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CONTROVERSIES IN PHYSICS

The hidden-variables controversy in quantum physics

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Recent studies of controversies in science have shown that they are not always settled by appeals to Nature alone. Social and political factors as well as scientific factors often combine to produce the outcome (see for example Forman 1971, Collins 1975, Frankel 1976 and Wynne 1976). The 'truth', it seems, emerges from what can be a surprisingly volatile struggle, very unlike the rarified atmosphere of noblesse within which such debates are generally thought to take place.

Traditionally, scientific knowledge is portrayed as stemming from relatively unproblematic 'readings' of Nature—essentially science is seen as a process in which humans play a passive role. This view has been challenged by those who wish to argue that science is, first and foremost, a product of human activity—that is, that scientific knowledge results from the creative activity of *scientists* (Kuhn 1970). Scientific knowledge is a social product constructed, and indeed fought for, by scientists in particular social and historical settings. In this view it is at times of scientific controversy, when all or part of such knowledge comes under challenge, that the social dimensions of science become clearest. Just as natural scientists often learn most about the system under study when it is experiencing its greatest perturbation or stress, so too can the student of the scientific enterprise find the stress produced by a scientific controversy most rewarding for revealing the social processes of science.

The hidden-variables controversy, which raged so vociferously in the 1950s and early 1960s following the challenge posed by hidden-variables theories to the orthodox version of quantum theory, is a good example of a controversy which was obviously permeated by social influences. Take, for instance, the following statements by physicists concerned with the controversy:

'. . . the discussions which surround the quest for hidden variables in quantum mechanics have, on both sides of the camp, often been conducted in a spirit of aggressiveness which resembles more the defence of orthodoxy of one ideology than a spirit of scientific objectivity' (Jauch 1973, introduction).

'The entirely reasonable question, Are there hidden-variable theories consistent with quantum theory and if so what are their characteristics?, has been unfortunately clouded by emotionalism' (Ballentine 1970, p374).

Perhaps some of the acrimonv which has surrounded this debate can be seen in the following comment on the work of hidden-variable theorists made by Leon Rosenfeld, an eminent physicist and defender of the orthodox view of quantum theory:

'That such irrational dogmatists should hurl the very accusation of irrationality and dogmatism at the defenders of the common-sense, uncommitted attitude of other scientists is the crowning paradox which gives a touch of comedy to a controversy so distressingly pointless and untimely' (Rosenfeld 1958, p658).

These are hardly the sorts of comments we would expect to follow from unproblematic readings of Nature's secrets. So what was at stake in this dispute? To answer this question we need to go back to the revolution in physics brought about by the development of quantum theory in the 1920s.

Statistical nature of quantum theory

The quantum theory is fundamentally a statistical theory replacing the causal description given by classical mechanics. The statistical nature of the theory is manifest in many fundamental processes, such as radioactivity. Although it is known that at some point a radioactive atom will decay, the exact moment cannot be specified according to the quantum theory. Radioactive decay, like all quantum processes, is essentially statistical, and all that can be given is a probability that the atom will decay in a certain time interval. No such hiatus existed in classical physics. The laws describing physical systems were fully causal and their behaviour could, in principle, be determined throughout space and time.

When it became apparent that the quantum theory was a statistical theory, the question arose in the minds of the early quantum physicists as to whether there was some causal substratum underlying the world of statistical effects. Perhaps Nature did obey deterministic laws but we did not yet have a good enough theory to produce such a description. The phenomenon of Brownian motion was called upon as an analogy. The seemingly random 'joggling' motion of a smoke particle suspended in a gas can be explained in terms of the many collisions of gas molecules with the smoke particle. These gas molecules move according to the laws of classical mechanics and it is only their aggregate properties which appear to be random. The purpose of hidden-variables theorists in quantum mechanics was to

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postulate a substratum of such 'hidden' variables analogous to the gas molecules in classical statistical mechanics. These new variables would allow the statistical theory to be embedded in a more fundamental deterministic theory. The problem was the reverse of that encountered in statistical mechanics where the behaviour of ensembles of systems has to be generalised from the behaviour of individual systems. In quantum physics the aim of hidden-variables theorists was to provide an explanation for the behaviour of individual systems based on the statistics of their ensembles.

Hidden-variables approaches thus do not attempt a radical break from conventional quantum mechanics. Quantum mechanics is much too successful a theory to be completely incorrect. Rather a hidden-variables theory will supplement or refine the conventional viewpoint and will account for most if not all of the data explained by the usual theory. The hope was that the level at which the hidden variables operated would eventually become accessible to experiment and then a crucial test for the viability of such theories could be made.

The early debate over hidden variables in quantum theory was settled by the work of the German mathematician, John von Neumann. In the same treatise in which he outlined the quantum theory as an operator calculus in a Hilbert space he showed by his famous 'impossibility proof' that no hidden-variables interpretation could be consistent with the established theory (von Neumann 1955). von Neumann's proof was based on four axioms which he used to deduce the normal statistical predictions of quantum theory. He showed that the type of ensembles implied by the existence of hidden variables could not be derived from these axioms. The proof consisted of a highly esoteric, mathematical argument but the conclusion was plain enough:

'It is therefore not, as often assumed, a question of a reinterpretation of quantum mechanics: the present system of quantum mechanics would have to be objectively false, in order that another description of the elementary processes than the statistical one be possible' (von Neumann 1955, p325).

Most quantum physicists accepted this and felt that it put an end to the matter. However, there were some dissenters who hoped that a more satisfactory version of the theory would be produced. The most notable of these was, of course, Einstein. He never accepted the quantum theory as the last word in microscopic physics—a view he summarised in his famous aphorism, 'I do not believe that God plays dice'.

Bohm's work on hidden variables

Einstein spent his last twenty years at Princeton, isolated from mainstream thought in quantum theory, and it was in this later part of his life that a young physicist came to talk to him about the theory. This physicist was David Bohm and it is he who has been at the centre of the hidden-variables controversy. Bohm was teaching at Princeton having first obtained his PhD at the University of California, Berkeley. He had become interested in the foundations of the theory when attending J Robert Oppenheimer's lectures on quantum mechanics at Berkeley. Bohm was not altogether satisfied with the theory, so he thought that the best way to get to understand it was to write a book about it. His book, entitled *Quantum Theory*, was published in 1951 (Bohm 1960) and was favourably reviewed by several eminent quantum physicists (it has since become one of the standard texts). Einstein in particular liked the book and thought it was the best presentation of the theory that could be had, and he invited Bohm to come and discuss it. Having written the book and come down in favour of the orthodox version of the theory, Bohm still found quantum mechanics hard to understand. Stimulated by Einstein's criticisms and by the criticisms made by the Soviet physicists Blokhintsev and Terletzkii, Bohm proceeded to attempt to construct a hidden-variables version. He found that he could produce such a theory and, furthermore, that it was logically consistent and accounted for all the data which the normal version explained. Bohm sent out a preprint of the paper to several quantum physicists. The paper was eventually published in *Physical Review* (Bohm 1952).

Meanwhile Bohm found himself a victim of senator McCarthy's Committee on unAmerican Activities and as a result he lost his post at Princeton and took up a new post at the University of Sao Paulo in Brazil. As if Bohm did not have troubles enough, he found that physicists were rejecting his hidden-variables version of the theory. In particular both Pauli and de Broglie referred him back to de Broglie's attempts to construct a similar theory (the 'double solution' theory) in 1927. Even Einstein regarded Bohm's theory as unsatisfactory. Bohm had been unaware of the earlier theory of de Broglie which had had to be abandoned because of technical objections. When Bohm looked up these objections he found he could overcome them by extending his theory to account for the measurement process. Bohm's hidden-variable account of measurement was published in *Physical Review* as a sequel to the main paper.

Bohm's hidden-variable theory

The theory centred on a new physical interpretation of Schrödinger's equation. By writing the wavefunction ψ as $\psi = R \exp(iS/\hbar)$, where R and S are real functions, Bohm was able to express Schrödinger's equation in a form similar to a classical Hamilton-Jacobi equation. By giving every particle of the ensemble a position x and a momentum mv, he could then define a continuous trajectory for the particle if its initial position was known. In practice, experiments did not allow the initial position to be precisely determined and hence x was a 'hidden variable'. Using the Hamilton-Jacobi analogy, Bohm concluded that the particle could be regarded as being subject to a quantum potential $U(x)$ as well as the classical potential $V(x)$. The quantum potential was given by:

$$U(x) = -\hbar^2\nabla^2 R/2mR.$$

Thus, in this theory, ψ was not an abstract mathematical symbol from which certain probabilities could be derived but an *objectively real field* which exerted a force $-\nabla U$ on the particle in a similar way to that in which an electromagnetic field affects charges through the Lorentz force. Bohm was able to show how this theory treated several standard problems of nonrelativistic quantum mechanics, such as the stationary state, the many-body problem, scattering problems and the famous double-slit experiment. Because it was based on Schrödinger's equation, Bohm's theory was not at variance with the conventional formalism and thus accounted for all the same data. However, if the hidden variables (the positions of the particles) were no longer hidden, then the theory could be directly tested. Bohm held out the hope that, as physics entered new domains (dimensions of the order 10^{-13} cm or less), his approach would lead to novel predictions but, as in practice the position of a particle could not be accurately determined, it was experimentally indistinguishable from conventional quantum mechanics. It was, however, conceptually very different. The type of description of quantum systems it gave was at variance with the usual viewpoint. As Bohm put it: 'In contrast to the usual interpretation, this alternative interpretation permits us to conceive of each individual system as being in a precisely definable state, whose changes with time are determined by definite laws, analogous to (but not identical with) the classical equations of motion' (Bohm 1952, p166).

The thrust of the orthodox view was that any modelling of quantum reality was impossible. All that could be hoped for was a mathematically consistent theory which gave the probable outcomes of certain experimental measurements. By modelling quantum systems in terms of hidden variables, Bohm was attempting to circumvent this restriction on theorising. Although Bohm's approach attempted to restore a classical view of quantum reality, his theory was itself nonclassical because, in his treatment of the quantum measurement process, he associated hidden variables with the measuring apparatus as well as the quantum system. Thus, as in the conventional view, Bohm held that a measurement disturbs the system being measured. By modelling this disturbance using hidden variables, he claimed to be able to go beyond the usual view that such disturbances were inherently unanalysable.

Response to Bohm's theory

In general the reaction to Bohm's work was negative, although he did win over some important allies. The most important of these was Louis de Broglie who responded to Bohm's paper by readopting the hidden-variables approach he had abandoned twenty-five years previously. Apart from his own theoretical work and encouragement, de Broglie publicly endorsed the attempts to reconstruct the foundations of quantum mechanics when he wrote the foreword to the book that Bohm produced on hidden variables in 1957 (Bohm 1957). de Broglie also defended Bohm in *Nature* against attacks made by Leon Rosenfeld (de Broglie 1958). However, there was very little active support shown for the hidden-variables enterprise and it was mainly Bohm, de Broglie and other physicists at the Institute Henri Poincaré in Paris (the most notable being Jean-Paul Vigier) who carried the banner of the radical physicists. The hidden-variables approach was developed by these physicists throughout the 1950s and early 1960s but met with little success.

The main type of criticism to be levelled at Bohm's theory was that it was 'metaphysical' because it did not lead to any experimental divergences from the orthodox theory. Bohm was able to respond to this type of criticism by pointing out that the orthodox theory itself relies on metaphysical assumptions, *viz* that *the most complete* possible specification of an individual system is in terms of a wavefunction that gives only probable results of actual measurement processes. Bohm at least replaced such untestable assumptions by ones which might be testable as physics advanced into new domains.

Another frequent objection was that Bohm's theory destroyed the symmetry which, in the words of one critic, constituted 'the power and the glory of quantum theory' (Hanson 1963, p88). It seems that this criticism was directed towards what was held to be a range of nonsymmetrical properties of Bohm's theory such as, for instance, its removal of particle-wave duality (particles were acted upon by real force fields), and the different roles attributed to pairs of variables such as position (which was now a hidden variable) and momentum (which was left defined as in the orthodox theory). It was also felt that a suggestion of Bohm's for an additional term in Schrödinger's equation, which might become important as physics entered new domains, destroyed the linearity of the theory. However, such criticisms seem unconvincing when used to reject Bohm's theory because they are inevitably a matter of taste. For instance, in a different context, nonlinear field theories were actively sought as a way of avoiding the notorious divergencies in quantum field theory. Although principles such as symmetry and linearity are undoubtedly important guiding principles in physics, they hardly seem strong enough to use in order to reject a theory—after all, Nature might not obey our aesthetic tastes. Although some critics did attempt to focus on more concrete points Bohm was able to reply to these criticisms.

It is important to realise that Bohm's theory was not one that could be quietly forgotten: Bohm himself had a good reputation as a physicist (even his critics were forced to acknowledge this), and with some support from the old guard (references to conversations with Einstein in his papers plus de Broglie's support) and a lengthy paper in the leading physics journal, such a challenge to the establishment would not go unnoticed. With the issues at stake being no less than the foundations of one of the most important theories of physics, it is not surprising that defenders of orthodoxy felt compelled to expose the mistake which Bohm must have made. The future direction of research in quantum mechanics could not be left to a matter of taste.

After the earlier battles to get the Copenhagen interpretation accepted at the famed Solvay congresses in the 1920s it was hardly likely that the physics elite would let the foundations of the theory be undermined by the post-war generation of physicists. And there is no doubt that several of the younger physicists (i.e. those of Bohm's generation) were becoming increasingly dissatisfied with quantum theory, as is evidenced by the whole host of novel interpretations which appeared in the 1950s and 1960s. However, to dismiss Bohm's work in a convincing manner was not easy, for, as the establishment was quick to acknowledge, Bohm's theory was very cleverly constructed so as to be logically consistent and to predict all the same results as the quantum theory. The usual way of dismissing an invalid theory is to show that it is empirically inadequate or based on mistaken reasoning—but here both paths were closed. Yet there was one way to reject the theory. This was to recall von Neumann's impossibility proof which had served well for twenty years in preventing any hidden-variables theory emerging as it was felt that such a task was foredoomed—if von Neumann's arguments were correct.

von Neumann's impossibility proof

One of the main responses to Bohm's theory was simply to declare that it was invalid because von Neumann had shown that all hidden-variables theories were impossible. In other words, no theory which introduced hidden variables could both be consistent with quantum theory and explain all the same empirical data. The use of von Neumann's proof against Bohm's work was succinctly described by P W Bridgman in a review published in 1960:

'Now the mere mention of concealed parameters is sufficient to automatically elicit from the elect the remark that John von Neumann gave absolute proof that this way out is not possible'.

What more definitive way was there to dismiss Bohm's work than to declare it to be impossible? The esoteric mathematical proof which had been used to prevent speculation over the foundations of quantum theory twenty years earlier was once more revived. However, there was one crucial difference between the earlier situation and that of 1952. Bohm's theory *did exist*—and no one had yet managed to show where (if anywhere) it was inconsistent or which data it did not explain. Thus, physicists relying on von Neumann's proof were, in effect, declaring an actual existing theory to be impossible without showing why this was so.

Much of the 'heat' generated by the hidden-variables controversy can, I think, be traced to the extraordinary faith which some people placed in von Neumann's arguments. Clearly, hidden-variable theorists were likely to interpret this as a blank refusal to believe, based on prejudice and dogma, while the establishment, on the other hand, was likely to see the refusal to accept von Neumann's arguments (which after all had in turn never been shown to be invalid) as irresponsible and likely to open once more the doors to pointless speculation over the foundations of the theory.

Clearly, if von Neumann's proof did make hidden variables impossible and Bohm's theory did exist, then one of the two must be invalid. Over the next fifteen years considerable efforts were devoted to the examination of von Neumann's proof in attempts to find where it was in error and to tighten up the reasoning in order to rule out theories such as Bohm's. The culmination of these efforts was a paper by J S Bell (1966), which showed that one of the axioms adopted by von Neumann in his proof implicitly ruled out hidden variables (Bell 1966). Thus it turned out that all that von Neumann had done was to show that hidden variables as defined by him were impossible. von Neumann's mathematical reasoning was correct but he had overgeneralised from one particular class of hidden-variables theory (and not a very likely one) to all such theories. Thus it seems as if the error lay in the application of von Neumann's proof rather than Bohm's theory. Indeed, to this day, neither the logical inconsistency nor empirical inadequacy of Bohm's theory has ever been demonstrated.

Of course, physics has moved on since the 1950s and Bohm's work on hidden variables no longer attracts much interest today, but this particular episode in the history of physics gives an invaluable lesson to those who maintain that science, especially physics, is not permeated by social factors. For how else are we to explain the faith placed in von Neumann's arguments? It seems unlikely that parts of the physics establishment should suffer a collective hallucination. I have offered elsewhere an explanation for the power that von Neumann's arguments were thought to have (Pinch 1977). Briefly I claim that it is the esoteric mathematical nature of these arguments which gave them their authority and which made it difficult to see their physical basis. In view of the establishment's need to defend itself against Bohm's challenge, von Neumann's proof was the most definitive weapon at hand.

It should be pointed out that I am not criticising the rationality of the scientific enterprise. The point is that, when science is viewed as essentially a human activity, it makes sense for scientists, like the rest of us, to defend our interests by whatever means are possible. The interests of the establishment clearly lay in the orthodox view of quantum theory which had proved to be such a successful theory, while Bohm's interests were in trying to establish a radical new basis to the quantum theory which might prove more successful as physics entered new domains. Such a clash of interests is almost bound to produce the type of acrimony which we normally associate with overtly social conflicts but which is generally hidden in science. The significance of such clashes in science is that they show that scientific knowledge, produced by humans, is *ipso facto* permeated by social influences.

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Further reading

For more details of the debates over the foundations of quantum theory the reader is referred to Jammer (1974). For a technical account of hidden-variables theories see Belinfante (1973). For more details of the use of impossibility proofs against hidden-variable theories see Pinch (1977).

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CONTROVERSIES IN PHYSICS

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Scientific controversies are the bread and butter of scientific development. The dynamic nature of scientific knowledge entails a constant tension between the stability of established theories and methods, and new ideas and approaches which develop or even overturn—and always to some degree threaten—the intellectual *status quo.* Not all conflicts and potential conflicts in science become controversial of course. Many are resolved or at least set aside without any strong mobilisation and polarisation of opposing schools of thought, and without too much emotional heat being generated by polemical pyrotechnics.

In the last decade or so it has been recognised by many historians and sociologists of science interested in the nature of scientific knowledge that scientific controversies illustrate in particularly clear profile some of the general connections between the development of knowledge and the social processes by which that development takes place and by which knowledge and 'nonknowledge' (error, ideology,