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The story of entanglement unentangled

Entanglement: The Greatest Mystery in Physics
Amir D Aczel
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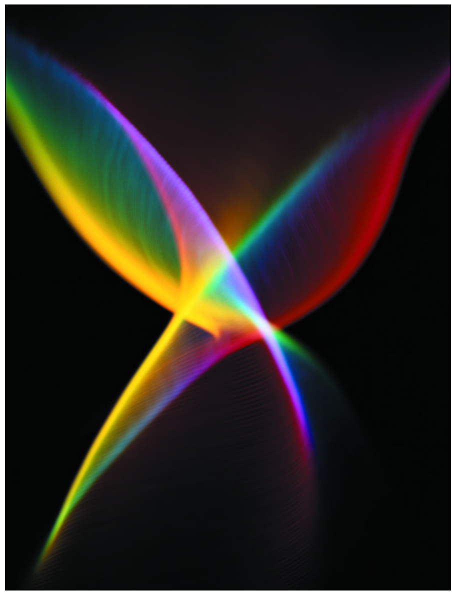
There are two main kinds of books about quantum mechanics. There are those in which we learn about abstract concepts such as Hilbert spaces, state vectors and density matrixes, but where the author never addresses – or only pays lip-service to – the question of what quantum mechanics actually means. This is the approach often taken in textbooks. The other, quite opposite, approach focuses on the interpretative question – drawing all kinds of conclusions and analogies, talking about telepathy and other mysteries, and perhaps even claiming that quantum mechanics transcends Western philosophy.

Neither approach is very helpful when one wants to understand what quantum mechanics really means in a deep philosophical sense. Amir Aczel's new book on entanglement – falling as it does into neither category – avoids such pitfalls.

Formally speaking, the history of entanglement begins with Pauli's solution of the electronic states of the helium atom – where the two electrons have to be considered to be in an entangled state. But the story really takes off in 1935, when Albert Einstein, Boris Podolsky and Nathan Rosen published their famous paper "Can quantum-mechanical description of physical reality be considered complete?".

The paper was the first time that anyone had explicitly discussed the entanglement of two particles. Einstein, Podolsky and Rosen considered the quantum-mechanical consequences of realism (i.e. the fact that each element of physical reality must have a counterpart in a complete physical theory) and locality (i.e. whatever happens here and now must be independent of what happens at other locations at the same time). They found that, under certain assumptions, realism and locality together imply that quantum mechanics is incomplete.

Niels Bohr's reply, in a paper with the same title, concluded the momentous Bohr–Einstein dialogue about the meaning of quantum mechanics. Bohr suggested that a distinction has to be made between a classical and a quantum-mechanical description of physical phenomena. He also said that one of the most fundamental notions to be learned from quantum mechanics is "complementarity" – or the idea that the quantum-mechanical description of phenomena excludes the possibility of the precise prediction of two complementary quantities like momentum and position.



Mysterious matter – entanglement lies at the heart of quantum communication and cryptography.

In the same year, Erwin Schrödinger, in his "Schrödinger's cat" paper, also analysed entanglement, which he called "the essence" of quantum mechanics. To him, the most interesting feature was the observation that it is possible in quantum mechanics to have an "expectation catalogue" about possible measurement results that predicts perfect correlations between two systems, even though the individuals do not carry any expectation catalogues of their own. It was Schrödinger who coined both the English term "entanglement" and also the German *Verschränkung*.

The field then essentially lay dormant for nearly 30 years until 1964. That was the year when John Bell proved that there is a measurable contradiction between the predictions of quantum mechanics for entangled systems and those of any local realistic theory. His paper on this topic triggered a flurry of experiments, which eventually confirmed quantum mechanics as the correct theory of the microscopic world.

In performing these experiments – which were made possible only through the development of high-power lasers – the scientific community accumulated a detailed knowledge of how to handle individual quantum systems. This experience, together with the associated thinking about individual quantum systems, led quite unexpectedly to the development of a completely new field known as "quantum information". One of the hottest areas of science today, it covers quantum cryptography, quantum computation and quantum teleportation. Many people believe that this new field, which is barely 10 years old, will open up new avenues for communication and information processing (see "Quantum theory: weird and wonderful" by Tony Leggett *Physics World* December 1999 pp73–77).

Aczel approaches the subject of entanglement by discussing a series of characteristic experiments about the foundations of quantum mechanics. These range from the famous two-slit experiment all the way up to quantum teleportation. He places a strong focus on what experimentalists actually do in the laboratory and on what they finally observe. Many other texts, in contrast, only discuss *Gedanken* (or thought) experiments.

This approach is supplemented by many quotes from personal discussions that the author has had with many of the leading players in the field of entanglement worldwide. What emerges is something of an oral history, although without any claims for scholarly correctness or completeness. A charming feature of the book is that Aczel – through his personal and warm style of writing – lets the scientists involved come very much to life. The reader should be warned, however, that some of the accounts reflect the memories of the individuals, and not necessarily the facts.

A major asset of the book is that Aczel avoids prematurely answering the question raised by the final chapter entitled "What does it all mean?". Instead, he believes that true comprehension of entanglement will only come when we can answer John Wheeler's question "Why the quantum?". Yet I feel that Aczel's presentation of the essence of the various debates and his presentation of some of the key experiments provides marvellous food for thought for anyone interested in these very questions.

What certainly shines through in the book is that this field of research – including quantum information processing – came into being through the raising of "mere" philosophical questions. As so often in the history of physics and the natural sciences in general, such questions can lead to truly novel and interesting developments – particularly if answering these questions can be brought out of the realm of *Gedanken* experiments and into the real physics laboratory.

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