Appendix A.15 Measurement in quantum mechanics

Gregory Falkovich

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Quantum-mechanical uncertainty is not produced by our ignorance. There is nothing to be ignorant about — no hidden variables determining the measurement outcome. Nor are we ignorant about the simultaneous values of the coordinate and momentum of a given particle - those values simply do not exist. Since particle as a mechanical object is defined by its coordinate and momentum, such object does not exist in quantum mechanics. Note that momenta and coordinates of different particles (and different components for the same particle) commute, that is coexist. It is sometimes expressed as "Correlations have physical reality; that which they correlate does not" (Mermin 1998). Particular types of correlations correspond to measurements. The coordinate of a particle comes into being when measured.

When do we leave the quantum domain and collapse a superposition wave function into a single measured value? What exactly qualifies some physical systems to play the role of "measurer"? (Bell 1990). One can include any measuring device into the wave function (von Neumann 1932). Interaction between the object and the measuring instrument entangles them. This is still a quantum superposition state: the object is not in an eigenstate of the measured observable, and the instrument does not indicate a definite numerical value of that observable. One could imagine, however, the instrument so large that its entanglement with the environment leaks most of the quantum information out. Phase-scrambling entanglement with environment depends on temperature - even macroscopic bodies cold enough could be in a quantum state (of superfluidity or superconductivity, for instance). However, when the phases are indeed randomized by the environment, the interference between the eigenstates of the observable is getting vanishingly small. That creates almost classical states of the object, instrument and environment, where the probability has sharp peaks around eigenvalues of the measurable observable, since they are compatible with the majority of the environment states. In other words, the wave function in Hilbert space spreads out in the environment variables, but shrinks in the variables to be measured - here we effectively contract from an enormous Hilbert space of quantum mechanics to the small phase space of classical mechanics made of definite coordinates and momenta. Which eigenvalue from the initial superposition is chosen in a given measurement depends on the environment. The interpretation of measurement as a gradual process from quantum to classical domain is called *quantum decoherence* (Zeh 1970).

One could add to this a final act of observation. What separates observer off the quantum-mechanical world is consciousness - the ability to go beyond correlations with other subsystems to a direct perception of its own underlying reality. While an isolated quantum particle does not exist, my individual consciousness does exist even in isolation. "Cogito, ergo sum". Assuming that there are no superpositions of different states of mind corresponding to different instrument readings, one concludes that the moment of observation must collapse the wave function (London and Bauer 1939, Wigner 1961). Since an observer is an information device, then the wave function (incidentally, designed by the same mind) describes the state of our knowledge and expectations of the system rather than the state of the system itself.

In this picture, the ultimate collapse of a wave function happens inside our heads. It is then natural (rather than surprising) that a measurement in one part of an entangled system can instantly change the wave function of another part arbitrarily far away. For example, a zero-spin particle decays into two 1/2-spin particles with equal probability of spin projection to any direction in space. Measuring the spin projection of one particle, one instantly determines also the spin of the other one (Einstein, Rosen, and Podolski 1935). No matter how distant in space are the particles at the moment of measurement, knowledge exists and changes within a single head.

We thus see that uncertainty is not ignorance-produced but is intrinsic and fundamental in quantum mechanics because of its informational nature.