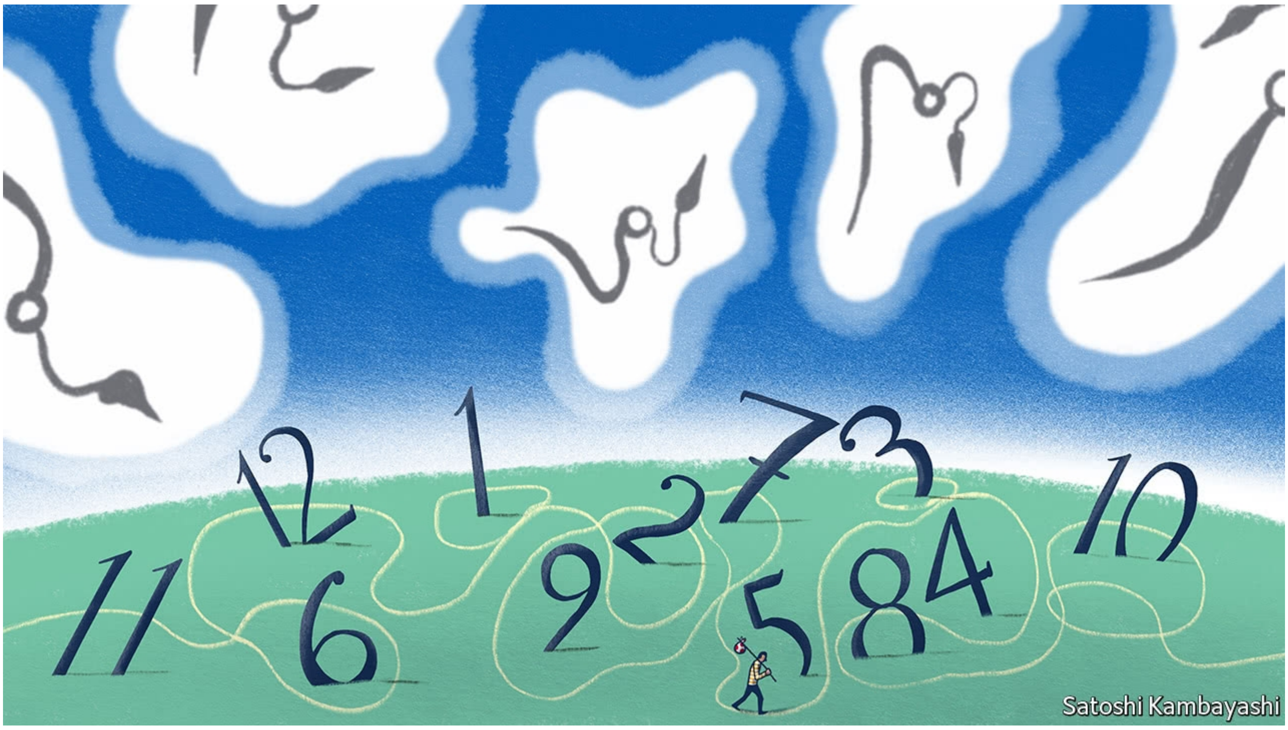
Quantum mechanics, relativity theory and the nature of time

Time may be fuzzy. If so, the idea of causality may be in trouble

Does one thing lead to another?



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THE thing about *Gedankenexperimente*—or thought experiments, for those who find Albert Einstein's native tongue too twisting—is that you never know where they might lead. For Einstein, they led to the theory of relativity. For James Clerk Maxwell, they conjured an imaginary demon who could violate the second law of thermodynamics. For Erwin Schrödinger, they created an existentially confused cat that was simultaneously dead and alive.

Physicists like to devise *Gedankenexperimente* because they are a way to consider ideas that cannot be tested for real, usually because the technology needed is not yet available or even envisaged. Though not a substitute for true experimentation, a good *Gedankenexperiment* may point to conclusions that proper experiments can indeed test. And, though the famous *Gedankenexperimente* mentioned above are all quite old now, the idea of conducting them has neither gone out of fashion nor lost its ambition. Indeed, some of the most recent such thought experiments, carried out by a group of quantum physicists led by Caslav Brukner of the University of Vienna, are questioning the nature of one of the fundamental aspects of the universe, time itself.

That one thing happens after another, and that there is no doubt about which came first, is intrinsic to the commonsense notion of time. It was also intrinsic to the development of the theory of relativity, the *Gedankenexperimente* for which often depend on clocks moving relative to one another. Add quantum theory to the mix, though, and then think through the consequences, and doubts start to emerge about what order events are really happening in.

Let's do the time warp again

The first thought experiment that Dr Brukner's group came up with, published earlier this year in the *Proceedings of the National Academy of Sciences* by him and two of his students, Esteban Castro Ruiz and Flaminia Giacomini, involved an imaginary clock of great precision. The accuracy with which such a clock could be read is constrained by Werner Heisenberg's uncertainty principle. This limits how well pairs of properties of any physical system (such as location and velocity) can be measured. The more precisely one member of a pair is known, the more uncertain is the value of the other.

In the case of a clock, the time it tells and the energy required to run it form a Heisenberg pair: the more accurately the clock is read, the less accurately the quantity of energy involved can be determined. The result is that the clock's energy is in a state called a quantum superposition. The energy in question may be large or small, both at the same time—just as Schrödinger's cat is both alive and dead.

At this point, quantum mechanics and relativity collide. One consequence of Einstein's theories is that energy and mass are equivalent. This means energy, like mass, has a gravitational pull. A second consequence is that gravity changes the flow of time. Such gravitational time dilation is a well-established phenomenon. Atomic clocks kept at different altitudes on Earth, for example, get out of sync with one another because they are subjected to different gravitational forces.

Dr Brukner and his colleagues observed that in the case of their own hypothetical clock, the quantum superposition of its energy states means that the gravitational effects of those energy states also exist in a quantum superposition. The time dilation created by these gravitational effects thus becomes superposed, too. Worse, a second quantum effect, entanglement, means other clocks within the gravitational influence of the first will be affected by the superposition as well, and, reciprocally, will affect the original clock in a similar manner. Since clocks, whatever the specific details of their mechanisms, are the only way time can be measured, the whole concept of time itself therefore becomes fuzzy.

Nor is that the end of it. In the wake of the clock paper Dr Brukner and his colleagues are working on another *Gedankenexperiment*. This investigates the consequences that superposing gravitational fields has for causality—the idea that one event can truly be said to cause another.

The metric system

Besides mass-energy equivalence and gravitational time dilation, a third concept which emerges from the mathematics of relativity is something known as the metric field. Just as general relativity is an extension of Isaac Newton's theory of gravity, so the metric field is the relativistic extension of the Newtonian idea of gravitational potential—namely that the strength of the gravitational interaction between two objects depends on the distance separating those objects. The strength of gravitational interaction in a metric field similarly depends on the distance between objects. But because general relativity treats time as a fourth dimension, equivalent to the three dimensions of space, in a way that Newtonian gravity does not, metric-field distance is measured in both space and time.

According to Dr Brukner, the clock thought experiment shows that the metric field is yet another phenomenon which is subject to Heisenberg's principle, and therefore to superpositional effects. As a consequence, it is no longer only location in space that becomes uncertain, but also location in time. Often, therefore, it would no longer be possible to say which of two events came first.

The new *Gedankenexperiment* the team have devised to test this involves a giant atom in a superposition of two divergent energy states. They are attempting to calculate the consequences of such an object for the concept of causality, namely the idea of event A causing event B. They believe that if the atom’s two energy states are sufficiently different it will become impossible to say whether A or B came first, and causality will thus disappear.

Although, like all *Gedankenexperimente*, this latest one cannot be conducted with current experimental technologies, all of the assumptions behind it have been so tested in the past. It therefore obeys both quantum mechanics and the theory of general relativity. But one big question nags. If the *Gedankenexperimente* that led to relativity relied on a linearity of time that the theory itself is now helping call into question, can those original thought experiments themselves be relied on?

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