https://doi.org/10.1038/s41563-022-01435-7

Quantum recognition

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Experiments with entangled photons, which enabled the pioneering of quantum information science, have been awarded this year's Nobel Prize in Physics.

Few could claim to be surprised when the names of this year's winners of the Nobel Prize in Physics were announced[1]. Alain Aspect, John Clauser and Anton Zeilinger have been among the prime candidates for the award for years. The trio's ground-breaking experiments helped to settle a historical dispute between Albert Einstein and Niels Bohr at the heart of fundamental physics: can quantum mechanics be considered a complete theory?[2] Quantum mechanics required a departure from determinism and locality — whereby a system can only be directly influenced by its immediate surroundings — principles that underpin the laws of classical physics. Einstein rejected the notion of non-locality inherent to quantum correlations (entanglement), a concept he famously dubbed as "spooky action at a distance" and that appeared to violate the laws of special relativity. Einstein laid out his concerns in his 1935 paper, written with Boris Podolsky and Nathan Rosen[2]. In this thought experiment, they formulated their qualms with regard to entanglement and non-locality in quantum mechanics in what is now known as the Einstein–Podolsky–Rosen (EPR) paradox. It was the thorough questioning and scepticism of Einstein, formulated in the EPR paradox, that sowed the seeds for the work of Aspect, Clauser and Zeilinger.

A breakthrough in the discussion came from John Stewart Bell who in his take on the EPR paradox[3] proved that quantum mechanics and alternative theories that were local were mutually exclusive. Bell's theorem did not prove nor disprove quantum mechanics but, crucially, it provided a quantitative prediction — Bell's inequality — that would only be satisfied by local theories but would be violated by quantum mechanics. This opened a route to experimentally test quantum entanglement.

First to take up the challenge was Clauser, who tested Bell's inequality by employing entangled photons. This work provided the experimental indications that Bell's inequality was violated, in agreement with the predictions of quantum mechanics. However, experimental limitations left loopholes open that made it premature to rule out local theories. Over the following decades, with stand-out contributions from Aspect and Zeilinger, increasingly intricate experiments were performed, closing most loopholes. These experiments continue to stubbornly confirm quantum mechanics predictions.

Niels Bohr and Albert Einstein debating.

It could be said that the profound impact of Bell's theorem and its experimental implementations is in itself deserving of a Nobel Prize. However, the announcement of the Nobel Prize award[1] also highlights the growing importance of technological applications in quantum information science. On that note, the 2023 Breakthrough Prize in Fundamental Physics was awarded to four other pioneers of quantum information science[4]: Charles Bennett and Gilles Brassard, who developed the first quantum key distribution protocol, founding the field of quantum cryptography and quantum communications, and David Deutsch and Peter Shor for their pioneering work on quantum computation and developing the first quantum computing algorithms.

Indeed, it seems that the time is ripe for quantum information science. Major economies are jostling for position in the quantum race[5], raising public and private investment on the multi-billion-dollar scale. Quantum information technologies are finding commercial applications in fields such as quantum communications, and quantum sensing and metrology. We are still awaiting clear-cut practical use cases for quantum computing. In the meantime, big tech giants are competing in a crowded quantum computing hardware market and the number of software-focused start-ups is rising. There are pressing challenges ahead: enhancing qubit capacity and quality along with fault tolerance and quantum error correction will be essential to fully harness quantum computing capabilities. Whether the quantum computers of the future rely on superconducting wires, trapped ions, colour centres, photons or other alternatives, as the number of qubits increases, materials scientists will need to provide solutions to suppress decoherence and noise, scale up integration, and manipulate and read-out these qubits. In quantum communications, there is a push towards on-chip integration and the development of quantum repeaters. There are also sceptics pointing to a quantum bubble and it is easy to see some parallels with previous technology bubbles in terms of investment exuberance. It will be essential for quantum technologies to consolidate market readiness and applicability. Time will tell whether the quantum bubble will burst, but ambitious short-term projections suggest that this decade could be the make or break decade for quantum technologies.

We have come a long way from the philosophical thought experiments of the 1930s to the industry-driven quantum technologies of the 2020s. Nobel recognition may have been overdue, but it is great to see the enablers of this transition celebrated in this pivotal moment in quantum information science.

Published online: 24 November 2022

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