The message of the quantum

Einstein challenged physics to describe "the real factual situation". But an understanding of the very concepts that he criticized a century ago may provide the best clues yet about reality 'out there'.

Anton Zeilinger

In the first of his papers from 1905, his *annus mirabilis*, Einstein proposed the idea of particles of light, later called photons. From this paper, a very realistic picture of light particles emerged, as being much like the particles in an ideal gas. But the paper also contained the seeds of Einstein's later criticisms of quantum mechanics. As he described in his *Autobiographical Notes*, Einstein challenged physics, including the concepts of quantum mechanics, to describe "the real factual situation", or, in other words, what is out there.

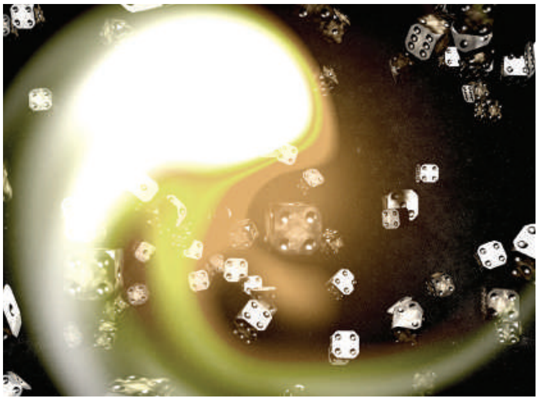
The concepts that Einstein criticized were randomness, entanglement and complementarity. These have become the core principles of newly emerging quantum information technologies: quantum computation, quantum teleportation and quantum cryptography. But although we may have realized that Einstein was wrong about these concepts, have we today understood the message of the quantum?

The discovery that individual events are irreducibly random is probably one of the most significant findings of the twentieth century. Before this, one could find comfort in the assumption that random events only seem random because of our ignorance. For example, although the brownian motion of a particle appears random, it can still be causally described if we know enough about the motions of the particles surrounding it. Thus, as Werner Heisenberg put it, this kind of randomness, of a classical event, is subjective.

But for the individual event in quantum physics, not only do we not know the cause, there is no cause. The instant when a radioactive atom decays, or the path taken by a photon behind a half-silvered beam-splitter are objectively random. There is nothing in the Universe that determines the way an individual event will happen. Since individual events may very well have macroscopic consequences, including a specific mutation in our genetic code, the Universe is fundamentally unpredictable and open, not causally closed.

Most striking is the case of entanglement, which Einstein called "spooky", as it implies that the act of measuring a property of one particle can instantaneously change the state of another particle no matter how far apart the two are. Distances over which this phenomenon have been verified experimentally are in the order of 100 kilometres. How is it possible that two events, each one objectively random, are always perfectly correlated?

John Bell showed that the quantum predictions for entanglement are in conflict with local realism. From that 'natural' point of view any property we observe is (a) evidence of elements of reality out there and (b) independent of any actions taken at distant locations simultaneously with the measurement. Most physicists view the experimental confirmation of the quantum predictions as evidence for nonlocality. But I think that the concept of reality itself is at stake, a view that is supported by the Kochen–Specker paradox. This observes that even for single particles it is not always possible to assign definite measurement outcomes, independently of and prior to the selection of specific measurement apparatus in the specific experiment.



Chancing it: the Universe is fundamentally unpredictable.

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A criticism of realism also emerges from the notion of complementarity. It is not just that we are unable to measure two complementary quantities of a particle, such as its position and momentum, at the same time. Rather, the assumption that a particle possesses both position and momentum, before the measurement is made, is wrong. Our choice of measurement apparatus decides which of these quantities can become reality in the experiment.

So, what is the message of the quantum? I suggest we look at the situation from a new angle. We have learned in the history of physics that it is important not to make distinctions that have no basis — such as the pre-newtonian distinction between the laws on Earth and those that govern the motion of heavenly bodies. I suggest that in a similar way, the distinction between reality and our knowledge of reality, between reality and information, cannot be made. There is no way to refer to reality without using the information we have about it.

Maybe this suggests that reality and information are two sides of the same coin, that they are in a deep sense indistinguishable. If that is true, then what can be said in a given situation must, in some way, define, or at least put serious limitations on what can exist.

These ideas can be brought to fruition through understanding the three concepts criticized by Einstein. It is natural to assume that the information represented by a quantum system scales with its size. The randomness of the individual event is then a direct consequence of the fact that not enough information is available to pre-define the outcomes of all possible measurements. The same holds for complementarity, implying that the information available only suffices to define the outcomes of one of a number of mutually complementary measurements. Finally, entanglement is the observation that the finite information available to characterize two (or more) systems can either be used to define the properties of the individual systems, as in classical physics, or to define the results of joint observations of both or all systems together.

So the experimentalist, by choosing the apparatus, can define which quality of a number of possibilities will become reality in the measurement. But the individual measurement result remains objectively random because of the finiteness of information. I suggest that this randomness of the individual event is the strongest indication we have of a reality 'out there' existing independently of us. Maybe Einstein would have liked this idea after all. ■

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FURTHER READING

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