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Quantum mechanics and the nature of physical reality

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Abstract

The discovery of quantum theory in the first quarter of the twentieth century brought about the greatest revolution in our understanding of the nature of the physical world since the discoveries of Isaac Newton in the late seventeenth century. Compared to this revolution, even the great discovery of relativity theory seem to have been no more than variations on a classical theme. With the advent of quantum theory, the physical world, which in our everyday experience of it seems so clear and reliable, was found to be cloudy and fitful at its subatomic roots.

Modern quantum mechanics was brought to birth in its fully articulated form by the discoveries of Erwin Schroedinger and Werner Heisenberg in the *anni mirabiles* of 1925-26. At first sight the approaches of the two men seemed quite different, but the equivalence of their theories was soon established. At the same time, Paul Dirac was able to identify the nature of the critical difference between quantum physics and classical Newtonian physics, by his formulation of the *superposition principle.* This permits the existence in quantum mechanics of states that mix properties that classical physics and commonsense would say were totally immiscible. In the everyday world there is a state where the billieard ball is "here" and a state where it is "there'. In the quantum world there are also states of an electron in which it is in an unpicturable mixture, or superposition, of these two possibilities. This fact immediately implies the cloudy unvisualisability of the quantum world and further analysis shows that the probabilities of finding the electron "here" or "there" after an act of experimental measurement are related to the proportions in which the two states are present in the superposition.

The superposition principle implies that the logic that holds in the quantum world is different from the classical logic of Aristotle and everyday commonsense. The latter depends upon the law of the excluded middle, namely that there is no possibility intermediate between A ("here") and not-A ("there"), but in the quantum world there is an infinite range of intermediate possibilities, corresponding to the superposition of A and not-A. Consequently a new form of quantum logic has to hold.

The superposition principle helps to explain the otherwise seemingly oxymoronic property of the wave/particle duality of light, whose discovery played a leading role in bringing quantum mechanics to birth. Anyone in 1899 could have "proved" that it was impossible for something to behave sometimes like a wave (spread-out and oscillating) and sometimes like a particle (a little bullet). The superposition principle explains this counterintuitive possibility of wave/particle duality because it allows there to be states which have an *indefinite* number of particles present in them, since they are superpositions of the states with different definite particle numbers. It turns out that it is these states that possess wavelike properties (that is, have a definite phase).

Quantum cloudiness found expression in a quantitative form when Heisenberg discovered the *uncertainty principle.* In the classical world, one can know both momentum (how a particle is moving) and position (where it is). Through an analysis of the measurement process that took careful account of the fact that there is an irreducible degree of disturbance involved in the act of measurement due to the non-zero amount of energy carried by a single photon, Heisenberg showed that in quantum mechanics the more accurately one tried to measure position, the greater would be the uncontrollable disturbance to the particle's momentum, and vice versa. In the quantum world, therefore, one has access to only half the definite knowledge that one can attain in the classical world of everyday.

In consequence, quantum mechanics does not permit exact prediction of all details of future behaviour. Its character is necessarily statistical. All physicists accept this, but philosophically there are two possible ways of interpreting the source of this unpredictability. Is its character epistemological or ontological? If it is simply *epistemological*, all events are in fact tightly determined, but the physicist does not have access to knowledge of all the factors involved in the determination. An everyday example would be the fall of dice, highly sensitive to the smallest details of the shaking process. However, if unpredictability is an *ontological* property, it must arise from an intrinsic indeterminism present in the subatomic processes. In other words, the issue is whether the uncertainty principle is a principle of unavoidable ignorance or is it the sign of an actual degree of causal openness present in physical processes?

In the early days of quantum mechanics, the physicists, under the paternal influence of Niels Bohr, endorsed the second option, a move which came to be called *the Copenhagen interpretation.* However, in the 1950s, David Bohm produced an alternative interpretation that led to exactly the same experimental consequences, but which was fully deterministic in its character. Bohm achieved this remarkable feat by divorcing wave and particle, which Bohr had decreed were inseparably complementary aspects of a single entity. In Bohm's theory there are not only particles, which are uncompromisingly objective in character, but also a hidden wave that encodes instantaneous knowledge of the whole environment. This wave influences the motion of the quasi-classical particles in a very highly sensitive manner which succeeds in producing statistical consequences that agree with experimental findings.

Bohr and Bohm present strikingly different pictures of the nature of the physical world, but the empirical equivalence between the consequences of their two theories means that the choice between them cannot be made on physical grounds alone. It requires an act of metaphysical decision. Almost all physicists side with Bohr against Bohm, not just because he was first in the field but also because Bohm's theory, though clever and instructive, seems to be too contrived to be metaphysically persuasive. For example, Bohm's wave must satisfy a wave equation and to get the right results this must be the Schroedinger equation. In conventional quantum theory, this equation arises from following a persuasive line of argument, but Bohm has simply to borrow it ad hoc from Schroedinger.

This controversy leads to the acknowledgement of a significant philosophical insight: *The nature of causality is constrained by physics but not fully determined by it.* Making the choice between Bohr's indeterminism and Bohm's determinism requires recourse to metaphysical assessment. Two other philosophical insights can also be derived from quantum physics. First, *there is no universal epistemology.* Entities can only be known in a manner that accords with their actual natures. The uncertainty principle implies that any attempt to know the quantum world with a classical clarity is condemned to failure. Secondly: *There is no universal form that rationality has to take.* The discussion of quantum logic makes the point. The essence of rationality is to seek to respond to the actual nature of the entities under consideration, and it cannot be laid down a priori what this will be. In the late 1920s, the distinguished biologist J.B.S. Haldane, commenting on the discoveries of his physicist colleagues, said that the universe had not only turned out to be queerer than we thought, but queerer than we could have thought without the nudge of nature pushing us in a counterintuitive direction.

Quantum mechanics has been extraordinarily successful in the account that it gives of the subatomic physical world. *Quantum electrodynamics* (the theory of the interaction of photons and electrons) has led to calculations whose answers are in agreement with experimental measurements to an exquisite degree of accuracy. Nevertheless, perhaps the greatest quantum paradox is that, more than 80 years after the great foundational discoveries, we still do not fully understand the theory. The central unresolved problem relates to the attempt to understand how the clear and realiable world of our everyday experience actually emerges from its cloudy and fitful quantum substrate. The issue can be illustrated by reference to the *measurement problem*: if an electron is in a state which is a superposition of "here" and "there", how does it come about on a particular occasion of measurement that the particular answer 'here' is obtained? Currently there is no entirely satisfactory or universally accepted answer to this wholly reasonable question. Niels Bohr had suggested that it is the intervention of classical measuring apparatus that produces the definite result, but this is to give an unacceptably dualist picture of the physical world, populated by both quantum entities and classical apparatus, while we know that those measuring instruments are themselves composed of quantum constituents. A recent insight called *decoherence*, which takes into account the influence on quantum entities of their interactions with their environment, such as with low-grade background radiation, shows how this interaction can induce a more classical-like behaviour, but this idea still does not explain how a particular result emerges on a particular occasion. Other suggestions have included supposing that it is the interaction with human consciousness that induces the specific result (but does this mean that before consciousness evolved no quantum process had a definite outcome?), or that all possible outcomes occur, but in the different worlds of an edlessly proliferating multiverse (a proposal of astonishing ontological prodigality). None of these proposals seem wholly satisfactory.

The truth of the matter is that our knowledge of the physical world is distinctly patchy, with connections between different domains (classical, quantum) ill-understood. The problem of quantum chaology further illustrates the point. The exquisite sensitivity of *chaotic systems* is such that their future behaviour soon appears to come to depend on fine details of their circumstances that lie below the limits of the uncertainty principle. However, quantum theory and chaos theory cannot be combined, since they are mutually incompatible. Quantum mechanics has a scale, giving a meaning to “large” or “small” in terms of Planck’s fundamental constant, while the fractal character of chaos theory means that it is scale-free, the same all the way down.

The surprising strangeness of the quantum world has been further revealed by the discovery of *quantum entanglement.* Einstein had been one of the grandfathers of quantum mechanics through his 1905 explanation of the photoelectric effect in terms of the particle aspect of light, but he came to loathe his grandchild. Einstein had a passionate belief in the independent reality of the physical world, but he wrongly came to believe that this could only be defended if that world were unproblematically objective in the sense of classical physics. In consequence, he was always trying to show that there was something incomplete in quantum mechanics. In the 1930s, working with two young colleagues, he felt he had found the Achilles heel of the theory. They showed that conventional quantum theory implied that there was a counterintuitive entanglement between two quantum entities which had interacted with each other that resulted in their retaining a power of instantaneous mutual influence, however far they had subsequently separated. Einstein felt that this was too “spooky” to be true. However, after his death, some clever experiments performed in Paris in the 1980s showed that quantum entanglement in indeed a property of nature. It appears that even the subatomic quantum world cannot be treated purely atomistically. The physical world is deeply relational.

All the strange consequences of quantum mechanics have encouraged some philosophers of science to take the positivist stance of suggesting that quantum physics is not about what the microscopic subatomic world is actually like, but it is simply a way to make calculations that agree with the results of macroscopic measurements. Almost all physicists reject this view in favour of a realist account of quantum physics. If science were not telling us what the physical world is actually like, the labour of scientific research would lose much of its motivation. Defence of this realist position appeals to *intelligibility* as the grounds for its belief in reality. We believe that there are photons and electrons because that belief grants powerful understanding of great swathes of more directly accessible empirical experience, from the periodic table of chemistry, to the phenomenon of superconductivity, to the construction of devices such as the laser, and much more. This proven fertility would seem to be an unbelievably happy accident unless there actually were such entities whose properties are being invoked.

Quantum mechanics has shown us that the physical world is suprising in its character, exhibiting properties that were beyond our myopic powers of prevision to anticipate. In consequence, the natural question for the scientist to ask about a proposition, both within science and beyond it, is not "Is it reasonable?", as if we felt we knew beforehand the shape that rationality had to take. Instead, there is a different question to ask, "What makes you think that might be the case?" This question is open, in the sense that it does not attempt to lay down beforehand the shape of an acceptable account of the nature of reality, but it is also demanding, in the sense that if a surprising answer is given, adequately motivating evidence must be offered in its support before it will be accepted. I personally am content to approach my beliefs, including my religious belief, in just this manner. Perhaps this is the most important lesson of all that we can learn from quantum mechanics.