MILESTONE 12

Distant relations

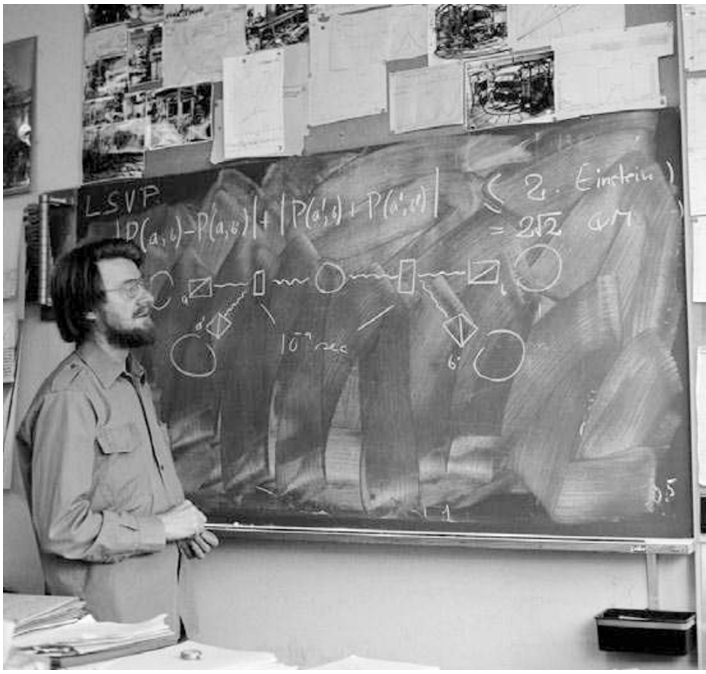
Hard on the heels of the struggle to understand wave–particle duality was the confrontation of something just as bizarre and foreign: non-locality. Is all of the information that is relevant to a physical object or interaction contained at the point in space and time where that object or interaction is located? The same quantum formalism that produced wave–particle duality answered 'no'. Like duality, non-locality had a history stretching back at least to Sir Isaac Newton, whose theory of gravity implied instantaneous communication over arbitrary distances and drew accusations of mysticism. And, like duality, clear answers started to emerge in the early twentieth century.

Quantum mechanics described reality as inherently non-local. To some physicists, this simply meant that quantum mechanics was incomplete. The most famous incompleteness argument was developed by Albert Einstein, Boris Podolsky and Nathan Rosen, and then refined by David Bohm. It pointed out that the measurement of the spin of two widely-separated atoms must be correlated if they originated from a molecule with a known total spin. A spin measurement along one axis of one atom meant that the spin along the same axis was known for the other atom.

Quantum mechanics, however, also stated that the spin of an atom could be known along only a single axis. Therefore, the atom that was second to be measured had an indeterminate (unknowable) spin along *x* and *y* if the first atom was measured along *z*, but it had an indeterminate spin along *y* and *z* if the first atom was measured along *x*. How could that second atom instantaneously 'know' to assume a particular spin along a particular axis, (and an 'unknowable' spin along the others), unless it carried with it all of the relevant information for every axis? Einstein, Podolsky and Rosen concluded that it could not, given that instantaneous communication between the atoms violated Einstein's own theory of relativity. As quantum mechanics did not account for such local information (indeed, it explicitly denied it), it must originate from 'hidden variables', and posed a serious challenge to the emerging quantum picture.

Einstein, Podolsky and Rosen published their argument in the *Physical Review* in 1935, and a reply was published in the same year and the same journal by that famous opponent to Einstein's point of view, Niels Bohr. However, it was not until John Bell tackled the problem in 1964 that a clear, quantitative and testable opposition between hidden variables and quantum mechanics was established. His argument, and subsequent experiments, have fallen strongly, if not decisively, on the side of quantum mechanics.

At the core of Bell's treatment are Bell's inequalities. These place an upper limit on the correlations between measurements of remote particles in the case that those correlations are determined by hidden local variables. Bell showed that these limits are broken by the predictions of standard quantum mechanics. Whereas Bell considered measurements on electrons, the strongest tests of his inequalities — by John Clauser and Stuart Freedman, and later by Alain Aspect — have used photons passed through optical polarizers the directions of which are set after the photons have left their source. This restricts the effect of any hidden variables in the system to be local to the travelling photons. Although no airtight test has been performed as yet, Bell's theorem and the experiments it has inspired have shown to a high degree of confidence that nature is, at least to some extent, not local.



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John Bell with a sketch of Alain Aspect's experimental set-up.

This framework was later extended to entanglement of more than two particles, most importantly by Daniel Greenberger, Michael Horne and Anton Zeilinger, whose 'GHZ state' became a crucial ingredient to an entirely new field: quantum information science (MILESTONE 17).

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