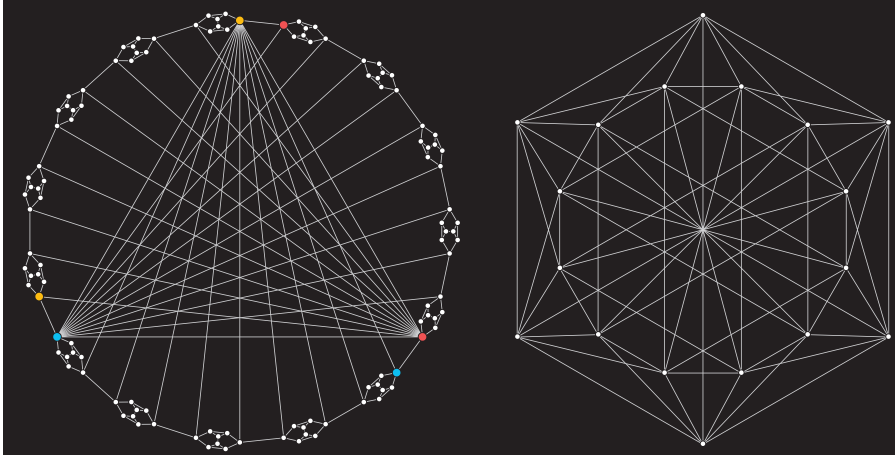
QUANTUM CONTEXTUALITY

Researchers have simplified the 117 contextual questions in the original 1967 Kochen-Specker theorem (left) to a more manageable 18 (right). Colours indicate duplicated questions.

• Yes/no question about quantum state of the system

— Connects questions whose answers cannot both be yes



SOURCE: KOCHEN AND SPECKER (1967)/D'AMBROSIO *ET AL.* (2013)

QUANTUM MECHANICS

Photons test quantum paradox

Contextuality theorem could improve secure communication.

BY EUGENIE SAMUEL REICH

Like Schrödinger's cat, it was only supposed to be a thought experiment to elucidate the strange mathematics of quantum mechanics.

Now, the 46-year-old Kochen–Specker theorem, which describes the quantum dance of observer and observed, has passed its toughest test yet in the real world. The test, published in February (V. D'Ambrosio *et al. Phys. Rev. X* **3,** 011012; 2013), is indicative of growing interest in the theorem, triggered by new capabilities for manipulating photons and cold atoms (see 'A quantum revival').

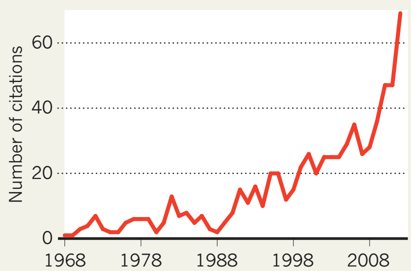
"We can test things that until now were just mathematics," says Adán Cabello, a physicist at the University of Seville in Spain, and a co-author of the paper. "We've been waiting for the technology." Although his team has focused on the pure maths of the theorem, follow-up work may eventually find practical use in defending encrypted conversations against attack, and in improving random-number generators.

The theorem, first published in 1967 by mathematicians Simon Kochen and Ernst Specker, shows that it is incorrect to assume that the results of a quantum mechanics experiment are determined before measurements are made (S. Kochen and E. P. Specker *J. Math. Mech.* **17,** 59–87; 1967). That assumption is valid in classical physics; for example, the heat content of a cup of tea is unaffected by the thermometer measuring it. But it breaks down in quantum mechanics, where measurements change their subjects in ways that depend on what else is being measured — as if a set of thermometers conspired to create the heat that they measure.

This behaviour is called quantum contextuality. One example of the principle is 'spooky action at a distance', in which the quantum states of two particles are entangled such that measurements on one particle instantaneously influence the other, even if it is far away.

A QUANTUM REVIVAL

Citations of the 1967 Kochen–Specker theorem have soared since physicists have been able to test it with specially prepared atoms and photons.



SOURCE: ISI WEB OF KNOWLEDGE

Testing contextuality for particles that are not entangled has been hard because the Kochen–Specker theorem is so complex: it considers the answers to a set of 117 measurements on a single quantum particle that can exist in three or more quantum states. Preparing photons or atoms in more than two quantum states has been possible only in the past few years.

The latest demonstration is the most faithful validation of the theorem yet, because it tests a set of 18 measurements that are mathematically very similar to the 117 described by Kochen–Specker (see 'Quantum contextuality'). Cabello and his colleagues manipulated the angular momentum and polarization of identical photons to create different combinations of four quantum states, then watched how the photons produced interference patterns in a detector. The researchers confirmed that the outcomes of the measurements are coordinated, just as Kochen–Specker implies has to be the case for quantum mechanics to hold.

Specker died in 2011. Kochen, an emeritus mathematician at Princeton University in New Jersey, is impressed with the demonstration. "We thought it was a *Gedankenexperiment*, a thought experiment," he says.

Tests of the theorem might have practical uses. Contextuality holds promise for cryptography, says Cabello, because it implies that a spy eavesdropping on messages sent through quantum systems will influence measurements by the agents trying to communicate. If the agents find disruptions to the contextuality of their messages, they can halt the communication.

Similarly, the results of quantum contextual measurements can generate random numbers, which are also valuable in cryptography, says Luming Duan, a physicist at the University of Michigan in Ann Arbor who has done simplified Kochen–Specker tests on cold atoms. Only pure quantum measurements are truly random, and Kochen–Specker tests can verify that no classical effect has interfered with the random-number generation, he says. "Contextuality provides a way to do this without using entangled states", which are delicate and easily destroyed.

Some physicists have doubts about the technological applications. Adrian Kent, a quantum theorist at the University of Cambridge, UK, says that Kochen–Specker measurements are difficult to perform, and that an unknown classical aspect of a measurement could upset the quantum measurement. That loophole could be used to hack encryption based on the Kochen–Specker theorem, he notes.

Fabio Sciarrino, a physicist at the Sapienza University of Rome and a co-author of the latest paper, says that his group has quantified the extent of this loophole in its test. He is confident that the test is precise enough to prevent classical objects from masquerading as quantum ones. "We found very high agreement between experiment and theory," he says. That, at least, keeps the strangeness of quantum mechanics on a sure footing. ■