classical and quantum properties of matter. Classically, all forces are assumed to fall off eventually to zero, as particles separate, whereas in the quantum theory the quantum potential may still strongly connect particles that are even at macroscopic orders of distance from each other. In fact, it was just this feature of the quantum theory, as brought out in the causal interpretation, that later led Bell[10] to develop his theorem, demonstrating quite precisely and generally how quantum non-locality contrasts with classical notions of locality.

As important as this new feature of non-local connection is, however, the quantum potential implies a further move away from classical concepts that is yet more radical and striking. This is that the very form of the connection between particles depends on the wave function for the state of the whole. This wave function is determined by solving Schrödinger's equation for the entire system, and thus does not depend on the state of the parts. Such a behaviour is in contrast to that shown in classical physics, for which the interaction between the parts is a predetermined function, independent of the state of the whole. Thus, classically, the whole is merely the result of the parts and their preassigned interactions, so that the primary reality is the set of parts while the behaviour of the whole is derived entirely from those parts and their interactions. With the quantum potential, however, the whole has an independent and prior significance such that, indeed, the whole may be said to organize the activities of the parts. For example, in a superconducting state it may be seen that electrons are not scattered because, through the action of the quantum potential, the whole system is undergoing a co-ordinated movement more like a ballet dance than like a crowd of unorganized people. Clearly, such quantum wholeness of activity is closer to the organized unity of functioning of the parts of a living being than it is to the kind of unity that is obtained by putting together the parts of a machine.

If the whole is such a primary notion in the quantum theory, how do we account for our usual experience of a world made up of a vast set of essentially independent parts that can correctly be understood in terms of ordinary mechanical notions? The possibility of accounting for this is grounded in the fact that when the wave function reduces to a set of constituent factors, the quantum potential reduces to a sum of independent components. As a result, the activity of the whole reduces to that of a set of independent sub-wholes. As explained in detail elsewhere,[11] under conditions of temperature commonly found on the large-scale level, such factorization comes about in an entirely objective way, depending neither on our knowledge nor on the existence or functioning of any kind of observing or measuring apparatus. Nevertheless, more generally (especially on the small-scale level but, under suitable conditions, as for example in superconductivity, also on a larger-scale level), it is an equally objective implication of the theory that the wave function does not factorize, so that the whole cannot then be divided into independent sub-wholes.

To sum up, then, the quantum potential is capable of constituting a non-local connection, depending directly on the state of the whole in a way that is not reducible to a preassigned relationship among the parts. It not only determines an organized and co-ordinated activity of whole sets of particles, but it also determines which relatively independent sub-wholes, if any, there may be within a larger whole. I want to emphasize again how radically new are these implications of the quantum theory. They are hinted at only vaguely and indirectly by the subtle arguments of Bohr, based on the usual interpretation of the quantum theory as nothing more than a set of mathematical formulae yielding statistical predictions of the phenomena that are to be obtained in physical observations. However, by putting quantum and classical theories in terms of the same intuitively understandable concepts (particles moving continuously under the action of potentials), one is able to obtain a clear and sharp perception of how the two theories differ. I felt that such an insight was important in itself, even if, as seemed likely at the time that I proposed it, this particular model could not provide the basis for a definitive theory that could undergo a sustained development. However, a clear intuitive understanding of the meaning of one's ideas can often be helpful in providing a basis from which may ultimately come an entirely new set of ideas, dealing with the same content.

These proposals did not actually 'catch on' among physicists. The reasons are quite complex and difficult to assess. Perhaps the main objection was that the theory gave exactly the same predictions for all experimental results as does the usual theory. I myself did not give much weight to these objections. Indeed, it occurred to me that if de Broglie's ideas had won the day at the Solvay Congress of 1927, they might have become the accepted interpretation; then, if someone had come along to propose the current interpretation, one could equally well have said that since, after all, it gave no new experimental results, there would be no point in considering it seriously. In other words, I felt that the adoption of the current interpretation was a somewhat fortuitous affair, since it was affected not only by the outcome of the Solvay Conference but also by the generally positivist empiricist attitude that pervaded physics at the time. This attitude is in many ways even stronger today, and shows up in the fact that a model that gives insight without an 'empirical pay-off' cannot be taken seriously.

I did try to answer these criticisms to some extent by pointing out that the enriched conceptual structure of the causal interpretation was capable of modifications and new lines of development that are not possible in the usual interpretation.[12] These could, in principle, lead to new empirical predictions, but unfortunately there was no clear indication of how to choose such modifications from among the vast range that was possible. And so these arguments had little effect as an answer to those who require a fairly clear prospect of an empirical test before they will consider an idea seriously.

In addition, it was important that the whole idea did not appeal to Einstein, probably mainly because it involved the new feature of non-locality, which went against his strongly-held conviction that all connections had to be local. I felt this response of Einstein was particularly unfortunate, both during the Solvay Congress and afterwards, as it almost certainly 'put off' some of those who might otherwise have been interested in this approach. Although I saw clearly at the time that the causal interpretation was not entirely satisfactory, I felt that the insight that it afforded was an important reason why it should be considered, at least as a supplement to the usual interpretation. To have some kind of intuitive model was better, in my view, than to have none at all, for, without such a model, research in the quantum theory will consist mainly of the working out of formulae and the comparison of these calculated results with those of experiment. Even more important, the teaching of quantum mechanics will reduce (as it has in fact tended to do) to a kind of indoctrination, aimed at fostering the belief that such a procedure is all that is possible in physics. Thus new generations of students have grown up who are predisposed to consider such questions with rather closed minds.

Because the response to these ideas was so limited, and because I did not see clearly, at the time, how to proceed further, my interests began to turn in other directions. During the 1960s, I began to direct my attention toward *order*, partly as a result of a long correspondence with an American artist, Charles Biederman, who was deeply concerned with this question. And then, through working with a student, Donald Schumacher, I became strongly interested in *language*. These two interests led to a paper[13] on order in physics and on its description through language. In this paper I compared and contrasted relativistic and quantum notions of order, leading to the conclusion that they contradicted each other and that new notions of order were needed.

Being thus alerted to the importance of order, I saw a programme on BBC television showing a device in which an ink drop was spread out through a cylinder of glycerine and then brought back together again, to be reconstituted essentially as it was before. This immediately struck me as very relevant to the question of order, since, when the ink drop was spread out, it still had a 'hidden' (i.e. non-manifest) order that was revealed when it was reconstituted. On the other hand, in our usual language, we would say that the ink was in a state of 'disorder' when it was diffused through the glycerine. This led me to see that new notions of order must be involved here.

Shortly afterwards, I began to reflect on the hologram and to see that in it, the entire order of an object is contained in an interference pattern of light that does not appear to have such an order at all. Suddenly, I was struck by the similarity of the hologram and the behaviour of the ink drop. I saw that what they had in common was that an order was *enfolded*; that is, in any small region of space there may be 'information' which is the result of enfolding an extended order and which could then be unfolded into the original order (as the points of contact made by the folds in a sheet of paper may contain the essential relationships of the total pattern displayed when the sheet is unfolded).

Then, when I thought of the mathematical form of the quantum theory (with its matrix operations and Green's functions), I perceived that this too described just a movement of enfoldment and unfoldment of the wave function. So the thought occurred to me: perhaps the movement of enfoldment and unfoldment is universal, while the extended and separate forms that we commonly see in experience are relatively stable and independent patterns, maintained by a constant underlying movement of enfoldment and unfoldment. This latter I called the *holomovement*. The proposal was thus a reversal of the usual idea. Instead of supposing that extended matter and its movement are fundamental, while enfoldment and unfoldment are explained as as particular case of this, we are saying that the implicate order will have to contain within itself all possible features of the explicate order as potentialities, along with the principles determining which of these features shall become actual. The explicate order will in this way flow out of the implicate order through unfoldment, while in turn it 'flows back' through further enfoldment. The implicate order thus plays a primary role, while the explicate order is secondary, in the sense that its main qualities and properties are ultimately derived in its relationship with the implicate order, of which it is indeed a special and distinguished case.

This approach implies, of course, that each separate and extended form in the explicate order is enfolded in the whole and that, in turn, the whole is enfolded in this form (though, of course, there is an asymmetry, in that the form enfolds the whole only in a limited and not completely defined way). The way in which the separate and extended form enfolds the whole is, however, not merely superficial or of secondary significance, but rather it is essential to what that form *is* and to how it acts, moves and behaves quite generally. So the whole is, in a deep sense, *internally* related to the parts. And, since the whole enfolds all the parts, these latter are also internally related, though in a weaker way than they are related to the whole.

I shall not go into great detail about the implicate order[14,15] here; I shall assume that the reader is somewhat familiar with this. What I want to emphasize is only that the implicate order provided an image, a kind of metaphor, for intuitively understanding the implication of wholeness which is the most important new feature of the quantum theory. Nevertheless, it must be pointed out that the specific analogies of the ink drop and the hologram are limited, and do not fully convey all that is meant by the implicate order. What is missing in these analogies is an inner principle of organization in the implicate order that determines which sub-wholes shall become actual and what will be their relatively independent and stable forms. Indeed, in both these models, the order enfolded in the whole is obtained from pre-existent, separate and extended elements (objects photographed in the hologram or ink drops injected into the glycerine). It is then merely unfolded to give something similar to these elements again. Nor is there any natural principle of stability in these elements; they may be totally altered or destroyed by minor further disturbances of the overall arrangement of the equipment.

Gradually, throughout the 1970s, I became more aware of the limitations of the hologram and ink droplet analogies to the implicate order. Meanwhile, I noticed that both the implicate order and the causal interpretations had emphasized this wholeness signified by quantum laws, though in apparently very different ways. So I wondered if these two rather different approaches were not related in some deep sense – especially because I had come at least to the essence of both notions at almost the same time. At first sight, the causal interpretation seemed to be a step backwards toward mechanism, since it introduced the notion of a particle acted on by a potential. Nevertheless, as I have already pointed out, its implication that the whole both determines its sub-wholes and organizes their activity clearly goes far beyond what appeared to be the original mechanical point of departure. Would it not be possible to drop this mechanical starting point altogether?

I saw that this could indeed be done by going on from the quantum mechanical particle theory to the quantum mechanical field theory. This is accomplished by starting with the classical notion of a continuous field (e.g. the electromagnetic) that is spread out through all space. One then applies the rules of the quantum theory to this field. The result is that the field will have discrete 'quantized' values for certain properties, such as energy, momentum and angular momentum. Such a field will act in many ways like a collection of particles, while at the same time it still has wave-like manifestations such as interference, diffraction, etc.

Of course, in the usual interpretation of the theory, there is no way to understand how this comes about. One can only use the mathematical formalism to calculate statistically the distribution of phenomena through which such a field reveals itself in our observations and experiments. But now one can extend this causal interpretation to the quantum field theory. Here, the actuality will be the entire field over the whole universe. Classically, this is determined as a continuous solution of some kind of field equation (e.g. Maxwell's equations for the electromagnetic field). But when we extend the notion of the causal interpretation to the field theory, we find that these equations are modified by the action of what I called a super-quantum potential. This is related to the activity of the entire field as the original quantum potential was to that of the particles. As a result, the field equations are modified in a way that makes them, in technical language, non-local and non-linear.

What this implies for the present context can be seen by considering that, classically, solutions of the field equations represent waves that spread out and diffuse independently. Thus, as I indicated earlier in connection with the hologram, there is no way to explain the origination of the waves that converge to a region where a particle-like manifestation is actually detected, nor is there any factor that could explain the stability and sustained existence of such a particle-like manifestation. However, this lack is just what is supplied by the super-quantum potential. Indeed, as can be shown by a detailed analysis,[6,7] the non-local features of this latter will introduce the required tendency of waves to converge at appropriate places, while the nonlinearity will provide for the stability of recurrence of the whole process. And thus we come to a theory in which not only the activity of particle-like manifestations, but even their actualization, e.g. their creation, sustenance and annihilation, is organized by the super-quantum potential.

The general picture that emerges out of this is of a wave that spreads out and converges again and again to show a kind of average particle-like behaviour, while the interference and diffraction properties are, of course, still maintained. All this flows out of the super-quantum potential, which depends in principle on the state of the whole universe. But if the 'wave function of the universe' falls into a set of independent factors, at least approximately, a corresponding set of relatively autonomous and independent sub-units of field function will emerge. And, in fact, as in the case in the particle theory, the wave function will under normal conditions tend to factorize at the large-scale level in an entirely objective way that is not basically dependent on our knowledge or on our observations and measurements. So now we see quite generally that the whole universe not only determines and organizes its sub-wholes, but also that it gives form to what has until now been called the elementary particles out of which everything is supposed to be constituted. What we have here is a kind of universal process of constant creation and annihilation, determined through the super-quantum potential so as to give rise to a world of form and structure in which all manifest features are only relatively constant, recurrent and stable aspects of this whole.

To see how this is connected with the implicate order, we have only to note that the original holographic model was one in which the whole was constantly enfolded into and unfolded from each region of an electromagnetic field, through dynamical movement and development of the field according to the laws of classical field theory. But now, this whole field is no longer a self-contained totality; it depends crucially on the super-quantum potential. As we have seen, however, this in turn depends on the 'wave function of the universe' in a way that is a generalization of how the quantum potential for particles depends on the wave function of a system of particles. But all such wave functions are forms of the implicate order (whether they refer to particles or to fields). Thus, the super-quantum potential expresses the activity of a new kind of implicate order. This implicate order is immensely more subtle than that of the original field, as well as more inclusive, in the sense that not only is the actual activity of the whole field enfolded in it, but also all its potentialities, along with the principles determining which of these shall become actual.

I was in this way led to call the original field the first implicate order, while the super-quantum potential was called the second implicate order (or the super-implicate order). In principle, of course, there could be a third, fourth, fifth implicate order, going on to infinity, and these would correspond to extensions of the laws of physics going beyond those of the current quantum theory, in a fundamental way. But for the present I want to consider only the second implicate order, and to emphasize that this stands in relationship to the first as a source of formative, organizing and creative activity.

It should be clear that this notion now incorporates both of my earlier perceptions – the implicate order as a movement of outgoing and incoming waves, and of the causal interpretation of the quantum theory. So, although these two ideas seemed initially very different, they proved to be two aspects of one more comprehensive notion. This can be described as an overall implicate order, which may extend to an infinite number of levels and which objectively and self-actively differentiates and organizes itself into independent sub-wholes, while determining how these are interrelated to make up the whole.

Moreover, the principles of organization of such an implicate order can even define a unique explicate order, as a particular and distinguished sub-order, in which all the elements are relatively independent and externally related.[16] To put it differently, the explicate order itself may be obtainable from the implicate order as a special and determinate sub-order that is contained within it.

All that has been discussed here opens up the possibility of considering the cosmos as an unbroken whole through an overall implicate order. Of course, this possibility has been studied thus far in only a preliminary way, and a great deal more work is required to clarify and extend the notions that have been discussed in this paper.

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