Time-reversal of an unknown quantum state

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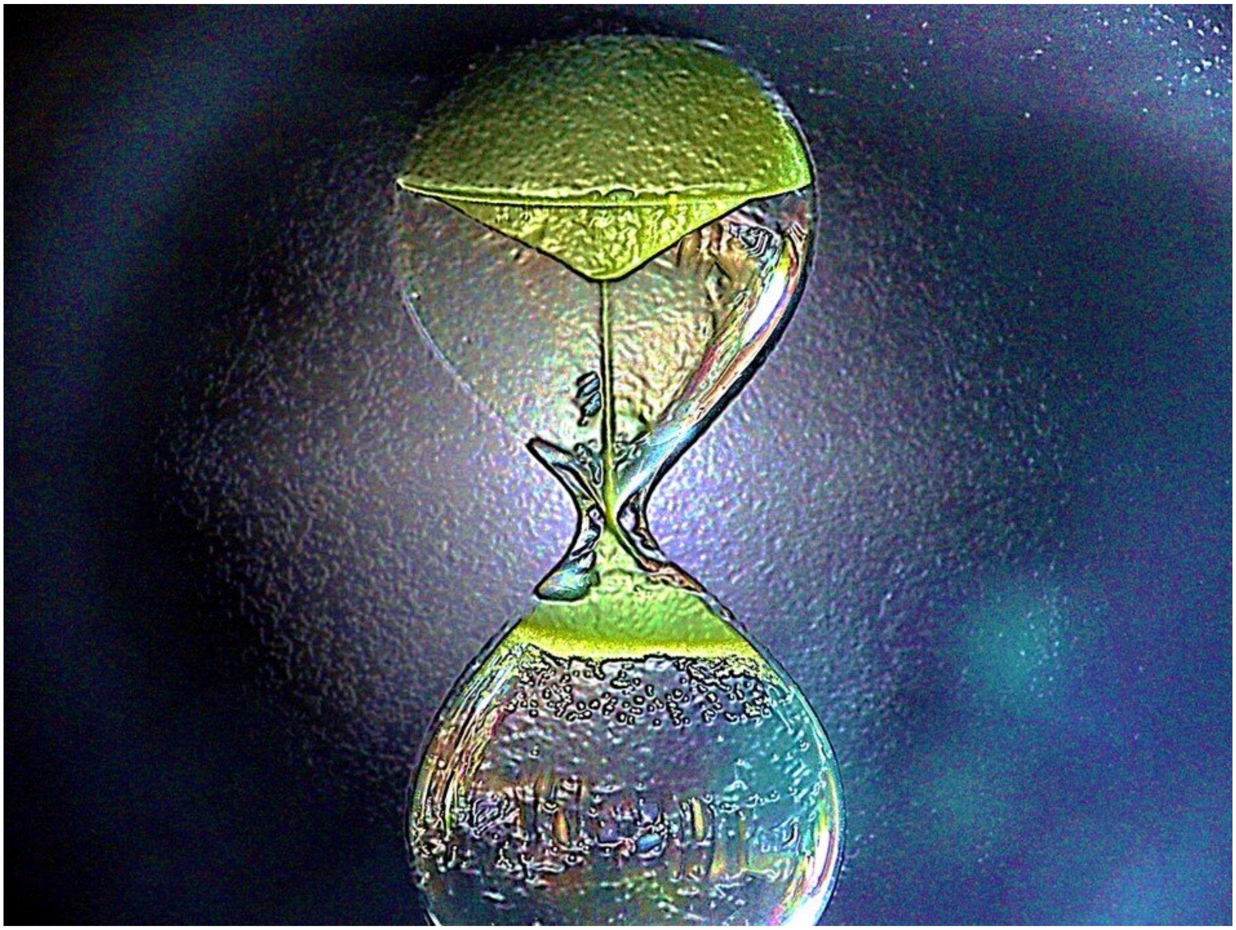

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Physicists have long sought to understand the irreversibility of the surrounding world and have credited its emergence to the timesymmetric, fundamental laws of physics. According to quantum mechanics, the final irreversibility of conceptual time reversal requires extremely intricate and implausible scenarios that are unlikely to spontaneously occur in nature. Physicists had previously shown that while time-reversibility is exponentially improbable in a natural environment—it is possible to design an algorithm to artificially reverse a time arrow to a known or given state within an IBM quantum computer. However, this version of the reversed arrow-of-time only embraced a known quantum state and is therefore compared to the quantum version of pressing rewind on a video to "reverse the flow of time."

In a new report now published in *Communications Physics*, Physicists A.V. Lebedev and V.M. Vinokur and colleagues in materials, physics and advanced engineering in the U.S. and Russia, built on their previous work to develop a technical method to reverse the temporal evolution of an arbitrary unknown quantum state. The technical work will open new routes for general universal algorithms to send the temporal evolution of an arbitrary system backward in time. This work only outlined the mathematical process of time reversal without experimental implementations.

The arrow of time and developing a time-reversal protocol

The arrow of time originates from expressing the direction of time in a singular route relative to the second law of thermodynamics, which implies that entropy growth stems from energy dissipation of the system to the environment. Scientists can therefore consider energy dissipation relative to the system's entanglement with the environment. Previous research solely focused on the quantum viewpoint of the arrow of time and on understanding the effects of the Landau-Neumann-Wigner hypothesis to quantify the complexity of reversing the arrow of time on an IBM quantum computer. In the present work, the scientists propose using a thermodynamic reservoir at finite temperatures to form a high-entropy stochastic bath to thermalize a given quantum system and experimentally increase thermal disorder or entropy in the system. However, experimentally, the IBM computers do not support thermalization, which forms the first step in the currently proposed cycle.

In theory, the presence of the thermal reservoir unexpectedly made it possible to prepare high-temperature thermal states of an auxiliary (alternative) quantum system elsewhere, governed by the same Hamiltonian (an operator corresponding to the sum of kinetic energy and potential energies for all particles in the system). This allowed Lebedev and Vinokur to mathematically devise an operator of backward-time evolution to reverse the chronological dynamics in a given quantum system.

Universal procedure and the auxiliary system

The team defined the universal time-reversal process of an unknown quantum state using the density matrix of a quantum system (a mixed state); to describe reversal of the temporal system's evolution to return to its original state. The quantum state of the new system could remain unknown while implementing the arrow of time reversal. In contrast to the previous protocol of time reversal of a known quantum state, the initial state did not have to be of a purely uncorrelated state either and could remain in a mixed state and correlate to past interactions with the environment. The team noted reduced time-reversal complexity for a mixed high-entropy state in the system.

Lebedev et al. drew upon the reversal procedure previously detailed by S. Lloyd, Mohseni and Rebentrost (LMR procedure) to construct or map the initial density matrix. The LMR procedure considered the combined arrangement of the system in question and an ancilla to accomplish reversible computation. The experimental system will be equipped with a thermodynamic bath to thermalize the ancilla and provide the desired state for reverse evolution. The hotter the system, the more chaotic it would become. By using a heat reservoir to expose the auxiliary system to an extremely high temperature, Lebedev et al. paradoxically aim to experimentally observe the primary system's cold and ordered past using the LMR formula. The authors reason that a universal time reversal algorithm can run a computation in reverse, without a specific quantum state to rewind to, as long as the algorithm facilitates time reversal to its point of origin.

Computational complexity of the time-reversal procedure

The work only outlined the mathematical analysis of time reversal without specifying experimental implementations. While exercising time reversal, the proposed system continued to maintain the forward evolution governed by its own Hamiltonian. The computational complexity of time reversal for an unknown quantum state was proportional to the square of the system's Hilbert space dimension (an abstract vector space). To accomplish this in practice, the experimental system will require a natural system that evolves under an unknown Hamiltonian alongside thermalization, which quantum computers do not support, paired with universal quantum gates to achieve time reversal. As a result, practical implementation of this work will require an upgrade to existing quantum computers to meet the outlined requirements.

A route to upgrade the existing design of quantum chips

Lebedev et al. therefore aim to upgrade the existing design of quantum chips to achieve a set of interacting qubits (quantum bits) that can thermalize on-demand in a high-temperature environment. To accomplish this, superconducting qubits can be coupled with a transmission line where high-temperature thermal radiation will be fed to set the qubits to a high-temperature state. Thereafter, they will require a second set of qubits that can store a quantum state similar to the original set of qubits. When the original set of qubits are then experimentally thermalized to implement the joint LMR evolution, subsequent qubits will be able to undergo time-reversed dynamics under the same Hamiltonian to reach the original state. If accurately implemented, the proposed mechanism will also facilitate error-correction of an upgraded quantum computer to confirm its correct function. Lebedev et al. envision implementing the procedure on emergent computers with on-demand thermalized qubits.

In this way, Lebedev and Vinokur demonstrated the time reversal procedure of an unknown mixed quantum state. The process relies on performing the LMR protocol and the existence of an ancilla system, whose dynamics can be governed by the same Hamiltonian as the Hamiltonian of the reversed system. To accomplish the reversal procedure the LMR protocol will need to be applied sequentially to the joint state of the system and ancilla, prepared in a thermal state. The work developed a formula to highlight the number of cycles that should be repeated to reverse the state of a given system towards earlier states in the past. This number will depend on the system's complexity and how far back in time it is supposed to go. When implementing the time reversal protocol, the operation rate of the LMR procedure should be sufficiently high, to overrun the forward time evolution of the reversed system.

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

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