

John Bell and the Moral Aspect of Quantum Mechanics

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Many years ago, during a pleasant lunch in the CERN cafeteria, with John's penetrating observations having demonstrated yet again his remarkable grasp of the foundations of physics, Mary Bell quietly said that her husband's secret ambition was to find an apartment on the *Boulevard des Philosophes*, an assertion that John let pass with a smile.

Bell's love of natural philosophy was tempered by the conviction that to earn one's daily bread in both the intellectual and material sense one must have a respectable profession, which for him happened to be ordinary theoretical physics [1], a *métier* he practised with superior skill on an exceptionally broad front, from the design of accelerators to the symmetries of fundamental interactions. This remarkable mixture of the practical and the contemplative reflected, on the one hand, the pragmatic British tradition in which he was schooled, and on the other, his deepest human needs. John Bell had a consuming commitment to wresting an *understanding* of the natural world from the great theories of physics. He held that a theory that merely succeeded in accounting brilliantly for data, without providing a satisfactory understanding of what it described, should be subject to stringent critical scrutiny, and if such an understanding was found to be unattainable the theory should be expected to crumble, its superficial triumphs notwithstanding. Quantum mechanics was number one on Bell's wanted list, and throughout his life he pursued the culprit and those who were content to rest with the proposition (with which he agreed) that "ordinary quantum mechanics is just fine for all practical purposes".

This quest for understanding had two distinct aspects. One led Bell to pin

down in a precise and powerful way some of the most dramatic features of the revolution in thinking that quantum mechanics forces on us, through penetrating examinations of the possibility of hidden-variables theories and the nature of quantum non-locality. The other yielded an unrelenting critique of the conventional formulation and interpretation of quantum mechanics and, by implication, of the purposes and goals of contemporary theoretical physics [2].

In two remarkable papers written some 25 years ago, Bell demolished a mythology that had inhibited clear thinking about the meaning of quantum mechanics since the mid-1930's, and reformulated the issues with a clarity and force that focused the energies of many hard-nosed theoretical and experimental physicists on questions that lie at the heart of quantum mechanics.

Hidden Variables

In the first of these papers (see page 72, [3]), Bell examined the old question of whether the states of quantum mechanics can be viewed as ensembles of "dispersion free" states, specified by additional variables whose values determine precisely the results of *individual* measurements. Since 1932, most physicists had gladly avoided such efforts because of von Neumann's famous theorem asserting that any attempt to embellish the conventional theory with hidden variables must necessarily disagree with some of the theory's quan-

N.D. Mermin, John Bell and K. Gottfried (from left to right) at Marsh House, Amherst College in June 1990 after a workshop on the foundations of quantum mechanics.



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titative predictions. In retrospect, it would seem that in the intervening decades few could actually have taken the trouble to penetrate von Neumann's 19 page proof since, as Bell pointed out, the hidden-variable theories the theorem actually excluded were required to satisfy a superficially plausible but physically unjustifiable — indeed, upon reflection, quite arbitrary — constraint.

Bell then went on to prove a theorem of his own, which reached von Neumann's conclusion without this unacceptable restriction, but which, as Bell pointed out, relied on a much more subtle assumption — "that so much follows from such apparently innocent assumptions leads us to question their innocence". His own prohibition of hidden variables, Bell noted, did not apply to theories in which "the result of an observation may ... depend not only on the state of the system (including the hidden variables) but also on the complete disposition of the apparatus". This was a "judo-like" *tour de force*, as Abner Shimony subsequently put it, for Bell had found hope for hidden variable theorists in the teachings of Bohr, the high priest of orthodoxy!

Possibly because Bell described it as a "corollary of Gleason's work", this major result is generally known as the Kochen-Specker theorem (in recognition of a later but independent derivation of essentially the same conclusion). For the sake of clarity this is probably just as well, for "Bell's theorem" — the very different content of the second paper [3], has now achieved a level of popular acclaim exceeded by few theorems in the history of mathematics and physics.

Bell's Theorem

What Bell's theorem demonstrated is that Bohr's lesson is much stranger than even Bohr may have realized. For in the second paper, Bell proved a no-hidden-variables theorem that applied to theories constrained only by the requirement that how the hidden variables influence the results of observations should not depend on the disposition of the apparatus *far away* from

where those observations are performed [2, p. 20]:

"In a theory in which parameters [hidden variables] are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that such a theory could not be Lorentz invariant."

This result is often characterized as a proof that no local hidden-variables theory can reproduce the results of quantum mechanics. But Bell's theorem is more than just that. His analysis, which is extraordinarily elementary, has the kind of generality one encounters at the foundations of thermodynamics. It uses *phenomena* displayed by photons, atoms, etc. to provide the data to which his argument is applied, but does not rely on a quantum mechanical description of those phenomena. In particular, there are circumstances, first identified by Einstein, Podolsky and Rosen (EPR) in 1935, where deep intuitions about locality and cause and effect seem to demand, whether the underlying theoretical description is classical, quantum mechanical, or still undiscovered, that certain kinds of measurements reveal pre-existing values. Bell's theorem applies directly to such experiments, and says that if their results are as predicted by quantum mechanics, then those pre-existing values ("hidden variables" only from the point of view of quantum mechanics) cannot exist. Bell's thoughts on the disquieting nature of this result are noteworthy [1, p. 84]:

"For me, it is so reasonable to assume that the photons in those [EPR] experiments carry with them programs, which have been correlated in advance, telling them how to behave. This is so rational that I think that when Einstein saw that, and the others refused to see it, *he* was the rational man. The other people, although history has justified them, were burying their heads in the sand ... Einstein's intellectual superiority over Bohr, in this instance, was enormous; a vast gulf between the man who saw clearly what was needed, and the obscurantist. So for me, it is a pity that Einstein's idea doesn't work. The reasonable thing just doesn't work."

Against Measurement

This then brings us to Bell's more general views regarding quantum mechanics. His sceptical attitude towards quantum mechanics did not stem from the counter-intuitive implications of the theory's successful passage of experimental tests that evolved from his theorem. He had expected that out-



John Bell sitting to the left of the row behind P.A.M. Dirac and W. Heisenberg (front, right) before a lecture in the mid-1960's to celebrate Dirac's birthday. Bell joked with tongue in cheek that this was the closest he got to Dirac and Heisenberg.

come, and — unlike Einstein — did not find utterly unacceptable the kind of non-locality it implied. Bell doubted that the theory was simply wrong, "but he *knew* it was rotten", and in saying so he liked to pronounce "rotten" with gusto [1, p. 20]. What he found rotten was the formulation of the theory [2, p. 27]:

"... the quantum mechanical description will be superseded. In this it is like all theories made by man. But to an unusual extent its ultimate fate is apparent in its internal structure. It carries in itself the seeds of its own destruction."

He found especially offensive the reliance of that formulation on the notion of «measurement». Indeed, his last article is called "Against «measurement»" [4], and advocates that "the word [measurement] has had such a damaging effect [that] it should be banned [5] altogether in quantum mechanics". To characterize standard treatments of «measurement» he introduced the biting acronym FAPP — "for all practical purposes" — which he occasionally amplified to QED FAPP to point to proofs he found to rest on "fuzzy logic".

Discussion of «measurement» has no place in the *formulation* of any fundamental theory, he argued, for this put the cart before the horse by introducing "an artificial division of the world, and an intention to neglect, or to take only a schematic (*i.e.*, FAPP) account of, the interaction across the split". He admonished colleagues to stay true to what he saw as the physicist's duty [4, p. 34]:

"In the beginning natural philosophers tried to understand the world around them ... they hit upon the idea of contriving artificially simple situations ... Divide and conquer. Experimental science was born. But experiment is a tool. The aim remains: to understand the world. To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise."

And he proclaimed that those who seek to advance this enterprise must obey Einstein's dictum "that it is the theory which decides what is observable", and not the other way around.

Having concluded that no interpretation of orthodox quantum mechanics could be devised that he would find acceptable, Bell was more than willing to countenance radical revisions. In responding to whether he [6] "would prefer to retain the notion of objective reality and throw away one of the tenets of relativity", he answered

"Yes. One wants to be able to take a realistic view of the world as if it is really there, even when it is not being observed ... [I] want to go back to the idea of an aether ..., because in these EPR experiments there is a suggestion that behind the scenes something is going faster than the speed of light And so it's precisely to avoid these [paradoxes of causality] that I want to say that there is a real causal sequence which is defined in the aether ... It is as if there is some kind of conspiracy, that something is going on behind the scenes which is not allowed to appear."

His assault on the "infamous «measurement» problem" led him to be intrigued by proposals [7] which postulate nonlinear stochastic modifications of Schrödinger's equation specifically designed to collapse the wave function to *one or another* of the outcomes of the orthodox theory in a time that, for simple systems, is sufficiently long to leave the standard predictions intact, but which assures that [8] "pointers very rapidly point, and cats are very quickly killed or spared".

Bell has had the greatest impact on the interpretation of quantum mechanics of anyone since the 1920's. He belonged, also, to that small company of physicists whom either of us would walk miles to hear lecture on any topic whatsoever. Bell spoke softly, but with intensity and passion, and explained matters of great subtlety with consummate skill. His wit was sparkling, but he also displayed something like the wrath of the Old Testament prophet for those who adhered to positions he judged superficial. He responded to challenging questions in beautifully formed, concise and simple sentences. The unforgettable music of his Irish voice was surely a part of the magic, but we can demonstrate that there was far more by letting him speak for himself [2, p. 125]:

"In my opinion, these views are too complacent [9]. The pragmatic approach which they exemplify has undoubtedly played an indispensable role in the evolution of contemporary physical theory. However, the notion of the 'real' truth, as distinct from a

truth that is presently good enough for us, has also played a positive role in the history of science. Thus Copernicus found a more intelligible pattern by placing the sun rather than the earth at the center of the solar system. I can well imagine a future phase in which this happens again, in which the world becomes intelligible to human beings, even to theoretical physicists, when they do not imagine themselves to be the center of it."

It was our good fortune to have spent a week last June with John and Mary in a workshop at Amherst College, where these issues were discussed at leisure and at length. Afterwards, driving back to Ithaca, we agreed that John was truly unique in the world of physics, as a personality and as an intellect — at once scientist, philosopher and humanist. He was a person to whom deep ideas mattered deeply. Fate has been most cruel to steal him from us when he was still so brimful of vitality. But he will live on through his profound and timeless work. That, and the privilege of having known him, must be our solace.

ADDITIONAL REFERENCES

- [1] [page 72, 2]: Bell listed his physics speciality in an official CERN document as "quantum engineering" (p. 12) and averred that "I am not like many people I meet at conferences on the foundations of quantum mechanics ... who have not really studied the orthodox theory [and] devote their lives to criticizing it ... I think that means that they haven't really appreciated the strengths of the ordinary theory. I have a very healthy respect for it. I am enormously impressed by it" (p. 85).
- [2] Most of Bell's shots across the bow of orthodoxy are collected in [page 72, 1].
- [3] [page 72, 3]: this and [page 72, 1] were actually written at about the same time.
- [4] Bell J.S., *Phys. World* 3 (1990) 33.
- [5] Other words that Bell sought to ban from the formulation of the theory (as compared to discussions of its applications) are system, apparatus, environment, microscopic, macroscopic, reversible, irreversible, information, and observables, the latter term to be replaced by a favorite concept, beables.
- [6] *The Ghost of the Atom*, Eds. P.C.W. Davies and J.R. Brown (Cambridge University Press, 1986) 50.
- [7] See, in particular, Ghirardi G.C., Rimini A. and Weber T., *Phys. Rev. D* 34 (1986) 470; 36 (1987) 3287; and [2, pp. 201-212].
- [8] [4, p. 40]: note the stress here on *or* in contrast to *and*.
- [9] John Bell (and Michael Nauenberg) expressed this same point with zest in a paper bearing the same title as this essay: "We emphasize not only that our view is that of a minority, but also that current interest in such questions is small. The typical physicist feels that they have long been answered, and that he will fully understand just how if ever he can spare just twenty minutes to think about it." [2, p. 28].

Bell's Early Work

Rudolf Peierls

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John Bell came to my department in Birmingham in October 1953 on a year's leave from the Atomic Energy Research Establishment, Harwell, UK. Technically his status was that of a graduate student, but he was evidently much more mature than his 25 years. He also had already had substantial research experience for in his four years at Harwell he had worked on accelerator design, particularly on aspects of particle orbits and focussing. It may well be that this experience, of approaching physics through work on concrete problems relating to hardware, influenced his later style. When dealing with abstract problems he would always find some simple, tangible example to test his ideas.

He quickly became popular in the department, and it did not take long before we were impressed with his ability and the clarity of his thoughts. We became accustomed to his way of speaking, which at first may have sounded pedantic but on closer acquaintance revealed care to get the essential points across.

Time Reversal and Field Theory

He had come to Birmingham to learn about modern theoretical physics: he started studying field theory and in a short time acquired an up-to-date knowledge of the subject. At the time we heard of experiments which seemed to reveal evidence for a negatively charged particle which was stable, but with a mass less than that of the proton. The experimenters asked us whether this could possibly be the antiproton. This seemed unlikely, but could it be firmly ruled out? Everybody expected particle and antiparticle to have the same mass, but was this strictly necessary?

This was a problem after his heart. He did not like to take commonly held views for granted, but tended to ask "How do you know?". In due course he came up with the "CPT theorem", that the results of any field theory must remain unchanged if one reverses the sign of the space coordinates and of time, and interchanges particles and antiparticles. (He said cautiously, "in any theory of the present form", but nobody has yet given an example of a sensible theory in which the theorem would not hold). The theorem ensures, in particular, that any particle and antiparticle must have the same mass.

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John Bell in 1956 in front of one of the post-war prefabricated homes at Chilton, UK where he lived with his wife Mary when they were first married.

Any evidence contradicting the theorem would be very hard to reconcile with our present basic physics; so far no such evidence has been found. Indeed, the experiment which had raised the question was not confirmed.

The proof of the theorem formed the basis of John's Ph.D. thesis [page 72, 8] completed after his return to Harwell. Before he had completed writing it the same result was published by Lüders. So John lost priority, but this did not diminish the merit of his insight.

After returning to Harwell, he retained his interest in problems relating to time reversal. He showed [1] that time-reversal arguments cannot be strictly applied to β decay because the inverse reaction is not in practice observable, but that useful conclusions can be drawn provided first-order perturbation theory is applicable, which of course it is to high accuracy. He also continued to think about field theory. He developed a formalism proposed by Skyrme [2] and together with him applied it to an attempt to calculate the magnetic moments of nucleons [3].

Nuclear Physics

But his main effort went into problems of nuclear physics which came up in the work at Harwell. Here again he was never satisfied with routine applications of standard methods, but always went back to foundations. For example, he showed [4] how the spin-orbit term in the shell-model potential could be derived from the spin-orbit force in the two-nucleon interaction.

He discussed how far β decay would be influenced by taking place in a many-body situation [5], and with Blin-Stoyle he considered the effect of virtual mesons in the nucleus of β decay [6]. Two papers with Mandl [7] discuss the identity relating polarization and asymmetry in scattering, and show that this is valid if longitudinal