

Physicist Proposes Solution to Arrow-of-Time Paradox

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A new theory suggests that we don't observe phenomena where entropy decreases because all evidence from these processes is erased when correlations are removed from the system. Image credit: cguu.com.

(PhysOrg.com) -- Entropy can decrease, according to a new proposal but the process would destroy any evidence of its existence, and erase any memory an observer might have of it. It sounds like the plot to a weird sci-fi movie, but the idea has recently been suggested by theoretical physicist Lorenzo Maccone, currently a visiting scientist at MIT, in an attempt to solve a longstanding paradox in physics.



The laws of physics, which describe everything from electricity to moving objects to energy conservation, are time-invariant. That is, the laws still hold if time is reversed. However, this time reversal symmetry is in direct contrast with everyday phenomena, where it's obvious that time moves forward and not backward. For example, when milk is spilt, it can't flow back up into the glass, and when pots are broken, their pieces can't shatter back together. This irreversibility is formalized through the second law of thermodynamics, which says that entropy always increases or stays the same, but never decreases.

This contrast has created a reversibility paradox, also called Loschmidt's paradox, which scientists have been trying to understand since Johann Loschmidt began considering the problem in 1876. Scientists have proposed many solutions to the conundrum, from trying to embed irreversibility in physical laws to postulating low-entropy initial states.

Maccone's idea, published in a recent issue of <u>Physical Review Letters</u>, is a completely new approach to the paradox, based on the assumption that <u>quantum mechanics</u> is valid at all scales. He theoretically shows that entropy can both increase and decrease, but that it must always increase for phenomena that leave a trail of information behind. Entropy can decrease for certain phenomena (when correlated with an observer), but these phenomena won't leave any information of their having happened. For these situations, it's like the phenomena never happened at all, since they leave no evidence. As Maccone explains, the second law of thermodynamics is then reduced to a mere tautology: physics cannot study processes where entropy has decreased, due to a complete absence of information. The solution allows for time-reversible phenomena to exist (in agreement with the laws of physics), but not be observable (in agreement with the second law of thermodynamics).

In his study, Maccone presents two thought experiments to illustrate this idea, followed by an analytical derivation. He describes two situations



where entropy decreases and all records of it are permanently erased. In both scenarios, the entropy in the systems first increases and then decreases, but the decrease is accompanied by an erasure of any memory of its occurrence. The key to entropy decrease in the first place is a correlation between the observer and the phenomenon in question. As Maccone explains, when an interaction occurs between an observer and an observed phenomenon that decreases the entropy of the correlated observer-observed system, the interaction must also reduce their quantum mutual information. When this information is destroyed, the observer's memory is destroyed along with it.

In the first situation where entropy decreases, Maccone describes a situation where Bob sends Alice some energy in the form of light, initially in a zero-entropy state. Using detectors, Alice receives the light and observes her detectors warming up, revealing that heat has been lost and entropy is increasing in her isolated lab.

However, Bob can theoretically manipulate the situation by withdrawing the energy he has sent Alice, and then erasing all evidence of the energy's existence - including erasing her memory and the notepads where she wrote the detectors' temperatures. First, to recover the energy, Bob must return the energy to a zero-entropy state. He does this by erasing all correlations between the energy and Alice, and any other macroscopic systems in the lab. By erasing all initial correlations, Bob can enable the system to lose entropy. Although the act of decorrelating requires energy, Maccone explains that it doesn't necessarily cause entropy to increase.

"Any physical transformation requires energy (no energy implies no time evolution, i.e. a static system)," he told *PhysOrg.com*. "This, however, doesn't automatically imply that entropy is increased. Entropy increases when (part of) the energy employed becomes unusable as waste heat.



"Some energy is employed in the decorrelation transformation. Not only is such energy still available afterwards, but the decorrelation might also decrease the entropy in two systems, and that can 'free' some more energy that was previously unavailable (as it was locked up as heat)."

The second situation where entropy decreases involves a quantum measurement instead of a classical one. Here, Bob sends Alice a particle in a specific spin state. Alice performs a quantum measurement that consists of coupling the particle with a macroscopic reservoir, which increases the entropy of the system. But once again, Bob can theoretically manipulate the situation, this time by inverting the transformation of Alice's measurement. This action decorrelates all records of Alice's measurement results from the spin state. Although Alice remembers performing the experiment, she has no memory or evidence of what the measurement result was, and the spin is back to its initial zero-entropy state.

Although theoretically possible, these situations in which entropy decreases would be very difficult to demonstrate experimentally, due to the difficulty in manipulating macroscopic correlations. That is why, for all practical purposes, these phenomena are unobservable by physics. Still, as Maccone explains, the theory is a straightforward application of quantum mechanics when applied to macroscopic systems, and could potentially be verified.

"I think that if quantum coherence can be indubitably proven on a macroscopic observer (not necessarily a human being), then my approach would be verified," he said. "An experiment of the sort of the second thought experiment, for example. The state of the art of experiments is quite far from anything of that sort. The biggest system where quantum coherence has been experimentally shown is, I think, some biological molecule composed of a few hundred atoms by A. Zeilinger's group in Vienna."



The explanation may also provide insight into understanding entropy in the universe. The approach supports the idea that the universe may be in a state of zero entropy, even though it appears to us observers to have higher <u>entropy</u>. As Maccone explains, the universe is in a zero-entropy pure state because it cannot be entangled with any other system.

"My theory requires that the global state of the observer plus the environment be in a quantum pure state," he said. "This means that it works only if we consider a sufficiently large system that it cannot be correlated with any other system. However, correlations (entanglement, in quantum systems) are very sticky; namely, systems get correlated very quickly also if they are very weakly interacting. This is why, when one considers macroscopic systems, the only safe choice is to consider the whole universe, which cannot be correlated with any other system, since, by definition, it comprises all physical systems."

More information: Lorenzo Maccone. "Quantum Solution to the Arrowof-Time Dilemma." *Physical Review Letters* 103, 080401 (2009).

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