Quantum Maxwell's demon 'teleports' entropy out of a qubit

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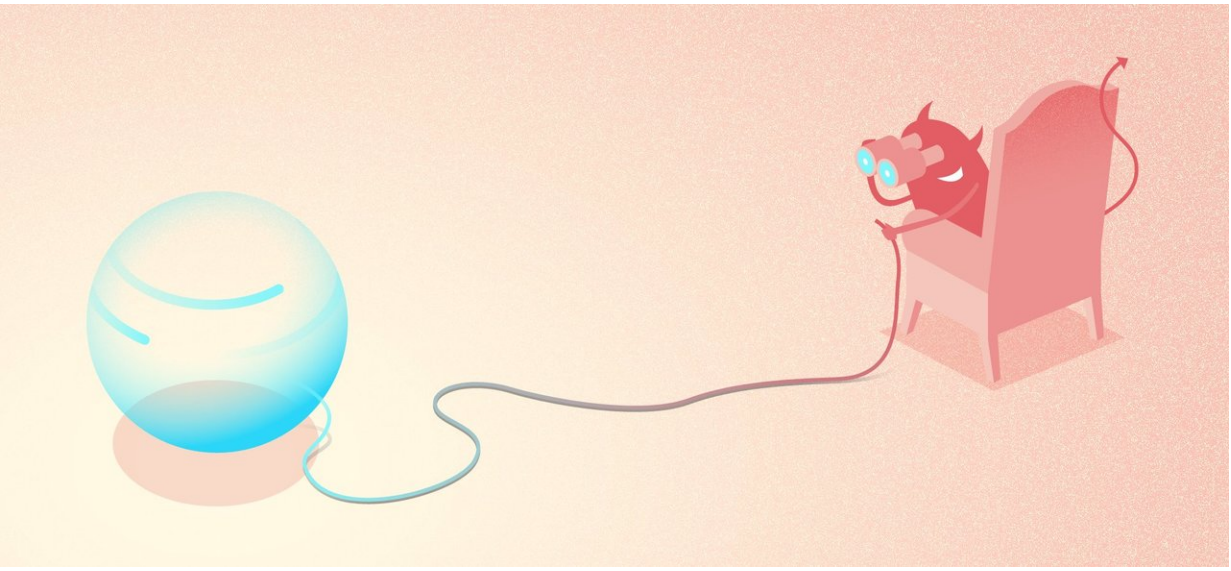

Extended Maxwell's demon. Credit: @tsarcyanide/MIPT

Researchers from the Moscow Institute of Physics and Technology, ETH Zurich, and Argonne National Laboratory, U.S, have described an extended quantum Maxwell's demon, a device locally violating the second law of thermodynamics in a system located one to five meters away from the demon. The device could find applications in quantum computers and microscopic refrigerators that cool down tiny objects with pinpoint accuracy. The research was published Dec. 4 in *Physical Review B*.

The second law of thermodynamics says that in an isolated system, entropy, the degree of disorder or randomness, never decreases.

"Our demon causes a device called a qubit to transition into a more orderly state," explained the study's lead author, Andrey Lebedev of MIPT and ETH Zurich. "Importantly, the demon does not alter the qubit's energy and acts over a distance that is huge for quantum mechanics."

All quantum Maxwell's demons described or created so far by the authors or other researchers have had a very limited range of action—they were situated near the object on which they operated.

Because the demon needs to be "initialized," or prepared, prior to each interaction with the qubit, some energy is inevitably spent at the location of the demon. This means that globally, the second law still holds.

Demonic 'purity'

The study proposes the qubit be implemented as a superconducting artificial atom, a microscopic device like the one the researchers previously proposed for use as a quantum magnetometer. Such a qubit would be made of thin aluminum films deposited on a silicon chip. The reason this system is called an artificial atom is that at temperatures close to absolute zero, it behaves like an atom with two basis states: the ground and the excited states.

A qubit can simultaneously exhibit mixed "pure" and "impure" states. If a qubit is in one of the two basis states, but it is not known for sure which, its state is referred to as "impure." If that is the case, a classical probability for finding the artificial atom in one of the two states may be calculated.

However, just like a real atom, the qubit may be in a quantum superposition of the ground and the excited states. A quantum superposition is a special state that can be reduced to neither of the basis states. This so-called pure state, which defies the classical notion of probability, is associated with more order, and therefore less entropy. It can only exist for a fraction of a second before degenerating back into an impure state.

The demon described in the paper is another qubit connected to the first one by a coaxial cable carrying microwave signals. A consequence of the Heisenberg uncertainty principle is that once connected by a transmission line, the qubits start exchanging virtual photons, portions of microwave radiation. This photon exchange enables the qubits to swap their states.

If a pure state is artificially induced in the demon, it can then swap states with the target qubit, endowing it with "purity" in return for an impure state of the same energy. By purifying the target qubit, its entropy is reduced but its energy is not affected. The result is that the demon channels entropy away from a system isolated in terms of energy—namely, the target qubit. This results in the apparent violation of the second law if the target qubit is considered locally.

Quantum nanorefrigerator

Being able to purify a target qubit over a macroscopic distance is important from a practical standpoint. Unlike the impure state, the pure one can be switched into the ground or the excited state in a relatively straightforward and predictable way using an electromagnetic field. This operation may be useful in a quantum computer, whose qubits need to be switched into the ground state upon launch. Doing this from a distance is important, since the presence of a demon close to the quantum computer would affect the latter in adverse ways.

Another possible application of the demon has to do with the following: Switching the target qubit into the pure and subsequently into the ground state makes its immediate environment slightly colder. This turns the proposed system into a nanosized refrigerator capable of cooling parts of molecules with pinpoint accuracy.

"A conventional refrigerator cools its entire volume, while the qubit 'nanofridge' would target a particular spot. This might well be more effective in some cases," explained the paper's co-author Gordey Lesovik, who heads MIPT's Laboratory of the Physics of Quantum Information Technology. "For example, you could implement what's known as algorithmic cooling. This would involve supplying the code of a primary, 'quantum' program with a subprogram designed to target-cool specifically the hottest qubits.

"A further twist is that with any 'heat machine,' you can run it in reverse, turning a heat engine into a refrigerator or vice versa," added the physicist. "This lands us with a highly selective heater, as well. To turn it on, we would switch the target qubit into the excited rather than the ground state, making the qubit's whereabouts hotter."

This cooling or heating cycle could be run repeatedly, since the target qubit retains its pure state for a brief time, after which it enters the impure state, consuming or emitting the thermal energy of the environment. With every iteration, the location of the qubit becomes progressively cooler or warmer, respectively.

Besides the range of the demon, the authors have estimated the maximum temperature of the coaxial cable running between the qubits. Above this temperature, the quantum properties of the system are lost and the demon no longer works. Although the cable temperature may not exceed a few degrees above the absolute zero, this is nevertheless about 100 times hotter than the working temperature of the qubits. This makes

it considerably easier to implement the proposed setup experimentally.

The team is already working on implementing the experiment.

More information: A. V. Lebedev et al. Extended quantum Maxwell demon acting over macroscopic distances, *Physical Review B* (2018). DOI: 10.1103/PhysRevB.98.214502

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