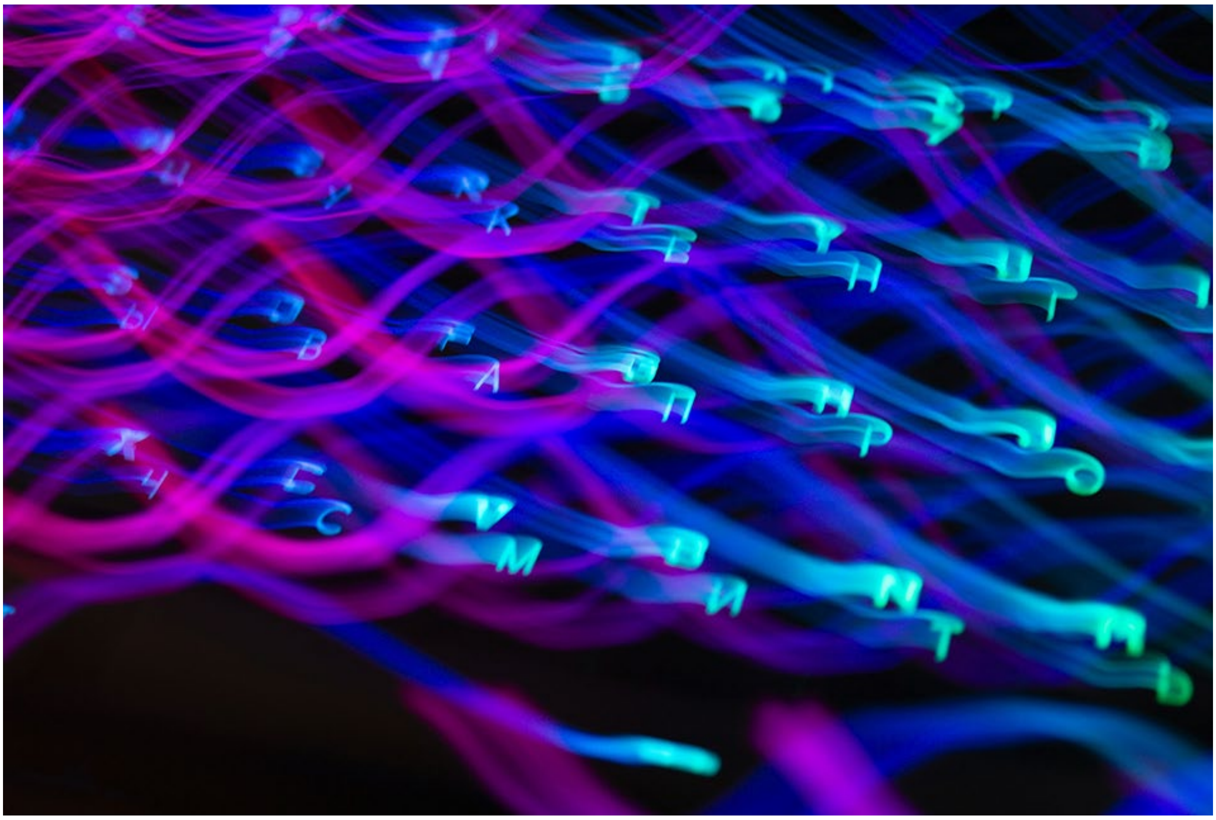
THE WHOLE IS THE TRUTH – RESEARCHNEWS – September 25, 2021



Quantum theory elevates randomness to a fundamental principle. Image: Anton Maksimov juvnsky, Unsplash.

ZURICH

We generally assume that the objects around us exist independently of us and of other objects. We can observe a glass as a well-defined object and investigate its chemical or physical properties in the lab. We can even predict its behaviour at any point in time as long as we know all the external factors acting on it. Science encounters a reality made up of clearly delineated objects: a reality that can be measured by scientific instruments and ultimately even be controlled. From the steam engine to the light bulb, many examples of scientific progress are based on this notion, all condensed by classical physics into verifiable laws of nature such as Newtonian mechanics, electrodynamics and thermodynamics. The realm of classical physics is ruled by determinism.

In the early 20th century, however, this deterministic view of the world began to crumble. Physicists such as Max Planck, Albert Einstein and Nils Bohr showed that classical physics could not describe phenomena at the level of atoms and elementary particles. The world of microscopic particles, it appeared, was governed by fundamentally different rules.

The end of determinism

Quantum physics breaks with the idea of a deterministic reality that breaks down into subsystems," says physicist and ETH professor Hans Christian Öttinger. He conducts research in quantum field theory in the Department of Materials and specialises in the philosophical and epistemological implications of quantum theory. "In the subatomic world, we can no longer observe things in isolation, because quantum physics tells us that everything can be correlated," says Öttinger.

If we measure or observe a system of electrons, photons or other microscopic particles, we inevitably interact with the system and become part of a larger holistic system. Viewed in this way, we are investigating not an independent reality but also all the changes that are unavoidably triggered by our measurements or other interventions. Moreover, while in classical physics seemingly random behaviour occurs only as a product of insufficient information or measurement error, quantum theory elevates randomness to a fundamental principle. "Our quantum physical representation of the world clearly implies a genuine randomness in the universe," says Öttinger.

The double-slit experiment

This is powerfully illustrated by the well-known double-slit experiment. If we fire photons from a light source onto a detector screen, they appear on the screen at random points spread over a wide area, even though they were fired under identical physical conditions. No pattern can be discerned; randomness prevails. Yet if we were to fire multiple bullets from a pistol, all under exactly the same experimental conditions, we could be confident of them all hitting the same spot. If we now position a plate containing two identical, parallel slits between the light source and the detector screen and then repeat the photon experiment, a pattern of alternating bands appears on the screen. This striped interference pattern can be represented mathematically by a wave function, which enables physicists to determine the probability of particles hitting a specific spot on the screen. In the quantum world, these kinds of probabilistic statements replace the determinism of classical physics. And the experiment has another surprise in store: if we place a particle detector at each slit so as to determine which of them each photon passes through, the pattern changes once again.

According to ETH professor Öttinger, this is only to be expected: "The moment we add the double-slit plate and the detectors to the experiment, we alter the world we were hoping to observe, because each interacts with the photons and affects their behaviour." This also applies to other elementary particles: neither whole atoms nor individual electrons can be measured without regarding them as part of a larger holistic system. But if everything is correlated, how is it possible that we can observe a glass and other large objects in isolation? Öttinger and other theoretical physicists argue that decoherence effects are at work: "Mutual correlations quickly decay in the case of large objects. That's why we can study a glass or a stone in isolation without having to consider its interactions with its surroundings."

Complementarity and contradiction

Öttinger's explanations on the holistic nature of quantum systems and decoherence certainly sound convincing. Yet they contradict the dominant reading of quantum theory originally proposed by Nils Bohr. Known as the Copenhagen interpretation, Bohr's version states that quantum mechanics does not describe reality itself, but rather a state of knowledge about reality. Bohr worked on the assumption that every object in quantum physics always exhibits properties of both a wave and a particle. Scientists refer to this as the complementarity principle, or wave-particle duality. In this interpretation, the light and dark bands of the interference pattern in the double-slit experiment are taken as an indication that photons really do pass through the two slits as waves. Measuring their motion with a detector causes a collapse of the wave function, which is why the photons subsequently appear on the screen as discrete particles. Öttinger and other physicists argue that this reading raises more questions than it answers. Why should we assume that particles travel in a wave-like manner? Doesn't this assumption contradict the notion of wave-function collapse? How exactly should we interpret the concept of a particle in quantum physics anyway? And can these particles really travel along paths?

Quantum field theory

According to Öttinger, such questions compel us to abandon classical terms such as particle, wave and motion. He regards quantum field theory as the most promising starting point for a fundamental explanation of quantum phenomena, even though its robust and graphic formulation throws up some major problems. In quantum field theory, new particles can appear and disappear at any time. Rather than focusing on individual particles, Öttinger prefers to talk about particle clouds or particle swarms, in which individual particles can only be discerned once a certain resolution is reached. Below this threshold, they are blurred or “smeared out”, much like a picture in which individual pixels only become visible when you zoom in, and where the exact pixel resolution is not important to the picture as a whole.

Whether this interpretation of the quantum world will ultimately prove more convincing is likely to remain a matter of debate for some time to come. Nonetheless, the applications of quantum theory have long since become part of our day-to-day lives, even if it seems we do not fully understand the mathematical formalism on which they are based. Taking that step would require a willingness to broaden our current range of experience by incorporating new insights.