Thermal chaos returns quantum system to its unknown past

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Credit: Daria Sokol, MIPT

Building on last year's breakthrough 'time reversal' experiment, two researchers from the Moscow Institute of Physics and Technology and Argonne National Laboratory have published a new theoretical study in *Communications Physics*. While their previous paper dealt with a predefined quantum state, this time the physicists have devised a way to time-reverse the evolution of an object in an arbitrary, unknown state.

Someday an improved reversal scheme could enable us to confirm the correct functioning of a quantum computer that is so powerful it would otherwise require an even bigger computer than itself to check, defeating the purpose.

Chaos reigns over time

There's a certain natural way the state of a quantum chip evolves if left to its own devices: from order to chaos. This is true about other things, too: With time, our bodies grow older, manmade structures deteriorate, and while an ice cube left on the dinner table invariably melts, another ice cube will certainly not pop into existence in a glass right out of the blue—although that might depend on what one has been drinking.

Through everyday experience we acquire a sense of time based on the distinction between the generally more ordered past states and the typically more chaotic future states of closed systems—ones like a glass of water with an ice cube, where melting is a one-way process. Physicists refer to this as temporal asymmetry, or the arrow of time. It stems from the tendency toward disorder, formally expressed by the second law of thermodynamics.

"One of our breakthroughs," says one of the authors, Argonne's Valerii Vinokur, "is the realization—that we put in practice—that a quantum computer is a piece of the real physical world but allowing for an unprecedented control over its evolution in time."

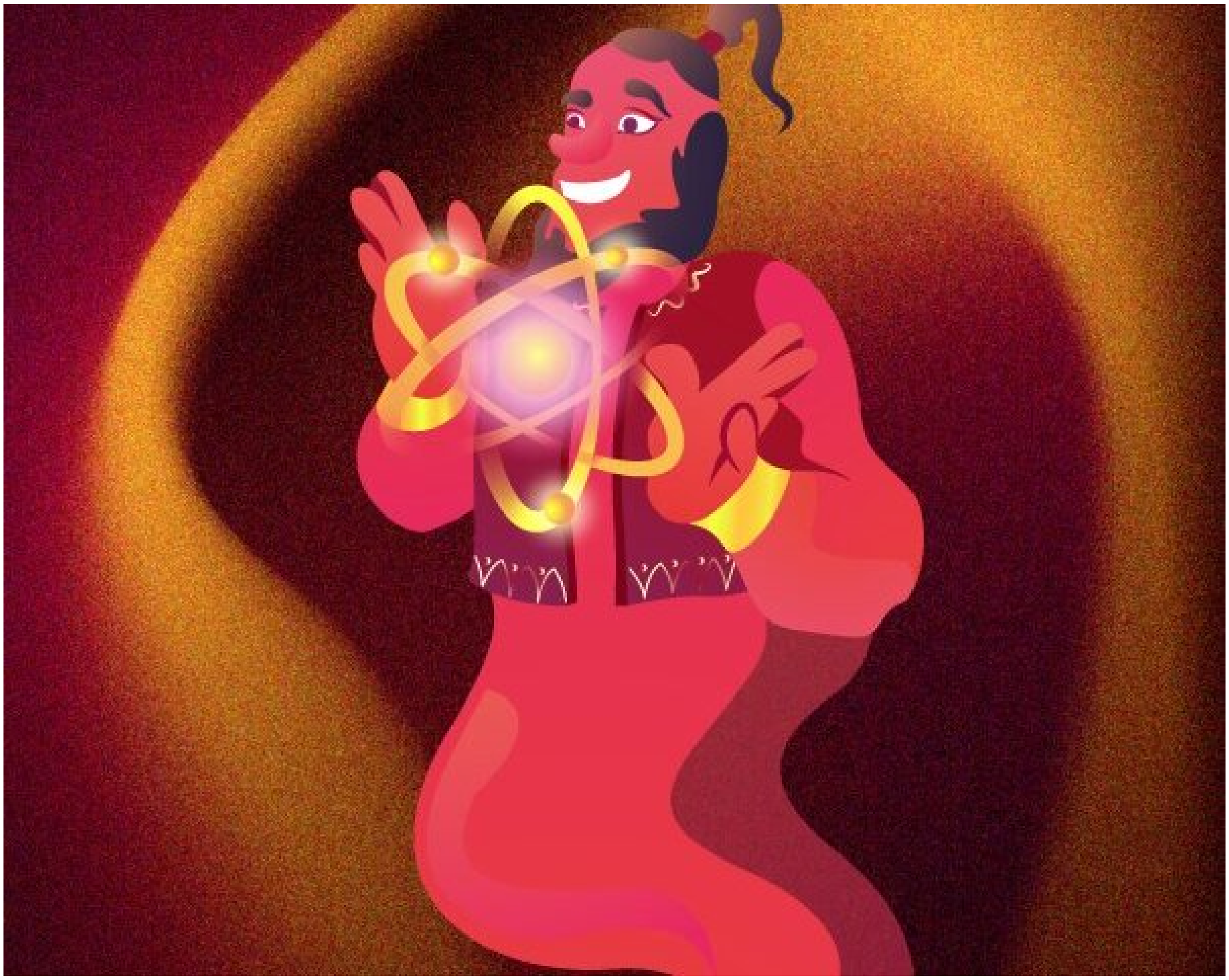
Spell book of algorithms

What many journalists hailed as a 'time machine' last year was the physicists' experiment that briefly reversed the arrow of time for a quantum computer. That is, the experiment took place in the computer, initially in an ordered state, evolving toward greater chaos for a brief period of time. After that, the team used its time reversal algorithm to modify the computer's state in such a way that it started tracing back whatever it had been doing previously, effectively evolving in reverse playback until it assumed the original ordered state.

The catch was that one had to know the state of the computer at the moment when the time reversal algorithm kicked in, because it was not universal. "Even that felt like magic, but the reworked procedure is a whole different kind of genie, if you permit the analogy," Vinokur commented. "Say you wanted to restore the Parthenon to its original splendor. The old genie would go, 'Well, I can do that, but you have to give me some information. I want a perfectly detailed plan of the ruins as they are now.' You see, that genie had no universal spell to turn back time. Instead, he had a great big book of spells, which you would have to leaf through together to find the right one. Very tedious fellow."

Practically speaking, the problem with having to know which state you are reversing is the need to record it. This was not really an issue for the small computer made up of two or three quantum bits, which was used in last year's study. But scaling up the experiment ramps up the memory requirements really fast: Each additional qubit doubles the amount of memory needed.

To address this, the researchers came up with a universal algorithm, so now they have a beast of a genie to order around that is flexible enough to adapt to any scenario. No matter in which particular way a quantum system has deteriorated, he can do his magic trick and rewind it back to its 'orderly' past. Admittedly, he will ask for tons and tons of marble and scorch it with the fires of hell, but it's never simple with genies. Perhaps this one's an afreet.



Genie Credit: Daria Sokol, MIPT

Magician's stage props

Here is a thought experiment to guide you through the process. Imagine you took a bunch of water molecules and used them to make a very unique-looking snowflake in a perfectly airtight box. Only you know the shape of the snowflake. You leave the box at room temperature for some time, and this ruins the snowflake in it. With the new time reversal algorithm—and some fancy thermal manipulations—the researchers claim they could restore your snowflake to its original shape. Here is how.

As conjuring tricks go, the physicists begin by complicating things a little with stage props: They will need an identical box with the same number of water molecules in it—remember the tons of marble. The water might be in a liquid or gaseous state, that is of no importance. You just have to guarantee that the two boxes contain the same stuff in the same amount. Now keep an eye on the sleight of hand that follows.

Once a twin box—also known as the auxiliary system—is available, the procedure involves four steps.

Step 1: **Thermalization**. Bring the twin box to a very high temperature by putting it in contact with a very hot body, called a heat reservoir.

Step 2: **Separation**. Disconnect the heat reservoir.

Step 3: **Manipulation**. Run a so-called noncomplete quantum SWAP operation between the twin box and the original one.

Step 4: **Reiteration**. Repeat steps 1 through 3 an ungodly number of times.

That sequence induces a time-reversed state of the original box with the ruined snowflake, meaning it will immediately begin backtracking its recent past until it assumes the initial state, freezing back into precisely the same shape you intended. Voila!

The paper in *Communications Physics* provides a formula for how many times the above cycle has to be repeated to reverse the state of a given system with respect to time. That is, to nudge it in precisely the right way to ensure backward evolution from the current state toward earlier states in the past. In short, the number is huge, and it rapidly grows with the system's complexity and with how far back in time it is supposed to go.

Genie Credit: Daria Sokol, MIPT

Pimp my qubit

Granted the Parthenon will probably have to wait, but the team is optimistic about a possible experiment that would briefly time-reverse a simple computer comprised by a small number of quantum bits. With two qubits, for example, it would take at least 16 cycle repetitions, with three it is 64, and so on.

Such an experiment is feasible with today's technology, but the problem is that the publicly available machines—such as the IBM quantum computer used in last year's study—do not support thermalization, which is the first step in the cycle. Come to think of it, expecting shared facilities to have specialized features of this kind is like asking your local car-sharing service for a jumping lowrider. So this time reversal experiment is awaiting a team willing to 'pimp up' a quantum computer of its own, custom-fitting it with a big bad heat reservoir.

While quantum mechanics as such is notoriously counterintuitive, there is one aspect of the new time reversal algorithm that leaves even physicists scratching their heads. "In general, the hotter a system, the more disorganized it gets. So if you think about it, what we are doing is using a tool associated with utter chaos—the heat reservoir—to bring about order," Andrey Lebedev explained. "We are repeatedly exposing the auxiliary system to an extremely high temperature with the ultimate goal of observing the primary system's cold and ordered past. It is a paradox we have yet to get our heads around."

How to test someone smarter than yourself

Universal time reversal algorithms might be used in the future to verify that a quantum computer operates correctly, and quantum advantage has been achieved. The thing is, once a quantum computer is vastly more powerful than other computers, how do you confirm it's not prone to errors without a comparable error-proof device?

Once a 52-qubit machine runs an advanced quantum algorithm, it will output an enormously complex quantum state. The conventional way for making sure no errors have been made would require a complete description of the end state. However, it would be beyond the powers of humanity.

That is where universal time reversal algorithms come in. If you can run the computation in reverse and do not care about the end state you are 'rewinding,' then there is no need to describe it. You just make sure you come back to precisely where you started.

So when quantum computers start cranking out scientific discoveries, time reversal will come in handy to confirm those are valid conclusions about the world rather than a quantum glitch of epic proportions.

More information: A. V. Lebedev et al. Time-reversal of an unknown quantum state, *Communications Physics* (2020). DOI: 10.1038/s42005-020-00396-0

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