THE HAUNTING QUESTION OF TIME

Time is a strange phenomenon. It is measurable, yet almost unfathomable. So does it even exist? And what does time travel have to do with physics? Three ETH researchers voice their opinions.

TEXT Florian Meyer

Do you remember Marty McFly? Or maybe those memories no longer – or don't yet – exist? Marty McFly was the main character in the *Back to the Future* science fiction films that wowed cinema audiences in the 1980s. He uses a time machine to travel from 1985 back to 1955, the year his parents fell in love. Marty's appearance on the scene alters the course of events, and he suddenly faces the risk that his parents will no longer fall in love – and he will never be born. But how is it possible for him to travel back into the past and change what happened if he wasn't even born?

The film derives many of its laughs from this curious sequence of events. Essentially, *Back to the Future* is a play on the thought experiment known as the grandfather paradox, in which someone travels to the past and kills their own grandfather before the conception of their father or mother, thus preventing the time traveller's own birth. Consequently, it is impossible for them to kill their grandfather, hence the paradox!

For philosopher and physicist Norman Sieroka, who wrote a book about the philosophy of time while working as a *Privatdozent* at ETH, any description of time travel implies particular views about time and about how it can manifest itself: "If someone is convinced that, by definition, the past no longer exists and the future does not yet exist, then this will very likely influence what that person thinks is physically possible," he says. "After all, any straightforward possibility of time travel would be excluded if the traveller's destinations in the past and the future do not even exist."

The time machine

Time travel has been a popular theme ever since science fiction emerged as a genre in the 19th century in parallel with the rise of industry, technology and science. Scientific discussion of the subject was prompted in the late 1940s by the logician Kurt Gödel, who was able to show that time travel was theoretically possible. He demonstrated that closed, timelike curves could exist under certain conditions within the framework of Einstein's general theory of relativity. In this theory, time is viewed as a geometrical dimension, meaning that – unlike classical physics – space and time are not independent, but form a single entity called space-time. This entity can be compared to a marble run: the planets orbit the sun along paths dictated by the curvature of space-time, much as marbles roll downwards along the grooves.

The "Gödel Universe" contains elements whose geometries are so severely curved that space-time actually bends around to form closed time-like curves, or loops. This allows space-time to take on the form of a rounded doughnut. Space travellers accelerating at tremendous speed along these loops in a rocket would eventually return to the point where they "had already been" and which "existed before". There, they could theoretically meet themselves or repeat their own past.

Nobody is suggesting that we could be building these kinds of time machines in the near future. The rocket would have to reach a maximum speed very close to the speed of light – and Renato Renner, ETH Professor for Theoretical Physics, argues that this is technically impossible: "General relativity does allow for closed time-like curves, but calculations show that many of these loops are actually impassable. Astronauts would need to endure an acceleration much greater than the Earth's gravitational pull over several years. That's simply inconceivable, but science fiction tends to downplay this issue to some degree." >

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A phenomenon – Time is such a fundamental dimension of life that it manifests itself in many, often mysterious, ways.

Gödel's solution was not intended as a work of science fiction. The purpose of thought experiments is to help us shed light on unexplained and elusive theoretical concepts and open them up for debate. In this sense, his thoughts on time travel represent a kind of "useful fiction". Gödel's model makes it clear that we should not confuse time in general relativity with subjectively experienced time, nor with time in classical physics. In both those latter cases, the world has an objective form of time as a superordinate factor that is the same everywhere and independent of humans and objects. In Gödel's Uni-verse, on the other hand, there is no all-encompassing, absolute time – and his description of travelling back into the past was his way of highlighting this fact. He didn't believe the past actually exists in a form we could visit.

The question is whether the universe constitutes a closed whole and time is an external variable in which things and events can be arranged as if they were in a box. This question arises because physicists regard objects as systems that have an environment – whether the objects are solar systems, individual atoms or even clocks. The universe is also a physical system, but does it have an environment?

The key to new physics

Just like space and gravity, time is one of the key concepts that must be included in any physical theory that seeks to explain the real world. Typically, it is physical time – as opposed to experienced time – that is the form of time measured and displayed by a clock. In classical physics, however, the time on a clock is part of the environment, in other words a form of time that is external to the system. The two great theories of modern physics – general relativity and quantum mechanics – have each shaken this concept of time in their own particular way. Yet, in some aspects, they fundamentally contradict each other. Renner therefore argues that time is a key factor in unifying them – and his approach to this challenge is to seek out the properties of time that are independent of these two theories.

For example, Renner says that we could resolve the grandfather paradox, which illustrates a principle of general relativity, by linking it to Schrödinger's cat, a well-known paradox of quantum mechanics in which the cat is simultaneously both dead and alive. Viewed in this way, the grandfather would be both dead and alive. This could work if the timelike loop through which the time traveller passes forms a figure eight, whose surface – like a Möbius strip – has two sides that merge smoothly into each other, so that they would sometimes be "on top" and sometimes "underneath".

This attempt to unify the theories is far from simple, because time in quantum mechanics – unlike in general relativity – is a distinct concept. Quantum mechanics describes how states of matter, for example molecules and atoms, change over time. Time is therefore a fixed background in which things change, yet its theoretical status is unclear.

Renner sees the measurement of time as a key issue. "If we model a clock in the two theories, it can lead us to a common concept of time – because the clock is the same." Renner focuses on the theoretical foundations of clocks in quantum mechanics, a task that has led him to work closely with Sieroka. One obstacle that has to be overcome is the fundamental uncertainty of quantum mechanics, which means it is impossible to observe a quantum system without altering it.

This also applies to the measurement of time, as Wolfgang Pauli – winner of the 1945 Nobel Prize in Physics and former ETH professor – was the first to discover. "In Pauli's day, the clock was something external. When it came to observing a quantum system, the classical clock was outside the system. But that's all changed," says Renner. "Nowadays, we also treat the clock as a quantum system, so obvious-

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ly the same thing applies: we can't read the time without altering the clock." Renner therefore argues that the smaller the quantum system used as a clock, the less and less accurate time measurement becomes. He is encouraged by the technological advances of the past ten years: "At ETH Zurich, we now have a whole series of highly sophisticated quantum technologies that help us understand how time works at an atomic and subatomic level.

The realm of attoseconds

Electrons are archetypal quantum objects. The movement of electrons in molecules and atoms takes place on a time scale of around 100 attoseconds, which in other words is equivalent to just 0.0000000000000001 seconds. In comparison, it takes one whole second to wink! Today's scientists use highly intense laser pulses to measure these ultra-short reactions. "Laser pulses can be very good clocks," says Axel Schild, an Ambizione fellow who works in the Ultrafast Spectroscopy and Attosecond Science group at ETH. He is developing a new computing method for simulating these kinds of dynamics in ultrashort laser fields.

So how does it work? It all starts with a closed quantum system – for example consisting of a molecule and a laser field. This system has next to no interaction with its environment. Within this closed system, the researcher arbitrarily defines one element as a clock and another element as the actual quantum system. Time is defined by comparing the changes of the clock and the quantum system. The interesting part is that, at first, time doesn't exist at all in the closed system. Time is only introduced through the different ways in which we treat the quantum system and the clock – for example by comparing the release of an electron from the molecule with the state of the laser field. "For a closed system – like the universe – there is no time because it has no relation to its environment," says Schild. "In fact, time really only exists if the chosen clock shows the time as clearly as the hand of a classical clock."

Even the accuracy of this process is a matter of choice: since we can define different clocks in the closed system, the measured time depends on the selected clock. Different clocks may show different times. Thus, the measurement result only corresponds to the idea of a clock-independent "real" time to a limited degree – which brings us back to philosophical questions. "Time is not just one philosophical concept among many," says Sieroka. "Time is a fundamental dimension of human existence that manifests itself in various ways." ○

FIND OUT MORE

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Axel Schild works in the Ultrafast Spectroscopy and Attosecond Science group. Supported by an Ambizione grant from the Swiss National Science Foundation, he is developing a new method of simulating the dynamics of electrons in molecules that interact with strong, ultrashort laser pulses.
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Norman Sieroka developed his own "philosophy of time" as a *Privatdozent*, the managing director of the Turing Centre and a member of the Critical Thinking initiative at ETH Zurich. He has been Professor for Theoretical Philosophy at the University of Bremen since April 2019.